INTERNATIONAL STANDARD

IEC 60041

Third edition
1991-11

Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

*This **English-language** version is derived from the original **bilingual** publication by leaving out all French-language pages. Missing page numbers correspond to the French-language pages.*

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Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

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IEC Publication 41
(Third edition – 1991)

Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

CORRIGENDUM 1

Page 3

CONTENTS

In the title of subclause 4.1, instead of

. . . provision for the test . . .

read

. . . provision for test . . .

Page 13

In clause 1, **Scope and object**, *change the numeration in order to obtain (as on page 12):*

1 **Scope and object**

1.1 *Scope*

1.1.1 This International Standard . . .

1.1.2 Model tests, when used . . .

1.1.3 Tests of speed . . .

1.2 *Object*

1.3 *Types of machines*

Page 17

In the table, subclause 2.3.1.7 (Limits), replace the existing symbols by the following new symbols:

. . . not to be exceeded 

. . . to be reached ○ or 

Page 29

In the table, subclause 2.3.6.4, third column, in the sixth line, instead of

$$\ldots \text{ and } \bar{g} = -\frac{g_3 + g_4}{2}$$

read

$$\ldots \text{ and } \bar{g} = \frac{g_3 + g_4}{2}$$

Page 35, figure 5b

In the upper part of the diagram, rearrange the two existing equations so as to place them together, on the right-hand side, above the diagram describing a "Horizontal shaft unit" as follows:

$$Z_1 = z_{1'} - z_1$$
$$Z_2 = z_{2'} - z_2$$

Page 37, figure 5c

Add, at the right-hand side of the diagram, level with the arrowhead, the following equation:

$$z_1 = z_2$$

Page 129

10.2.3.2 Additional requirements

In the fifth paragraph, instead of

Annexes F and G of ISO 3354:

read

Annexes H and J of ISO 3354:

Page 141

10.2.5.6 Computation of discharge

In the eighth line of text, instead of

m is the coefficient . . .

read

m is a coefficient . . .

Page 195, figure 34b

In the legends below the diagram, on the right-hand side; in the first line, instead of

. . . (geodesic . . .

read

. . . (geodetic . . .

third line, instead of

$$z_B{}' = z_B{}' - z_B \ldots$$

read

$$Z_B{}' = z_B{}' - z_B \ldots$$

Page 205, figure 37

Same correction as on page 35 (see above)

Page 207, figure 38

Same correction as on page 37 (see above)

Page 213

In the framed equation at the top of the page, after the H add an equal sign (=); instead of

$$E = \bar{g} \cdot H \frac{(p_{\text{abs}_1} - p_{\text{abs}\,2})}{} + \frac{(v_1^2 - v_2^2)}{2} + \bar{g} \cdot (z_1 - z_2)$$

read

$$E = \bar{g} \cdot H = \frac{(p_{\text{abs}_1} - p_{\text{abs}\,2})}{} + \frac{(v_1^2 - v_2^2)}{2} + \bar{g} \cdot (z_1 - z_2)$$

Page 215

In the equation following figure 41, instead of

$$NPSE = g_2 \cdot NPSH = \frac{(p_{\text{abs}_2} - p_{\text{va}})}{\rho_2} + \frac{v_2^2}{2} + g_2 \cdot (z_r - z_2)$$

read

$$NPSE = g_2 \cdot NPSH = \frac{(p_{\text{abs}_2} - p_{\text{va}})}{\rho_2} + \frac{v_2^2}{2} - g_2 \cdot (z_r - z_2)$$

Page 219, figure 42

In the legends under the diagram, instead of

d = 3 mm à 6 mm

read

d = 3 mm to 6 mm

Page 229, figure 45a

In the third line of the legends half-way up the diagram, instead of

Δp = differential-pressure

read

Δp = differential pressure

Under the diagram, in the formula for p_M, delete one Δ in order to read:

$$p_{\mathrm{M}} = p_1 + \rho \cdot g \cdot h_1 = p + \rho_{\mathrm{oil}} \cdot g \cdot (h_2 - h_1) + \rho \cdot g \cdot h_1 + \Delta p$$

Page 257

Under equation (4), in the last formula on the page, align indices; instead of

$$\cos \varphi_s = \frac{P_{\mathrm{as}}(2w)}{\sqrt{3} \cdot U_s \cdot I_s}$$

read

$$\cos \varphi_s = \frac{P_{\mathrm{as(2w)}}}{\sqrt{3} \cdot U_s \cdot I_s}$$

Page 303

In the penultimate line of the page:

instead of “ou”, *read* “or”.

Correction in the French text only

Page 323

Subclause 15.2.1.1, second paragraph, last line, instead of

. . . *n* theoretically equal to . . .

read

. . . *n* is theoretically equal to . . .

Page 357

In the first line and third line of text, just below table C.1, instead of "$\overline{Y}$*" and "*$\overline{Y}_r$*" read* Y_r

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

FIELD ACCEPTANCE TESTS TO DETERMINE THE HYDRAULIC PERFORMANCE OF HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES

FOREWORD

1) The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

2) They have the form of recommendations for international use and they are accepted by the National Committees in that sense.

3) In order to promote international unification, the IEC expresses the wish that all National Committees should adopt the text of the IEC recommendation for their national rules in so far as national conditions will permit. Any divergence between the IEC recommendation and the corresponding national rules should, as far as possible, be clearly indicated in the latter.

PREFACE

This International Standard has been prepared by IEC Technical Committee No. 4: Hydraulic turbines.

It replaces the second edition of IEC 41, the first edition of IEC 198 and the first edition of IEC 607.

The text of this standard is based on the following documents:

Six Months' Rule	Report on Voting
4 (CO) 48	4 (CO) 52

Full information on the voting for the approval of this standard can be found in the Voting Report indicated in the above table.

The following IEC publications are quoted in this standard:

Publications Nos. 34-2 (1972): Rotating electrical machines. Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests (excluding machines for traction vehicles).

34-2A (1974): First supplement: Measurement of losses by the calorimetric method.

185 (1987): Current transformers.

186 (1987): Voltage transformers.
Amendment No.1 (1988).

193 (1965): International code for model acceptance tests of hydraulic turbines.
Amendment No.1 (1977).

193A (1972): First supplement.

308 (1970): International code for testing of speed governing systems for hydraulic turbines.

497 (1976): International code for model acceptance tests of storage pumps.

545 (1976): Guide for commissioning, operation and maintenance of hydraulic turbines.

609 (1978): Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines.

805 (1985): Guide for commissioning, operation and maintenance of storage pumps and of pump-turbines operating as pumps.

ISO standards quoted:

Publications Nos.	31–3	(1978):	Quantities and units of mechanics. Amendment 01–1985.
	748	(1979):	Liquid flow measurements in open channels – Velocity-area methods.
	1438–1	(1980):	Water flow measurement in open channels using weirs and Venturi flumes-Part 1: Thin-plate weirs.
	2186	(1973):	Fluid flow in closed conduits – Connections for pressure signal transmissions between primary and secondary elements.
	2533	(1975):	Standard Atmosphere. Addendum 01–1985.
	2537	(1988):	Liquid flow measurement in open channels – Rotating element current-meters.
	2975:		Measurement of water flow in closed conduits – Tracer methods.
	2975–1	(1974):	Part I: General.
	2975–2	(1975):	Part II: Constant rate injection method using non-radioactive tracers.
	2975–3	(1976):	Part III: Constant rate injection method using radioactive tracers.
	2975–6	(1977):	Part VI: Transit time method using non-radioactive tracers.
	2975–7	(1977):	Part VII: Transit time method using radioactive tracers.
	3354	(1988):	Measurement of clean water flow in closed conduits – Velocity area method using current-meters in full conduits and under regular flow conditions.
	3455	(1976):	Liquid flow measurement in open channels – Calibration of rotating-element current-meters in straight open tanks.
	3966	(1977):	Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes.
	4373	(1979):	Measurement of liquid flow in open channels – Water level measuring devices.
	5167	(1980):	Measurement of fluid flow by means of orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full.
	5168	(1978):	Measurement of fluid flow – Estimation of uncertainty of a flow-rate measurement.
	7066:		Assessment of uncertainty in the calibration and use of flow measurement devices.
	7066–1	(1989):	Part 1: Linear calibration relationships.
	7066–2	(1988):	Part 2: Non-linear calibration relationships.

FIELD ACCEPTANCE TESTS TO DETERMINE THE HYDRAULIC PERFORMANCE OF HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES

SECTION ONE – GENERAL RULES

Scope and object

1 *Scope*

1.1 This International Standard covers the arrangements for tests at the site to determine the extent to which the main contract guarantees (see 3.2) have been satisfied. It contains the rules governing their conduct and prescribes measures to be taken if any phase of the tests is disputed. It deals with methods of computation of the results as well as the extent, content and style of the final report.

1.2 Model tests, when used for acceptance purposes, are dealt with in IEC 193 with Amendment No. 1, first supplement 193 A, and in IEC 497.

1.3 Tests of speed governing systems are dealt with in IEC 308.

2 *Object*

The purpose of this standard for field acceptance tests of hydraulic turbines, storage pumps or pump-turbines, also called the machine, is:

- to define the terms and quantities which are used;
- to specify methods of testing and ways of measuring the quantities involved in order to ascertain the hydraulic performance of the machine;
- to determine if the contract guarantees which fall within the scope of this standard have been fulfilled.

The decision to perform field acceptance tests including the definition of their scope is the subject of an agreement between the purchaser and the supplier of the machine. For this, it has to be examined in each case, whether the measuring conditions recommended in this standard can be realized. The influence on the measuring uncertainties, due to hydraulic and civil conditions has to be taken into account.

If the actual conditions for field acceptance tests do not allow compliance with the guarantees to be proved, it is recommended that acceptance tests be performed on models (see 1.1.2).

3 *Types of machines*

In general, this standard applies to any size and type of impulse or reaction turbine, storage pump or pump-turbine. In particular, it applies to machines coupled to electric generators, motors or motor-generators.

For the purpose of this standard the term turbine includes a pump-turbine functioning as a turbine and the term pump includes a pump-turbine functioning as a pump. The term generator includes a motor-generator functioning as a generator and the term motor includes a motor-generator functioning as a motor.

1.4 *Reference to IEC and ISO Standards*

IEC and ISO Standards referred to in this standard are listed in the preface. If a contradiction is found between this standard and another IEC or ISO standard, this standard shall prevail.

1.5 *Excluded topics*

1.5.1 This standard excludes all matters of a purely commercial interest except those inextricably bound up with the conduct of the tests.

1.5.2 This standard is concerned neither with the structural details of the machines nor with the mechanical properties of their components.

2. Terms, definitions, symbols and units

2.1 *General*

The common terms, definitions, symbols and units used throughout the standard are listed in this clause. Specialised terms are explained where they appear.

The following terms are given in 5.1.2 and Figure 11:

1) A *run* comprises the readings and/or recordings sufficient to calculate the performance of the machine at one operating condition.

2) A *point* is established by one or more consecutive runs at the same operating conditions and unchanged settings.

3) A *test* comprises a collection of data and results adequate to establish the performance of the machine over the specified range of operating conditions.

The clarification of any contested term, definition or unit of measure shall be agreed to in writing by the contracting parties, in advance of the test.

2.2 *Units*

The International System of Units (SI) has been used throughout this standard*.

All terms are given in SI base units or derived coherent units (e.g. N instead of $kg \cdot m \cdot s^{-2}$). The basic equations are valid using these units. This has to be taken into account, if other than coherent SI Units are used for certain data (e.g. kilowatt or megawatt instead of watt for power, kilopascal or bar (= 10^5 Pa) instead of pascal for pressure, min^{-1} instead of s^{-1} for rotational speed, etc.). Temperatures may be given in degrees Celsius because thermodynamic (absolute) temperatures (in kelvins) are rarely required.

Any other system of units may be used but only if agreed to in writing by the contracting parties.

2.3 *List of terms, definitions, symbols and units*

2.3.1 *Subscripts and symbols*

The terms high pressure and low pressure define the two sides of the machine irrespective of the flow direction and therefore are independent of the mode of operation of the machine.

* See ISO 31-3.

Sub-clause	Term	Definition	Subscript symbol
2.3.1.1	High pressure reference section	The high pressure section of the machine to which the performance guarantees refer (see Figure 1)	1
2.3.1.2	Low pressure reference section	The low pressure section of the machine to which the performance guarantees refer (see Figure 1)	2
2.3.1.3	High pressure measuring sections	Whenever possible these sections should coincide with section 1: otherwise the measured values shall be adjusted to section 1 (see 11.2.1)	1′, 1″, . . .
2.3.1.4	Low pressure measuring sections	Whenever possible these sections should coincide with section 2: otherwise the measured values shall be adjusted to section 2 (see 11.2.1)	2′, 2″, . . .
2.3.1.5	Specified	Subscript denoting values of quantities such as speed, discharge etc. for which other quantities are guaranteed	sp
2.3.1.6	Maximum Minimum	Subscripts denoting maximum or minimum values of any term	max min
2.3.1.7	Limits	Contractually defined values: – not to be exceeded – to be reached	
2.3.1.8	Ambient	Subscript referring to surrounding atmospheric conditions	amb

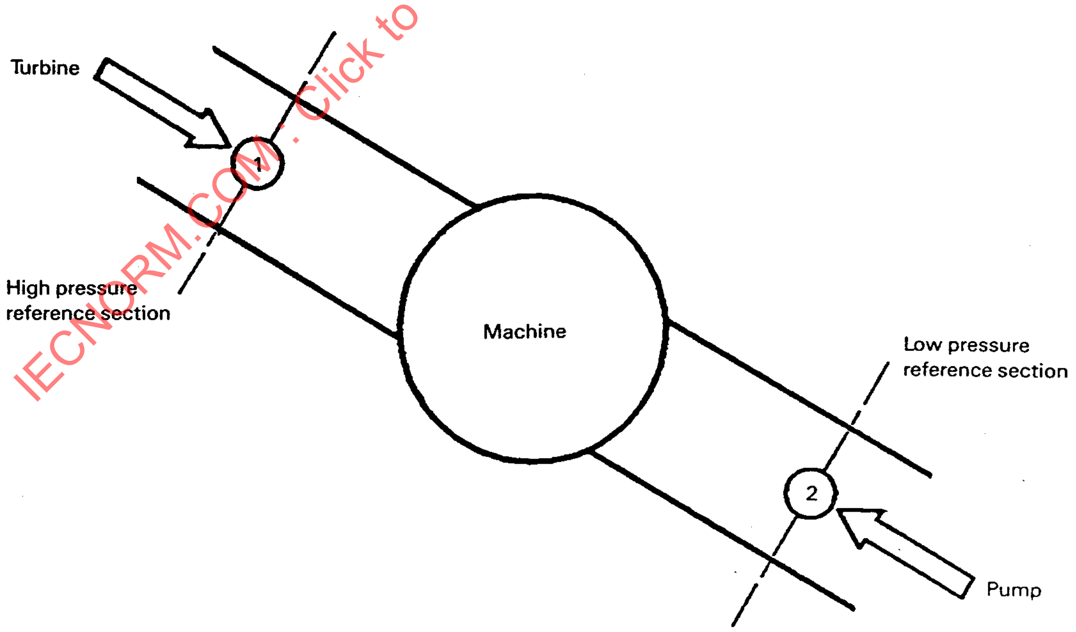


Figure 1 – Schematic representation of a hydraulic machine

2.3.2 *Geometric terms*

Sub-clause	Term	Definition	Symbol	Unit
2.3.2.1	Area	Net cross sectional area normal to general flow direction	A	m^2
2.3.2.2	Guide vane opening	Average vane angle measured from closed position* or average shortest distance between adjacent guide vanes (at a defined position, if necessary) (see Figure 2)	α a	degree m
2.3.2.3	Needle opening (impulse turbine)	Average needle stroke measured from closed position*	s	m
2.3.2.4	Runner blade opening	Average runner blade angle measured from a given position*	β	degree
2.3.2.5	Level	Elevation of a point in the system above the reference datum (usually mean sea level)	z	m
2.3.2.6	Difference of levels	Difference of elevation between any two points in the system	Z	m

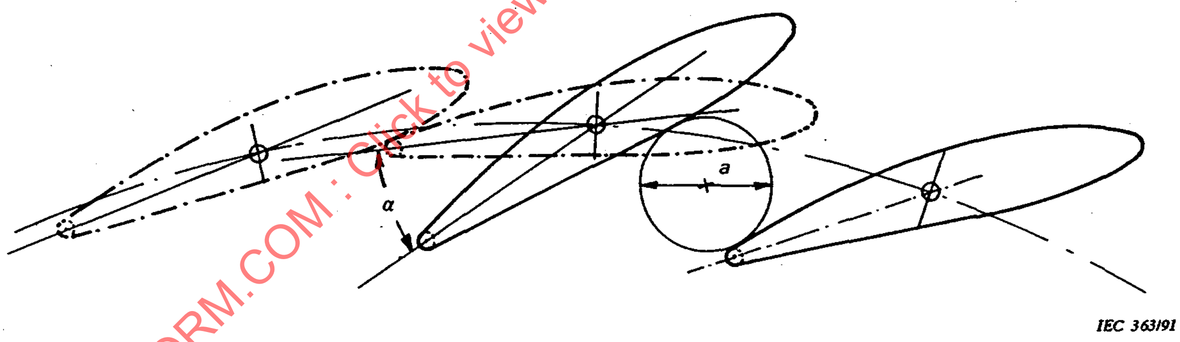


Figure 2 – Guide vane opening (from closed position)

* Under normal working oil pressure.

2.3.3 *Physical quantities and properties*

Sub-clause	Term	Definition	Symbol	Unit
2.3.3.1	Acceleration due to gravity	Local value of g as a function of altitude and latitude of the place of testing (see Appendix E, Table EI)	g	$m \cdot s^{-2}$
2.3.3.2	Temperature	Thermodynamic temperature; Celsius temperature $\vartheta = \Theta - 273,15$	Θ ϑ	K °C
2.3.3.3	Density	Mass per unit volume *a)* Values for water are given in Appendix E, Table EII (ϱ is commonly used instead of ϱ_w) *b)* Values for air are given in Appendix E, Table EIII. Usually the value of air density at the reference level of the machine (see 2.3.7.10) is used *c)* Values for mercury are given in Appendix E, Table EIV	ϱ ϱ_w ϱ_a ϱ_{Hg}	$kg \cdot m^{-3}$ $kg \cdot m^{-3}$ $kg \cdot m^{-3}$ $kg \cdot m^{-3}$
2.3.3.4	Specific volume	Volume per unit mass. Used only for water in this standard	$1/\varrho$	$m^3 \cdot kg^{-1}$
2.3.3.5	Isothermal factor	Factor characterizing a thermodynamic property. Values for water are given in Appendix E, Table EV	a	$m^3 \cdot kg^{-1}$
2.3.3.6	Specific heat capacity	The rate of change of enthalpy per unit mass with change in temperature at constant pressure. Values for water are given in Appendix E, Table EVI	c_p	$J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ or $J \cdot kg^{-1} \cdot K^{-1}$
2.3.3.7	Vapour pressure (absolute)	For purposes of this standard the absolute partial pressure of the vapour in the gas mixture over the liquid surface is the saturation vapour pressure corresponding to the temperature. Values for distilled water are given in Appendix E, Table EVII	p_{va}	Pa
2.3.3.8	Dynamic viscosity	A quantity characterising the mechanical behaviour of a fluid (see ISO 31-3)	μ	$Pa \cdot s$
2.3.3.9	Kinematic viscosity	Ratio of the dynamic viscosity to the density: $\nu = \frac{\mu}{\varrho}$	ν	$m^2 \cdot s^{-1}$

2.3.4 *Discharge, velocity and speed terms*

Sub-clause	Term	Definition	Symbol	Unit
2.3.4.1	Discharge (volume flow rate)	Volume of water per unit time flowing through any section in the system	Q	$m^3 \cdot s^{-1}$
2.3.4.2	Mass flow rate	Mass of water flowing through any section of the system per unit time. Both ϱ and Q must be determined at the same section and at the conditions existing in that section *Note.* – The mass flow rate is constant between two sections if no water is added or removed.	(ϱQ)	$kg \cdot s^{-1}$
2.3.4.3	Measured discharge	Volume of water per unit time flowing through any measuring section, for example 1′ (see 2.3.1.3 and 2.3.1.4)	$Q_{1'}$ or $Q_{2'}$	$m^3 \cdot s^{-1}$
2.3.4.4	Discharge at reference section	Volume of water per unit time flowing through the reference section 1 or 2	Q_1 or Q_2	$m^3 \cdot s^{-1}$
2.3.4.5	Corrected discharge at reference section	Volume of water per unit time flowing through a reference section referred to the ambient pressure (see 2.3.5.2) e.g. $Q_{1c} = (\varrho Q)_1 / \varrho_{p\,amb}$ (see 3.2.3) where $\varrho_{p\,amb}$ is the density at ambient pressure and the water temperature at the reference section	Q_{1c} or Q_{2c}	$m^3 \cdot s^{-1}$
2.3.4.6	No-load turbine discharge	Turbine discharge at no-load, at specified speed and specified specific hydraulic energy and generator not excited	Q_0	$m^3 \cdot s^{-1}$
2.3.4.7	Index discharge	Discharge given by relative (uncalibrated) flow measurement (see Clause 15)	Q_i	$m^3 \cdot s^{-1}$
2.3.4.8	Mean velocity	Discharge divided by the area A	v	$m \cdot s^{-1}$
2.3.4.9	Rotational speed	Number of revolutions per unit time	n	s^{-1}
2.3.4.10	No load turbine speed	The steady state turbine speed at no load with governor connected and generator not excited	n_0	s^{-1}
2.3.4.11	Initial speed	The steady state turbine speed just before a change in operating conditions is initiated (see Figure 3)	n_i	s^{-1}
2.3.4.12	Final speed	The steady state turbine speed after all transient waves have been dissipated (see Figure 3)	n_f	s^{-1}
2.3.4.13	Momentary overspeed of a turbine	The highest speed attained during a sudden specified load rejection from a specified governor setting (see Figure 3)	n_m	s^{-1}
2.3.4.14	Maximum momentary overspeed of a turbine	The momentary overspeed attained under the most unfavourable transient conditions (in some cases the maximum momentary overspeed can exceed the maximum steady state runaway speed)	$n_{m\,max}$	s^{-1}
2.3.4.15	Maximum steady state runaway speed	The speed for that position of needles or guide vanes and/or runner/impeller blades which gives the highest value after all transient waves have been dissipated with electrical machine disconnected from load or network and not excited, under the maximum specific hydraulic energy (head). The runaway speed particularly of high specific speed machines may be influenced by cavitation and thus depends on the available NPSE (see 2.3.6.9)	$n_{R\,max}$	s^{-1}

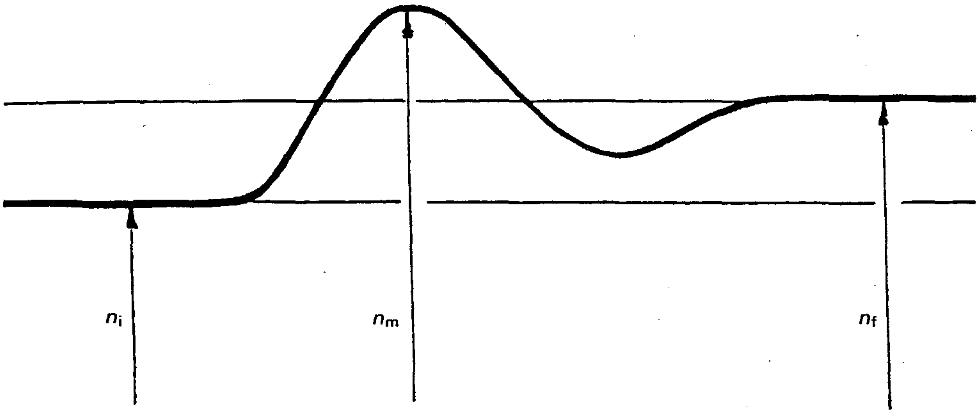


Figure 3 – Variation of turbine speed during a sudden load rejection

2.3.5 *Pressure terms*

Sub-Clause	Term	Definition	Symbol	Unit
2.3.5.1	Absolute pressure	The static pressure of a fluid measurement with reference to a perfect vacuum	p_{abs}	Pa
2.3.5.2	Ambient pressure	The absolute pressure of the ambient air	p_{amb}	Pa
2.3.5.3	Gauge pressure	The difference between the absolute pressure of a fluid and the ambient pressure at the place and time of measurement: $p = p_{abs} - p_{amb}$	p	Pa
2.3.5.4	Initial pressure	The steady state gauge pressure which occurs at a specified point of the system just before a change in operating conditions is initiated (see Figure 4)	p_i	Pa
2.3.5.5	Final pressure	The steady state gauge pressure which occurs at a specified point of the system after all transient waves have been dissipated (see Figure 4)	p_f	Pa
2.3.5.6	Momentary pressure	The highest/lowest gauge pressure which occurs at a specified point of the system under specified transient conditions (see Figure 4)	p^+_m p^-_m	Pa Pa
2.3.5.7	Maximum/ minimum momentary pressure	The momentary pressure under the most unfavourable transient conditions	$p^+_{m\,max}$ $p^-_{m\,min}$	Pa Pa

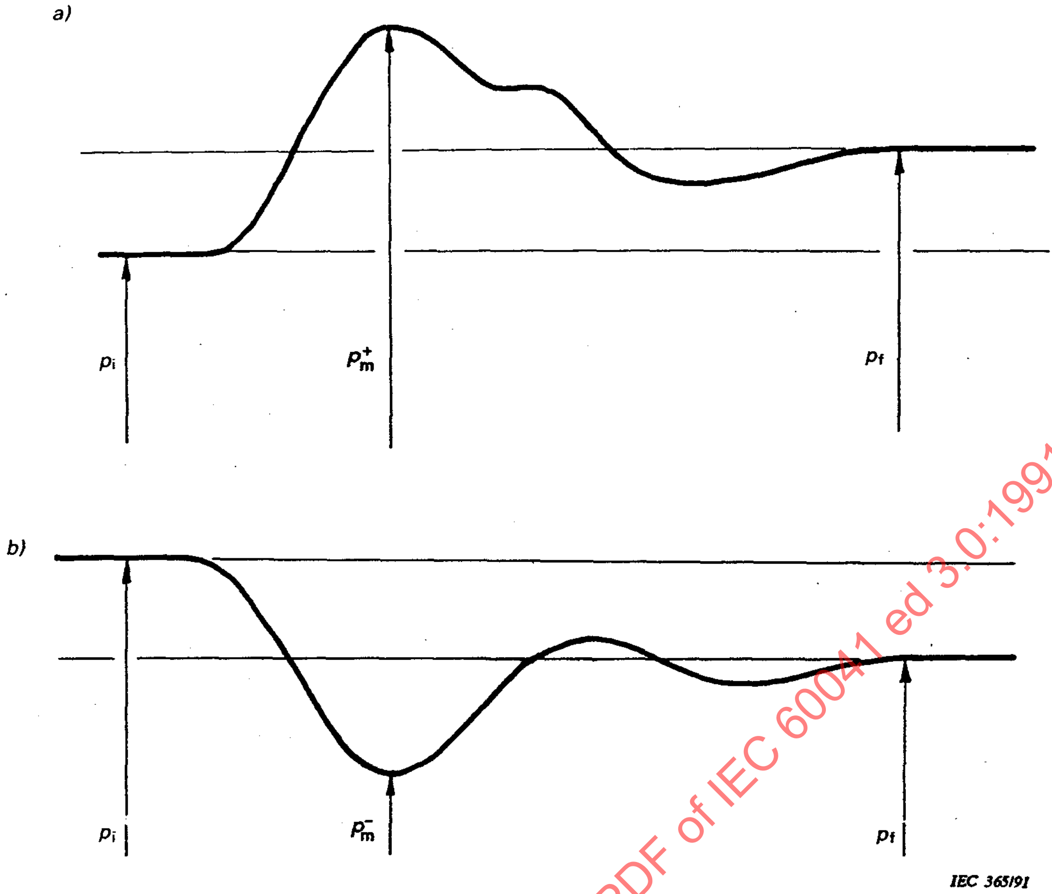


Figure 4a – Variation of pressure at the turbine high pressure reference section
a) when a specified load is suddenly rejected
b) when a specified load is suddenly accepted

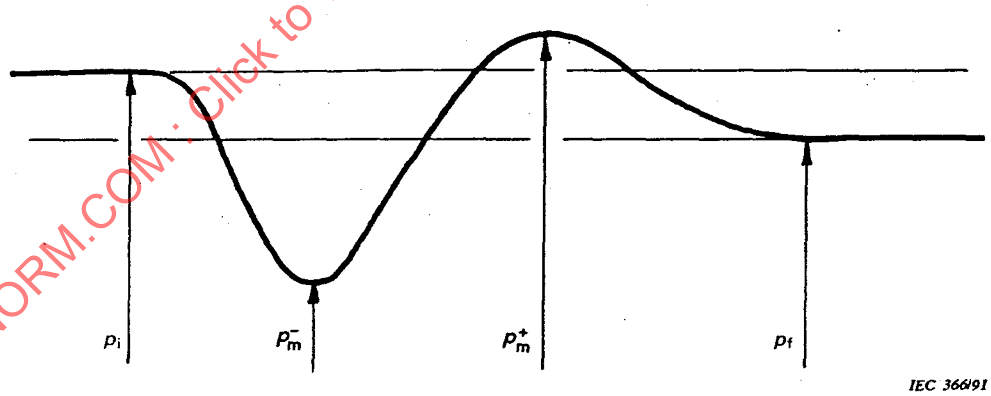


Figure 4b – Variation of pressure at the pump high pressure reference section during a power failure

2.3.6 *Specific energy terms*

In the International System of Units the mass (kg) is one of the base quantities. The energy per unit mass, known as specific energy, is used in this standard as a primary term instead of the energy per local unit weight which is called head and was exclusively used in the former IEC 41 and 198.

The latter term (head) has the disadvantage that the weight depends on the acceleration due to gravity g, which changes mainly with latitude but also with altitude. Nevertheless, the term head will still remain in use because it is very common. Therefore both related energy terms are listed, the specific energy terms in this sub-clause and the head terms in 2.3.7. They differ only by the factor g, which is the local value of acceleration due to gravity.

The symbol for specific energy at any section of flow is the small letter e; the symbol for the difference of specific energies between any two sections is the capital letter E. The same applies to h and H.

Sub-clause	Term	Definition	Symbol	Unit
2.3.6.1	Specific energy	The energy per unit mass of water at any section	e	$J \cdot kg^{-1}$ $(m^2 \cdot s^{-2})$
2.3.6.2	Specific hydraulic energy of machine	Specific energy of water available between the high and low pressure reference sections of the machine, taking into account the influence of the compressibility $E = \frac{p_{abs1} - p_{abs2}}{\overline{\varrho}} + \frac{v_1^2 - v_2^2}{2} + \overline{g}(z_1 - z_2)$ with $\overline{\varrho} = \frac{\varrho_1 + \varrho_2}{2}$ and $\overline{g} = \frac{g_1 + g_2}{2}$ *,** *Note.* – The value of gravity acceleration at the reference level of the machine (see 2.3.7.10) may be assumed as $\overline{g}$. The values of ϱ_1 and ϱ_2 can be calculated from p_{abs1} and p_{abs2} respectively, taking into account ϑ_1 or ϑ_2 for both values, given the negligible influence of the difference of the temperature on ϱ	E	$J \cdot kg^{-1}$
2.3.6.3	Specific mechanical energy at runner(s)/ impeller(s)	Mechanical power transmitted through the coupling of the runner(s)/impeller(s) and shaft (see Clause 14) divided by mass flow rate: $E_m = \frac{P_m}{(\varrho Q)_1}$ (for P_m, see 2.3.8.4)	E_m	$J \cdot kg^{-1}$
2.3.6.4	Specific hydraulic energy of the plant	Specific hydraulic energy available between head water level and tailwater level of the plant (see Figure 6) It is given by: $E_g = \frac{p_{abs3} - p_{abs4}}{\overline{\varrho}} + \frac{v_3^2 - v_4^2}{2} + \overline{g}(z_3 - z_4)$ with $\overline{\varrho} = \frac{\varrho_3 + \varrho_4}{2}$ and $\overline{g} = \frac{g_3 + g_4}{2}$ The water density at ambient pressure may be assumed as $\overline{\varrho}$	E_g	$J \cdot kg^{-1}$

* Figures 5a, 5b (reaction machines) and 5c (impulse turbines) illustrate some common cases of application of the basic formula for the specific hydraulic energy. The applicable simplified formula is given under each figure. Measurement methods for the evaluation of the specific hydraulic energy of the machine are described in detail in Clause 11.

** See Appendix F.

Sub-clause	Term	Definition	Symbol	Unit
2.3.6.5	Zero-discharge (shut-off) specific hydraulic energy of the pump	Pump specific energy at specified speed and specified guide vane and runner/impeller blade settings with high pressure side shut-off	E_0	$J \cdot kg^{-1}$
2.3.6.6	Specific hydraulic energy loss	The specific hydraulic energy dissipated between any two sections	E_L	$J \cdot kg^{-1}$
2.3.6.7	Suction specific hydraulic energy loss	The specific hydraulic energy dissipated between the tailwater level and the low pressure reference section of the machine (see figure 41)	E_{Ls}	$J \cdot kg^{-1}$
2.3.6.8	Suction specific potential energy of the machine	Specific potential energy corresponding to the difference between the reference level of the machine (see 2.3.7.10) and the piezometric level at section 2: $E_s = g_2(z_r - z_{2'}) = g_2 Z_s$ (see Figure 7)	E_s	$J \cdot kg^{-1}$
2.3.6.9	Net positive suction specific energy	Absolute specific energy at section 2 minus the specific energy due to vapour pressure p_{va}*, referred to the reference level of the machine according to Figure 7 $NPSE = \frac{p_{abs2} - p_{va}}{\varrho_2} + \frac{v_2^2}{2} - g_2(z_r - z_2)$**	$NPSE$	$J \cdot kg^{-1}$

2.3.7 *Height and head terms*

Sub-clause	Term	Definition	Symbol	Unit
2.3.7.1	Geodetic height of plant***	Difference in elevation between headwater level and tailwater level of plant (see Figure 6)	Z_g	m
2.3.7.2	Head	Energy per unit weight of water at any section $h = e/g$ For definition of e, see 2.3.6.1	h	m
2.3.7.3	Turbine or pump head	$H = E/\bar{g}$ For definition of E, see 2.3.6.2	H	m
2.3.7.4	Plant head***	$H_g = E_g/\bar{g}$ For definition of E_g, see 2.3.6.4	H_g	m
2.3.7.5	Zero-discharge (shut-off) head of pump	$H_0 = E_0/\bar{g}$ For definition of E_0, see 2.3.6.5	H_0	m
2.3.7.6	Head loss	$H_L = E_L/\bar{g}$ For definition of E_L, see 2.3.6.6	H_L	m

* See 2.3.3.7 and Appendix E, Table EVII.

** For definition of cavitation factor σ, see IEC 193A and 497.

*** Figure 6 shows the relationship between geodetic height of plant and plant head.

Sub-clause	Term	Definition	Symbol	Unit
2.3.7.7	Suction head loss	$H_{Ls} = \frac{E_{Ls}}{g}$ For definition of E_{Ls}, see 2.3.6.7	H_{Ls}	m
2.3.7.8	Suction height	$Z_s = \frac{E_s}{g_2}$ (see Figure 7) For definition of E_s, see 2.3.6.8	Z_s	m
2.3.7.9	Net positive suction head	$NPSH = \frac{NPSE}{g_2}$ For definition of $NPSE$, see 2.3.6.9	$NPSH$	m
2.3.7.10	Reference level of the machine	Elevation of the point of the machine taken as reference for the setting of the machine as defined in Figure 8	z_r	m

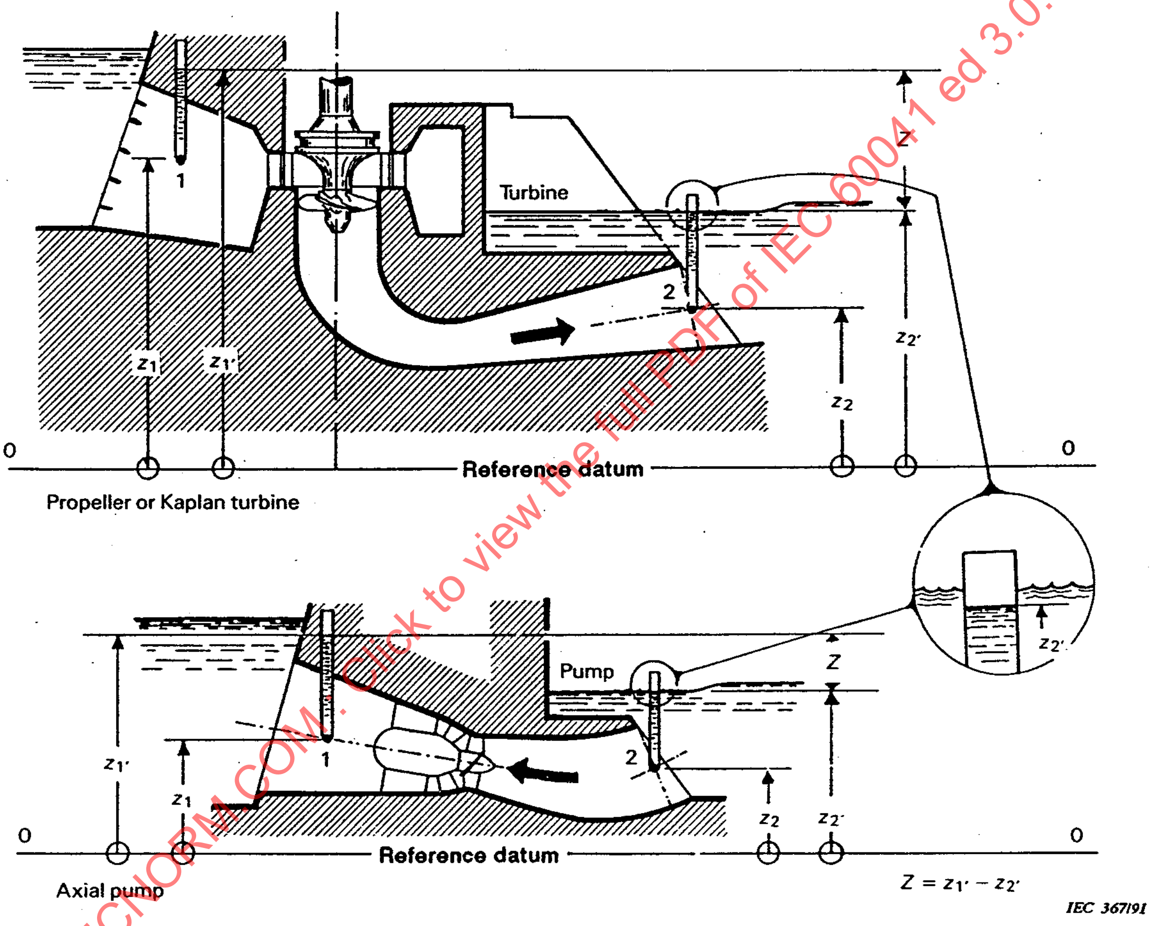


Figure 5a – Low-head machines – Determination of specific hydraulic energy of machine

Water column manometers are applied at point 1 and 2.

$$E = \overline{g}H = \frac{(p_{\text{abs1}} - p_{\text{abs2}})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g}(z_1 - z_2)$$

The compressibility of water is neglected because the difference of pressure between 1 and 2 is small therefore:

$$\varrho_1 = \varrho_2 = \overline{\varrho}$$

Hence:

$$p_{\text{abs}_1} = \overline{\varrho} \cdot \overline{g}(z_{1'} - z_1) + p_{\text{amb}_{1'}}$$
$$p_{\text{abs}_2} = \overline{\varrho} \cdot \overline{g}(z_{2'} - z_2) + p_{\text{amb}_{2'}}$$
$$p_{\text{amb}_{1'}} - p_{\text{amb}_{2'}} = -\varrho_{\text{a}} \cdot \overline{g}(z_{1'} - z_{2'})$$

and therefore the simplified formula is:

$$E = \overline{g} \cdot (z_{1'} - z_{2'}) \cdot \left(1 - \frac{\varrho_{\text{a}}}{\overline{\varrho}}\right) + \frac{(v_1^2 - v_2^2)}{2} = \overline{g} \cdot Z\left(1 - \frac{\varrho_{\text{a}}}{\overline{\varrho}}\right) + \frac{(v_1^2 - v_2^2)}{2}$$

The water density at ambient pressure may be assumed as $\overline{\varrho}$.

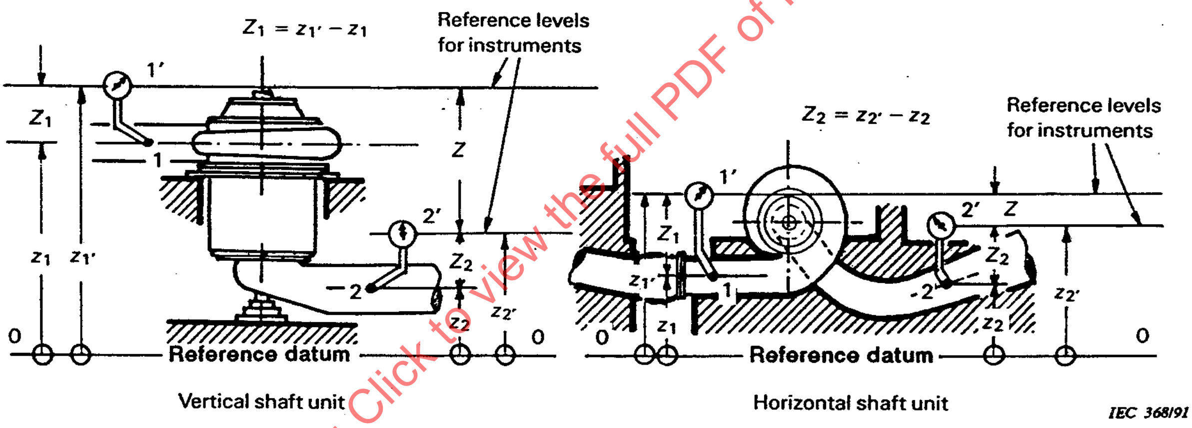


Figure 5b – Medium and high-head machines – Determination of specific hydraulic energy of machine

Pressure gauges manometers are applied at points 1 and 2.

$$E = \overline{g}H = \frac{(p_{\text{abs}_1} - p_{\text{abs}_2})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g}(z_1 - z_2)$$

The difference in ambient pressure between 1′ and 2′ is neglected because Z is small compared to H, therefore:

$$p_{\text{amb1}'} = p_{\text{amb2}'} = p_{\text{amb}}$$

Since both Z_1 and Z_2 are small compared to H, it may be assumed that:

$$Z_1 \cdot \frac{\varrho_1}{\overline{\varrho}} = Z_1 \quad \text{and} \quad Z_2 \cdot \frac{\varrho_2}{\overline{\varrho}} = Z_2$$

hence:

$p_{abs_1} = p_{1'} + Z_1 \cdot \varrho_1 \cdot \overline{g} + p_{amb}$ where $p_{1'}$ is the gauge pressure measured at 1′

$p_{abs_2} = p_{2'} + Z_2 \cdot \varrho_2 \cdot \overline{g} + p_{amb}$ where $p_{2'}$ is the gauge pressure measured at 2′

and therefore the simplified formula is:

$$E = \frac{(p_{1'} - p_{2'})}{\overline{\varrho}} + \overline{g} \cdot (z_{1'} - z_{2'}) + \frac{(v_1^2 - v_2^2)}{2} = \frac{(p_{1'} - p_{2'})}{\overline{\varrho}} + \overline{g} \cdot Z + \frac{(v_1^2 - v_2^2)}{2}$$

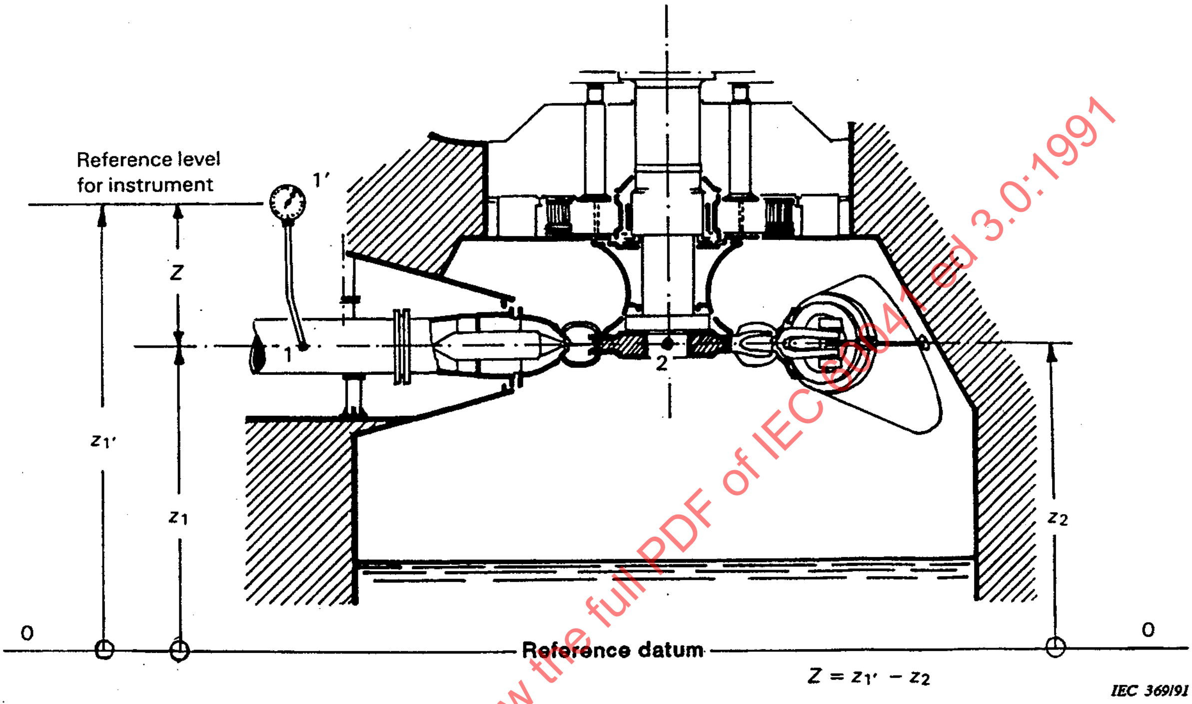


Figure 5c – Pelton turbines with vertical axis – Determination of specific hydraulic energy of machine

Case of non-pressurised housing:

It is conventionally assumed that the low pressure reference section corresponds to the plane at elevation z_2 and that the pressure inside the housing is equal to the ambient pressure in the case of non-pressurised housing.

$$E = \overline{g} \cdot H = \frac{(p_{abs_1} - p_{abs_2})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g} \cdot (z_1 - z_2)$$

The difference in ambient pressure between 1′ and 2 is neglected because Z is small compared to H, therefore:

$$p_{amb1'} = p_{amb2} = p_{amb}$$

For the same reason it is assumed that:

$$Z \cdot \frac{\varrho_1}{\overline{\varrho}} = Z$$

hence:

$p_{abs_1} = p_{1'} + Z \cdot \varrho_1 \cdot \overline{g} + p_{amb}$ where $p_{1'}$ is the gauge pressure measured at 1′

$p_{abs_2} = p_{amb}$

As $z_1 = z_2$ and assuming $v_2 = 0$, the simplified formula is:

$$E = \frac{p_{1'}}{\bar{\varrho}} + \bar{g} \cdot (z_{1'} - z_2) + \frac{v_1^2}{2} = \frac{p_{1'}}{\bar{\varrho}} + \bar{g} \cdot Z + \frac{v_1^2}{2}$$

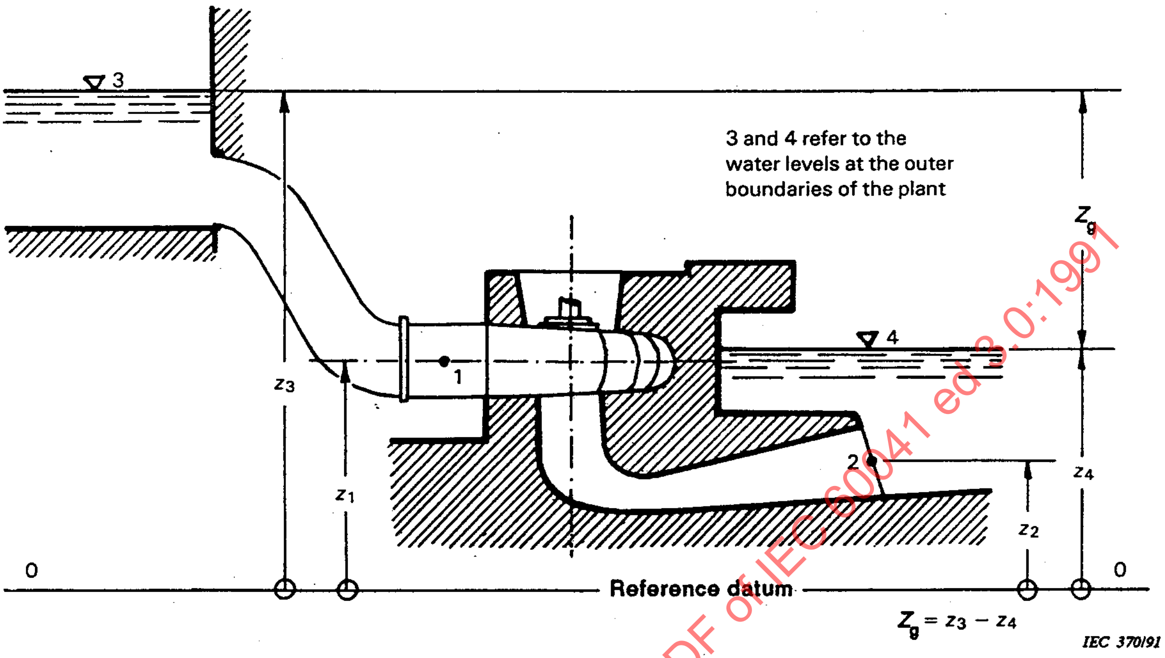


Figure 6 – Hydroelectric plant – Determination of specific hydraulic energy E_g and head H_g of plant through geodetic height of plant Z_g

The general formula is:

$$E_g = \bar{g}_{3-4} \cdot H_g = \frac{(p_{abs_3} - p_{abs_4})}{\bar{\varrho}_{3-4}} + \frac{(v_3^2 - v_4^2)}{2} + \bar{g}_{3-4}(z_3 - z_4)$$

Assuming $\bar{g}_{3-4} = \frac{g_3 + g_4}{2} = \bar{g}$,

$$p_{abs_3} - p_{abs_4} = -\varrho_a \cdot \bar{g} \cdot (z_3 - z_4);$$

assuming $v_3 = v_4 = 0$

and $\bar{\varrho}_{3-4} = \frac{\varrho_3 + \varrho_4}{2} = \bar{\varrho}$ water density at the ambient pressure, the formula becomes:

$$E_g = \bar{g} \cdot (z_3 - z_4) \cdot \left[1 - \frac{\varrho_a}{\bar{\varrho}}\right] = \bar{g} \cdot Z_g \cdot \left[1 - \frac{\varrho_a}{\bar{\varrho}}\right]$$

where ϱ_a is assumed equal to air density at the reference level of the machine.

Conversely:

$$E_g = E \pm \sum E_L \quad \text{where} \quad \begin{cases} + & \text{turbine} \\ - & \text{pump} \end{cases}$$

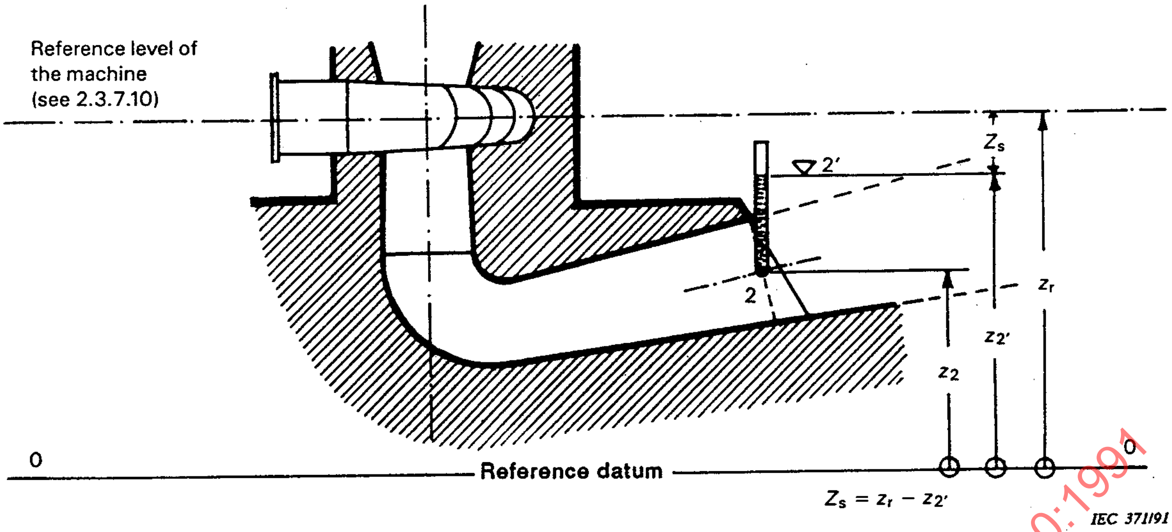


Figure 7 – Net positive suction specific energy, *NPSE*, and net positive suction head, *NPSH*

Water column manometer is applied at point 2.

$$NPSE = g_2 \cdot NPSH = \frac{(p_{abs_2} - p_{va})}{\varrho_2} + \frac{v_2^2}{2} - g_2 \cdot (z_r - z_2)$$

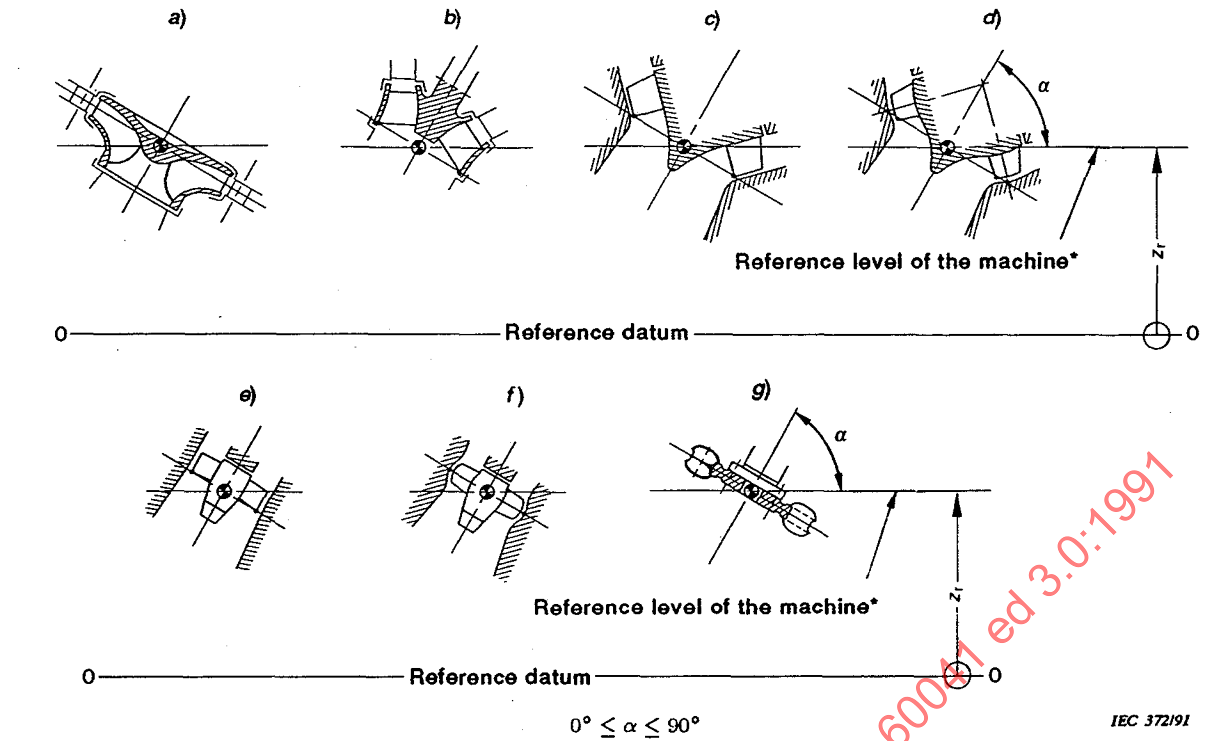
With:

$$p_{abs_2} = \varrho_2 \cdot g_2 \cdot (z_{2'} - z_2) + p_{amb_{2'}}$$

the simplified formula becomes:

$$NPSE = \frac{(p_{amb_{2'}} - p_{va})}{\varrho_2} + \frac{v_2^2}{2} - g_2 \cdot (z_r - z_{2'}) = \frac{(p_{amb_{2'}} - p_{va})}{\varrho_2} + \frac{v_2^2}{2} - g_2 \cdot Z_s$$

where Z_s is positive if the level 2′ is lower than the reference level of the machine and vice versa.



a) Radial machines, such as Francis turbines, radial (centrifugal) pumps and pump-turbines; for multistage machines: low pressure stage.

b) Diagonal (mixed-flow, semi-axial) machines with fixed runner/impeller blades and with runner/impeller band.

c) Diagonal (mixed-flow, semi-axial) machines with fixed runner/impeller blades, without runner/impeller band.

d) Diagonal (mixed-flow, semi-axial) machines with adjustable runner/impeller blades).

e) Axial machines, such as propeller turbines, tubular turbines**, axial pumps and pump-turbines with fixed runner/impeller blades.

f) Axial machines, such as Kaplan turbines, tubular turbines**, axial pumps and pump-turbines with adjustable runner/impeller blades.

g) Pelton turbines.

Figure 8 – Reference level of turbines, pumps and pump-turbines*

2.3.8 *Power terms*

Note. – All electrical power terms are defined in Clause 12.

Sub-clause	Term	Definition	Symbol	Unit
2.3.8.1	Hydraulic power	The hydraulic power available for producing power (turbine) or imparted to the water (pump) $P_h = E(\varrho Q)_1 \pm \Delta P_h$	P_h	W
2.3.8.2	Hydraulic power correction	Correction term to be evaluated after a relevant analysis according to contractual definitions and local conditions*** (see 9.2.3)	ΔP_h	W

* The reference level of the machine z_r does not necessarily correspond to the point with maximum cavitation.

** The term "tubular turbines" includes bulb, pit, rim generator and S-type units.

*** Example: if a small discharge q is taken from the system upstream of section 1 in a turbine and this water is contractually chargeable to the hydraulic machine, the hydraulic power is: $P_h = E(\varrho Q)_1 + E(\varrho q)$

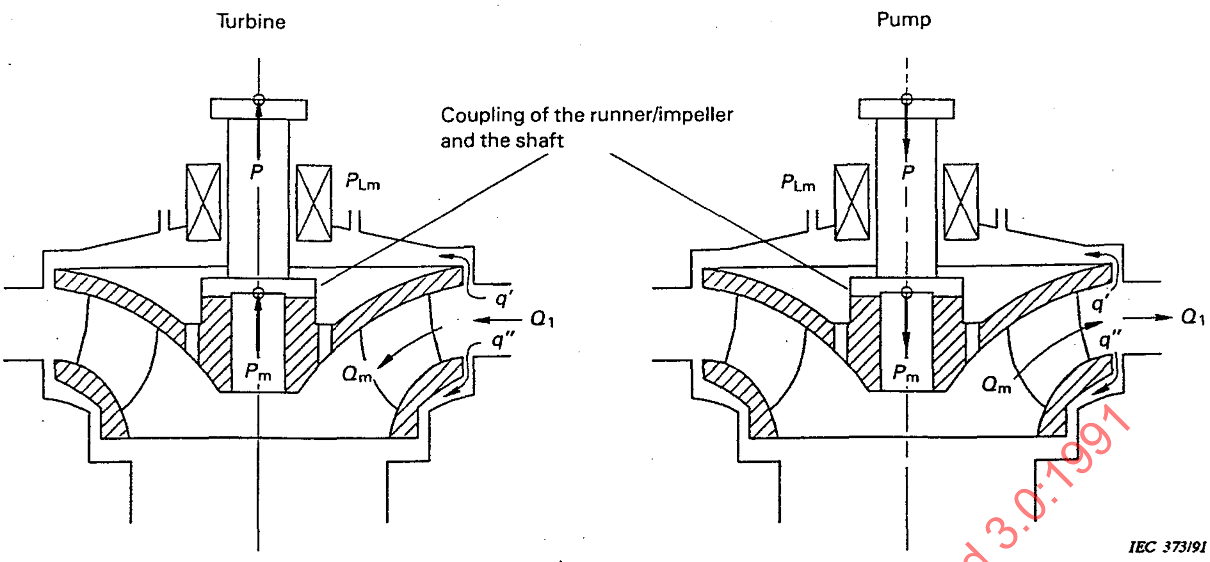
Sub-clause	Term	Definition	Symbol	Unit
2.3.8.3	Mechanical power of the machine (Power)	The mechanical power delivered by the turbine shaft or to the pump shaft, assigning to the hydraulic machine the mechanical losses of the relevant bearings (see Figure 9)	P	W
		– For a turbine: $$P = P_a + P_b + P_c + P_d + P_e - P_f$$ where:		
		P_a is the generator power as measured at the generator terminals	P_a	W
		P_b are the mechanical and electric losses in the generator, including windage losses (see 12.1.2.1)	P_b	W
		P_c are the thrust bearing losses due to generator. In the case of a common thrust bearing, the bearing losses shall be attributed to the turbine and generator in proportion to the thrust of each on the bearing (see 12.1.2.2)	P_c	W
		P_d are the losses in all rotating elements external to the turbine and to the generator, such as flywheel, if any, gear, pump impeller in air, if any, etc. (see 12.1.2.3)	P_d	W
		P_e is the power supplied to any directly driven auxiliary machine (see 12.1.2.4)	P_e	W
		P_f is the electric power supplied to the auxiliary equipment of the turbine (e.g. for the governor) if the contract specifies this to be chargeable to the turbine	P_f	W
		– For a pump: $$P = P_a - (P_b + P_c + P_d + P_e) + P_f$$ where:		
		P_a is the power to the motor as measured at the motor terminals	P_a	W
		P_b are the mechanical and electric losses in the motor, including windage losses (see 12.1.2.1)	P_b	W
		P_c are the thrust bearing losses due to the motor. In the case of a common thrust bearing, the bearing losses shall be attributed to the pump and motor in proportion to the thrust of each on the bearing (see 12.1.2.2)	P_c	W
		P_d are the losses in all rotating elements external to the pump and to the motor, such as flywheel, if any, gear, starting turbine runner, turbine runner rotating in air, etc. (see 12.1.2.3)	P_d	W
		P_e is the power supplied to any directly driven auxiliary machine (see 12.1.2.4)	P_e	W
		P_f is the electric power supplied to the auxiliary equipment of the pump (e.g. for the governor) if the contract specifies this to be chargeable to the pump	P_f	W

Sub-clause	Term	Definition	Symbol	Unit
2.3.8.4	Mechanical power of runner(s)/ impeller(s)	Mechanical power transmitted through the coupling of the runner(s)/impeller(s) and the shaft (see demonstrative sketch Figure 9): – in the case of a turbine: $P_m = P + P_{Lm} + P_f$ – in the case of a pump: $P_m = P - P_{Lm} - P_f$	P_m	W
2.3.8.5	Mechanical power losses	Mechanical power dissipated in guide bearings, thrust bearing and shaft seals of the hydraulic machine. See also 2.3.8.3 (P_c)	P_{Lm}	W
2.3.8.6	Zero-discharge (shut-off) power of the pump	Pump power at specified speed and at specified guide vane and impeller settings with high pressure side shut-off	P_0	W

2.3.9 *Efficiency terms*

Sub-clause	Term	Definition	Symbol	Unit
2.3.9.1	Hydraulic efficiency*	– For a turbine: $\eta_h = \frac{P_m}{P_h} = \frac{E_m}{E \pm \frac{\Delta P_h}{P_m} E_m}$ – For a pump: $\eta_h = \frac{P_h}{P_m} = \frac{E \pm \frac{\Delta P_h}{P_m} E_m}{E_m}$	η_h	–
2.3.9.2	Mechanical efficiency	– For a turbine: $\eta_m = \frac{P}{P_m}$ – For a pump: $\eta_m = \frac{P_m}{P}$	η_m	–
2.3.9.3	Efficiency	– For a turbine: $\eta = \frac{P}{P_h} = \eta_h \cdot \eta_m$ – For a pump: $\eta = \frac{P_h}{P} = \eta_h \cdot \eta_m$	η	–
2.3.9.4	Relative efficiency	Ratio of the efficiency at any given operating condition to a reference value	η_{rel}	–
2.3.9.5	Weighted average efficiency	The efficiency calculated from the formula: $\eta_w = \frac{w_1\eta_1 + w_2\eta_2 + w_3\eta_3 + \cdots}{w_1 + w_2 + w_3 + \cdots}$ where $\eta_1, \eta_2, \eta_3, \ldots$ are the values of efficiency at specified operating conditions and $w_1, w_2, w_3, \ldots$ are their agreed weighting factors respectively	η_w	–
2.3.9.6	Arithmetic average efficiency	The weighted average efficiency (2.3.9.5) with $w_1 = w_2 = w_3 = \cdots$	η_a	–

* The disk friction losses and leakage losses (volumetric losses) are considered as hydraulic losses in the formulae in 2.3.9.1. The "disk friction losses" are the friction losses of the outer surfaces of the runner/impeller not in contact with the active flow.



Turbine

$q = q' + q''$

$Q_1 = Q_m + q$

$P_h = E \cdot (\varrho \cdot Q)_1$ assuming $\Delta P_h = 0$

$P = P_m - P_{Lm}$ assuming $P_f = 0$

Volumetric efficiency $\eta_\nu = \dfrac{Q_m}{Q_1}$

Hydraulic efficiency[1] $\eta_h = \dfrac{P_m}{P_h}$

Efficiency $\eta = \dfrac{P}{P_h}$

Pump

$q = q' + q''$

$Q_1 = Q_m - q$

$P_h = E \cdot (\varrho \cdot Q)_1$ assuming $\Delta P_h = 0$

$P = P_m + P_{Lm}$ assuming $P_f = 0$

$\eta_\nu = \dfrac{Q_1}{Q_m}$

$\eta_h = \dfrac{P_h}{P_m}$

$\eta = \dfrac{P_h}{P}$

The formulae ignore the compressibility of the water.

1) The disk friction losses and leakage losses (volumetric losses) are considered as hydraulic losses in this formula. This "disk friction losses" are the friction losses of the outer surfaces of the runner/impeller not in contact with the active flow Q_m.

Figure 9 – Flux diagram for power and discharge (example)

3. Nature and extent of hydraulic performance guarantees

3.1 *General*

3.1.1 A contract for a regulated or non-regulated* machine should contain guarantees covering at least power, discharge, efficiency (see 3.2.5), maximum momentary overspeed and maximum/minimum momentary pressure, maximum steady state runaway speed (reverse runaway speed in case of a pump).

In the case of a pump the guarantees may also cover the maximum zero-discharge specific hydraulic energy (head) and the zero-discharge power, the latter one with impeller rotating in water and/or in air, for the specified speed.

These guarantees are considered as main hydraulic guarantees (see 3.2) and fall within the scope of this standard. Other guarantees (see 3.3) are not covered by this standard.

3.1.2 The purchaser shall arrange for the supplier of the machine to be provided with true, full and acceptable data covering all basins, inlet and outlet structures, waterways between the points of intake and discharge and all parts and equipment relating thereto, all the driven or driving machinery whether electric or not and the revolving parts thereof, and all governors, valves, gates and allied mechanisms.

3.1.3 The purchaser shall be responsible for specifying the values of all the parameters on which guarantees are based, including water quality and temperature**, specific hydraulic energies of the plant (see 2.3.6.4) and specific hydraulic energy losses (see 2.3.6.6), for the study of the plant, particularly the correct inlet and outlet conditions of the machine and for the co-ordination of what concerns the interaction between the machine and the waterways. Should the operational and guaranteed ranges differ, he shall indicate the limits of the operation.

3.1.4 If the electric generator or motor is to be used for measuring turbine or pump power (see 2.3.8.3), such electric generator or motor and its auxiliaries shall be given appropriate tests. It should be a condition of the contract that the supplier of the hydraulic unit or his representative shall have the right to be present at such tests. A certified copy of the generator or motor test calculations and results shall be given to the supplier of the hydraulic machine.

3.2 *Main guarantees*

3.2.1 *Practical plant operation*

Practical plant operation usually involves some variation in specific hydraulic energy (head). Therefore specifications shall state the specific hydraulic energies to which guarantees shall apply.

For practical reasons a transient test may not be conducted at the same time as a steady-state performance test.

* A regulated machine is a machine in which the flow is controlled by a flow-controlling device such as guide vanes, needle(s), and/or runner/impeller blades. A single regulated machine is a regulated machine with one flow-controlling device; a double regulated machine is a regulated machine with two flow-controlling devices. A non-regulated machine is a machine in which no flow-controlling device is provided.

** If the water temperature during the acceptance test is significantly different from the specified value (e.g. more than 10°C), the relevant scale effect should be taken into account.

3.2.2 *Power*

Power guarantees may be required at one or more specified speeds for:

a) a regulated turbine: power to be reached at one or more specified specific hydraulic energies (see Figure 10 a);

b) a non-regulated turbine: power to be reached and power not to be exceeded over a specified specific hydraulic energy range* (see Figure 10 b);

c) a non-regulated/regulated pump: power not to be exceeded over a specified specific hydraulic energy range (see Figure 10 c).

3.2.3 *Discharge*

Discharge guarantees may be required at one or more specified speeds for:

a) a regulated turbine: discharge to be reached at one or more specified specific hydraulic energies (see Figure 10 a);

b) a non-regulated turbine: discharge to be reached over a specified specific energy range (this guarantee is usually replaced by the corresponding power guarantee, see 3.2.2 *b*) and discharge not to be exceeded (see Figure 10 b);

c) a non-regulated/regulated pump: discharge over a specified specific hydraulic energy range, including values to be reached or not to be exceeded** (see Figure 10 c).

The guaranteed discharge may be referred to the ambient pressure (see 2.3.4.5).

3.2.4 *Efficiency*

3.2.4.1 Regulated turbine efficiency guarantees may be required at one or more specified speeds and specific hydraulic energies:

a) at one or more individual specified powers or discharges or as a curve (see Figure 10 a);

b) as weighted average efficiencies*** over a range of power or discharge;

c) as arithmetic average efficiencies*** over a range of power or discharge.

3.2.4.2 Non-regulated turbine or non-regulated/regulated pump efficiency guarantees may be required at one or more specified speeds:

a) at one or more individual specified specific hydraulic energies or as a curve (see Figures 10 b and 10 c);

b) as weighted average efficiencies*** over a specified range of specific hydraulic energies;

c) as arithmetic average efficiencies*** over a specified range of specific hydraulic energies.

3.2.5 *Choice of power, discharge and efficiency guarantees*

It is recommended that the contractual agreements avoid fixing more than one guarantee for correlated quantities; for instance, in the case of a regulated turbine efficiency shall be guaranteed versus discharge or power, but not versus discharge and power.

* For the contractual limits of the power corresponding to the specified specific hydraulic energies, see 6.3.1.

** For the contractual limits of the discharge corresponding to the specified specific hydraulic energies, see 6.3.2.

*** Weighted or arithmetic average efficiencies and a series of individual efficiencies shall not normally be guaranteed simultaneously.

3.2.6 *Maximum momentary overspeed and maximum/minimum momentary pressure**,** (see 2.3.4.14 and 2.3.5.7)

Maximum or minimum momentary pressure and maximum momentary overspeed should be guaranteed over the whole operating range, generally in accordance with IEC 308.

Since the characteristics of the hydraulic and electric machines, the governor and all or part of the conduit system may be involved in the determination of the maximum overspeed and maximum/minimum momentary pressure, manufacturers shall be supplied with all relevant information.

3.2.7 *Maximum steady state runaway speed* (see 2.3.4.15)

Guarantees should be given that the maximum steady state runaway speed (maximum reverse runaway speed in case of a pump) will not exceed specified values under conditions to be specified in the contract (e.g. specific hydraulic energy, net positive suction specific energy, etc).

It is generally recommended to avoid this test (see 7.1.2.2).

3.2.8 *Maximum zero-discharge specific hydraulic energy and zero-discharge (shut-off) power of a pump* (see 2.3.6.5 and 2.3.8.6)

In the case of a pump a guarantee should be given that the zero-discharge power – with watered and de-watered impeller – and the maximum specific hydraulic energy will not exceed a specified value for the specified speed.

3.3 *Other guarantees*

Additional guarantees may be given; the following are guarantees covered by other IEC publications.

3.3.1 *Speed governing systems*

Acceptance of speed governing systems should be carried out in accordance with IEC 308.

3.3.2 *Cavitation pitting*

The amount of cavitation pitting should be guaranteed subject to the limitation that the unit will be operated only within the prescribed ranges of power, discharge, speed, duration, water temperature and net positive suction specific energy *(NPSE)*. Recommendations on this subject are dealt with in IEC 609.

* This standard deals only with speed and pressure variations associated with specified sudden load rejection (turbine) or power failure (pump). The most unfavourable transient conditions appearing in the definitions at 2.3.4.14 and 2.3.5.7 shall be specified in the contract.

** For superimposed pressure fluctuations, if any, see 7.1.1 and 8.2.2.

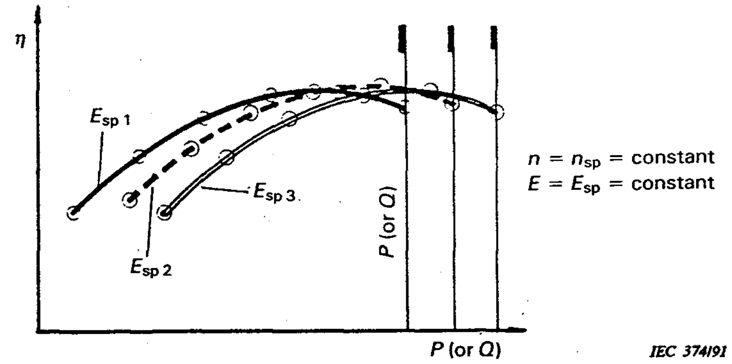


Figure 10 a – Regulated turbine

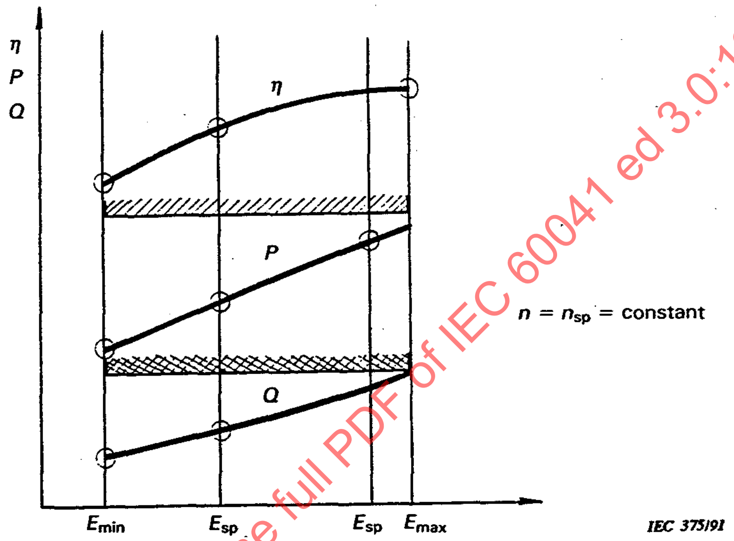


Figure 10 b – Non-regulated turbine

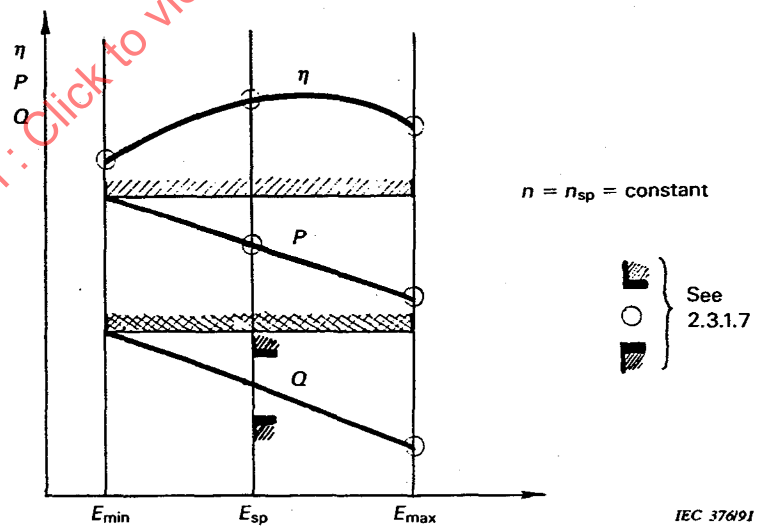


Figure 10 c – Pump

Note. – Usually only a part of the guarantees here described are required.

Figure 10 – Guarantee curves

4. Organisation of test

4.1 *Adequate provision for test*

It is recommended that attention should be given to provisions for testing when the plant is being designed. This applies particularly to the arrangements for measuring discharge and specific hydraulic energy. It is suggested that during the design stage of the plant and the machines to be tested, provision is made for more than one method of measuring discharge and pressure (or free water level). The methods of measurement should be fully covered in the specifications and in the contracts.

The conditions should also be considered when a prospective purchaser, or the engineers, submit an enquiry to possible suppliers. It should be stated at this time that the acceptance tests shall be performed in accordance with all applicable requirements of this standard. Any anticipated deviation from this standard should be clearly stated.

4.2 *Authority for test*

Subject to the provisions of the contract, both parties shall have equal rights in determining the test methods and procedures and in selecting all test personnel. The test may be entrusted to experts who hold independent positions with respect to both parties. If so, they and the Chief of test together with the contracting parties shall have final authority in selecting all other test personnel.

4.3 *Personnel*

The selection of personnel to conduct the test and procedures in connection therewith are matters of prime importance.

4.3.1 *Chief of test*

A Chief of test shall be appointed by agreement between the two parties. He should be competent to supervise all of the calibrations, measurements and calculations necessary to determine the performance of the machine. He shall exercise authority over all observers. He shall supervise the conduct of the test in accordance with this standard and any written agreement made prior to the test by the contracting parties. He shall be responsible for the calibration of all test instruments and for all test measurements. He shall report on test conditions and be responsible for the computation of results including the determination of the measurement uncertainties and the preparation of the final report. On any question pertaining to the test his decision, subject to the provisions of 4.5.1, 4.7.6 and 4.9.1, shall be final.

4.3.2 *Choice of personnel*

The testing team shall have the necessary competence and experience for the correct installation and utilization of the measuring equipment.

4.3.3 *Presence at test*

Both purchaser and supplier of the machine shall be entitled to have representatives present at all tests in order to verify that they are performed in accordance with this standard and any prior written agreements.

4.4 *Preparation for test*

4.4.1 *Submission of drawings and relevant data*

All drawings of importance for the test and all relevant data, documents, specifications, certificates and reports on operating conditions shall be placed at the disposal of the Chief of test.

4.4.2 *Inspection on site*

Shortly before the start of the test, the unit and all test equipment shall be subjected to thorough inspection by representatives of both parties and the Chief of test to ensure that conditions are such that the performance of the machine may be judged equitably (see also 4.8). It shall be verified that:

a) all machinery is complete and according to specifications;

b) the scales indicating the opening of the guide vanes and/or runner/impeller blades, where applicable, or the opening of nozzles and deflectors are calibrated and the relationship between openings is correct. The scales shall have sufficient resolution and will be accessible throughout the test. Provisions shall exist to block effectively the guide vane or nozzle openings during each point to promote stability and accurate repetition of openings;

c) no water passages are obstructed or restricted by any foreign matter;

d) no wear has taken place on vital parts, particularly in the form of cavitation damage to runners/impellers, guide vanes, nozzles or other water passage components and/or damage to wearing rings or labyrinths, that could have a significant effect on efficiency;

e) all pressure taps, piezometric tubes and connecting pipes have been properly formed and located and are clear of obstruction.

4.4.3 *Measurements before test*

The dimensions of the conduit at and between measurement sections, when required, shall be measured accurately before the unit is operated.

A main bench mark for levels shall be established. All secondary bench marks (levelling reference points) in the specific hydraulic energy measuring system shall be referred to it. All bench marks shall be retained undisturbed until the final report has been accepted.

When the indirect method of power measurement is used, the results of the generator/motor efficiency test should preferably be available prior to the hydraulic machine performance test. In case such information is missing the guaranteed values of generator/motor for losses may be used for preliminary computation of the results.

4.5 *Agreement on test procedure*

4.5.1 *Approval of procedure*

The test programme and procedure shall be prepared by the Chief of test, taking into consideration the plans previously prepared according to 4.1. All arrangements and plans shall be submitted to both purchaser and supplier in ample time for consideration and agreement. Approval or objection shall be given in writing.

4.5.2 *Date of test*

The acceptance test shall not take place until the commissioning tests, including speed and pressure variation trials, have been conducted. See also IEC 545 and 805.

It is for the purchaser to decide, with respect to plant operation and flow conditions, on the date of the acceptance test. This shall be within the contract guarantee period and preferably within six months after the machine has been handed over to the purchaser, unless otherwise agreed by both parties in writing.

4.5.3 *General programme*

The general programme shall be drafted by the Chief of test and shall include particulars concerning the following items:

4.5.3.1 Specific hydraulic energy for acceptance test

In those cases where guarantees are given for more than one specific hydraulic energy the general programme shall state at which value or values of specific hydraulic energy the acceptance test shall be carried out, on the basis of the purchaser's instructions.

4.5.3.2 Machines to be tested for efficiency

The contract shall specify whether several or only one of a group of identical machines are to be tested with regard to efficiency. The general programme shall specify the actual machine or machines to be tested. If only one is to be tested, it is recommended that the machine shall be chosen by mutual agreement between purchaser and supplier.

4.5.3.3 Extent and duration of test

The general programme shall include a statement on the number of points to be taken and the corresponding operating conditions. The number of points to be obtained depends on the nature and extent of the guarantees and shall be decided by the Chief of test. Prescriptions on the number of points, the mode of machine operation and other related items which shall be included in the general programme are detailed in 5.1 for the steady state performance test and in 7.1 for the transient operation test.

4.6 *Instruments*

4.6.1 *Identification of instruments*

The maker, serial number or other identification, and owner of each instrument shall be stated in the final report.

4.6.2 *Calibration of instruments*

All instruments, including electrical instrument transformers, shall be calibrated before the test and both purchaser and supplier may witness their calibration. Whether calibrated on or off site, the validity of all calibrations shall be verified by the Chief of test. In the case of an off-site calibration, a valid certificate, acceptable to both the purchaser and the supplier, shall be provided. All necessary correction and pre-test calibration curves of the instruments to be employed shall be available before any test is carried out.

Unless omitted by agreement, all calibrations shall be repeated after completion of the test. The dates and places of all calibrations shall be stated in the final report. The institutions that have performed the calibrations shall state in writing whether the variations between pre- and post-test calibrations are within acceptable limits. If such is the case, their arithmetical means shall be used in the computation of the final results. If not, either a special agreement shall be made as to how any disputed values shall be used or the test shall be repeated.

4.7 *Observations*

4.7.1 *Observation sheets*

Observation sheets which clearly indicate the items to be measured shall be prepared for use at each of the various stations. A sufficient number of copies of the observation sheets shall be prepared and each party to the test shall immediately be handed a complete set. These observation sheets shall:

a) record the power plant designation and the serial number of each machine to be tested and the serial numbers of the instruments as well as any other essential information to identify all instruments and their location;

b) record the positions of all nozzles needles, runner/impeller blades, and/or adjustable guide vanes;

c) record all readings made at each observation station and the time at which each reading was taken, together with any circumstances deserving attention;

d) be signed by the particular observer;

e) provide for other necessary signatures (see 4.7.5);

f) be examined by, and copies given to, all parties before the end of the test.

4.7.2 *Instrument readings*

All readings of direct-reading instruments shall be taken during the same period of time and the frequency of the reading shall be decided by the Chief of test. Care shall be taken that the time interval between readings does not coincide with the period, or any multiple thereof, of any steady state oscillations in the instrumentation or machine under test. Visual averaging is to be avoided, if possible, because this inevitably introduces some personal bias (see also 5.2.1). All readings for the preliminary test (5.1.3) shall be taken with the same care and accuracy as for the acceptance test.

4.7.3 *Instrument recordings*

Instrument recordings (analog or digital) may be used provided that the accuracy and resolution of the records are comparable to or better than instantaneous readings of direct reading test instruments. All recordings shall be averaged or interpreted under the direct supervision of the Chief of test, using the most suitable and accurate techniques.

4.7.4 *Preliminary calculation*

After completion of the test, the readings and recordings shall be examined by both parties and representative results shall be provisionally computed on site using the pre-test calibrations. All errors or inconsistencies thereby discovered shall be eliminated or taken into account. Only on this basis may the test be terminated and the test instruments removed (see 4.6.2).

4.7.5 *Signing of readings and recordings*

The test recordings shall be signed by the Chief of test and by representatives of both parties.

4.7.6 *Procedure in case of dispute or repetition*

If there is any dissatisfaction with the test for clearly explained reasons stated in writing, the dissatisfied party shall have the right to demand additional tests. Agreement at this stage shall not preclude either party from expressing dissatisfaction with the test when the final results are available. In such case, either party and/or the Chief of test may demand a repeat test. If final agreement as to the conduct of such a test cannot be reached, the matter shall be referred to an independent arbitrator acceptable to all parties.

The contract should fix the responsibility for the cost of any repeat test.

4.8 *Inspection after test*

If requested by either party or the Chief of test, the unit and all test equipment shall be available for inspection within two days after completion of the test. A request for this inspection should be made as early as possible and, in any case, before the completion of testing.

4.9 *Final report*

4.9.1 *Preparation of final report*

The Chief of test shall be responsible for the preparation of the final report. A draft form of the report shall be submitted to both the purchaser and supplier to obtain the approval of both parties on all items including calculations and presentation of results. Any dissatisfaction shall be resolved by both parties with each having equal rights in determining the final contents of the report. In case of lack of agreement, the matter shall be referred to an independent arbitrator acceptable to all parties.

4.9.2 *Content*

The final report shall include at least all the topics listed below but not necessarily in this order.

a) Object of test.

b) Records of all preliminary agreements pertinent to the test.

c) Personnel taking part in the test.

d) Identification, characteristics and description of the machine.

e) Description of associated equipment or works, for example pipelines, valves, gates, intake and outlet passages, and their condition, with drawings where appropriate.

f) Particulars concerning service conditions of the machine, for example operating hours, power, discharge and water levels from commissioning date up to the beginning of the acceptance test.

g) Comments on inspection of machine.

h) Details of performance guarantees.

i) Description of all test equipment including serial numbers, calibrations, and all checks made pertaining to the test (see 4.7.1).

j) Test procedures.

k) Detailed calculations, preferably tabulated, from the original rough data to the final curves for at least one point. All diagrams or their copies used, such as Gibson pressure-time diagram, salt-velocity curves, current-meter velocity distribution, etc. shall be included.

l) Daily log of the events of the test.

m) The tabulated results of all measurements including necessary intermediate data, the results of calculations for the specific hydraulic energy, discharge and power, the conversion of the values measured to the specified conditions E_{sp} and n_{sp}, the determination of the efficiency of the generator or motor and the calculation of turbine or pump efficiency.

n) An evaluation of the random and systematic uncertainties of each measured quantity and a calculation of the total uncertainty of data derived from combined measurements.

o) Graphs showing the principal results.

p) Discussion of the test results on the basis of the test graphs:

1) for regulated turbines at specified speed and at each specified specific hydraulic energy:

- efficiency-power or efficiency-discharge;
- power-discharge;
- discharge and power-guide vane or needle opening.

2) for non-regulated turbines or pumps at specified speed:

   – efficiency-specific hydraulic energy;

   – discharge-specific hydraulic energy (pumps) or power-specific hydraulic energy (non-regulated turbines).

In the case of machines with adjustable runner/impeller blades and adjustable guide vanes, curves shall be drawn for different blade/vane settings to indicate how the cam control for the optimum relationship was determined.

q) Comparison with guaranteed values and conclusions: unfavourable influences during the test shall be reported.

SECTION TWO – EXECUTION OF TEST FOR THE DETERMINATION OF THE STEADY STATE PERFORMANCE OF THE MACHINE

5. Test conditions and procedure

5.1 *General test procedure*

5.1.1 *Methods of measurement*

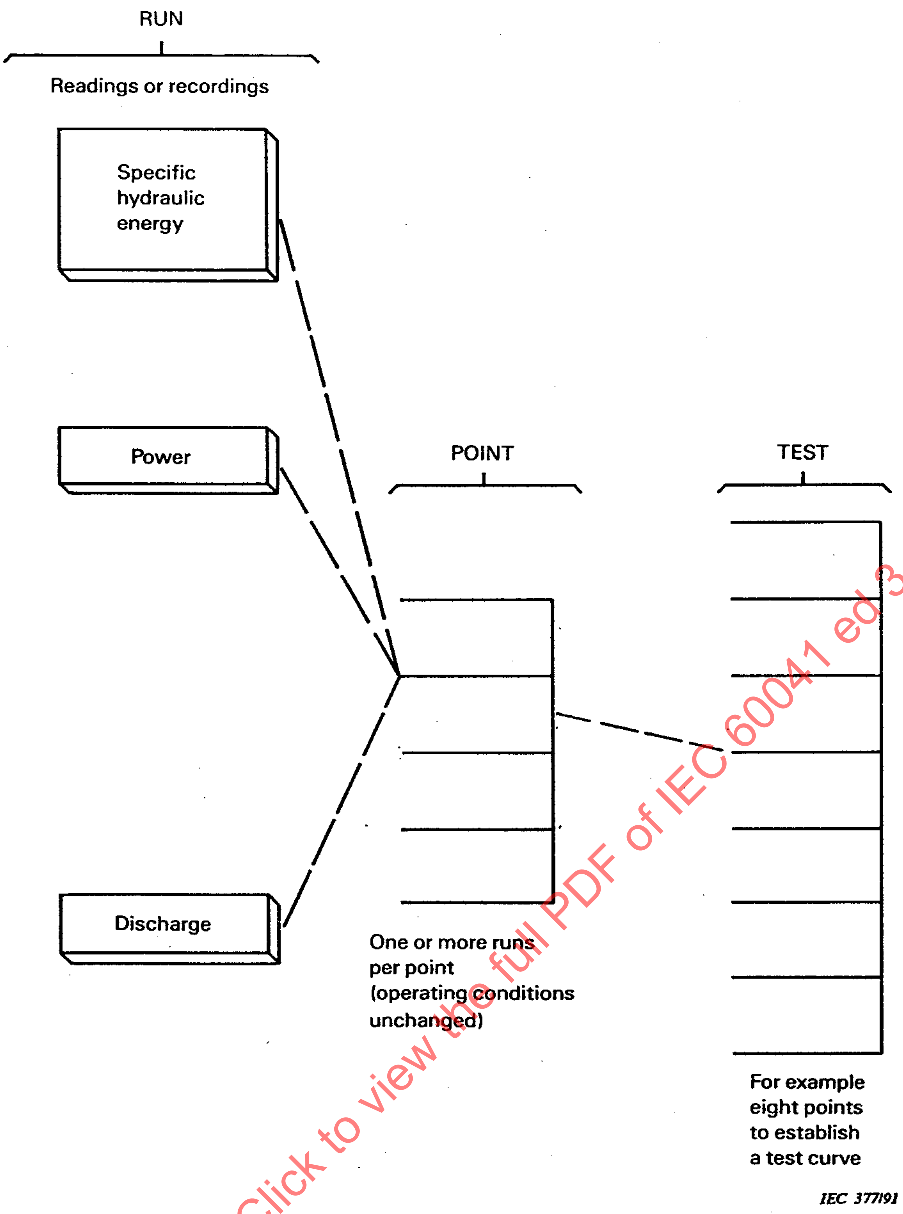
The methods to be used for the measurement or computation of discharge, power, specific hydraulic energy, efficiency, speed and losses shall be stated in the general programme. They are described in Clauses 9 to 14.

An additional index discharge measurement is recommended to overcome any difficulties that may arise from the chosen method. The index test methods are described in Clause 15.

5.1.2 *Number of points, runs and readings*

A performance curve such as that illustrated by Figure 10 a requires a minimum of six and preferably eight or ten points. Each point will be obtained from one or more runs (see 2.1 and 5.1.3). The number of measurements taken during a run depends upon the methods of measurement used, but for a statistical treatment (see Appendix C and D) at least five readings of direct-reading instruments per run are to be taken over an agreed time or over the duration of any time-based measurements. Figure 11 shows an example of a test schedule.

The interval of time during which all instantaneous readings and instrument recordings are made for each run shall generally be the same for each point. For some types of measurement such as the transit time method of discharge measurement, the time necessary to complete a run may vary significantly with discharge. It may then be appropriate to adjust the time interval between instantaneous readings so that each run contains the same number of readings or at least an agreed minimum number of readings. The sole exception is for any pressure-time method diagrams which shall be started within approximately 15 s after the last instantaneous reading or the end of recording of the other quantities.



Note. – The number of points to establish a curve, the number of runs per point and the number of readings per run depend on many factors (test methods, local conditions, type of machine, etc.) and shall be decided by the Chief of test. When Method A (see 5.1.3.1) is used, one run is sufficient for one point.

Figure 11 – Example of a test schedule

5.1.3 *Recommended test procedures*

Two procedures are recommended. The first (Method A) consists of testing a number of points over a range of operating conditions and drawing performance curves through them. The second (Method B) is based on testing several times one or a few specified operating points. Both methods may be supplemented as necessary by index tests.

For Method A, the quality of the measurements is judged by the deviations of the points from the best smooth mean curve drawn through them. For Method B, not applicable when test conditions can be maintained constant for a short time only, the quality of the measurements is judged by the deviations of the results of the individual runs from their arithmetical mean value at the operating point considered.

If a guarantee is given for peak efficiency, but the corresponding operating conditions are unknown or unspecified, a preliminary index test shall be carried out to determine these operating conditions, after which the necessary complete runs shall be made (see also 5.1.4).

A preliminary test should be carried out to instruct all participants in their respective duties and to verify satisfactory operation of all test equipment or to correct or improve it, if necessary. During both the preliminary and acceptance tests, all possible cross-checks of data and results should be carried out to reduce or eliminate errors. Provisional results should be calculated and plotted as fast as the data are gathered. These running plots of discharge and power versus gate opening for turbines or discharge and power versus specific hydraulic energy for pumps may reveal testing errors or abnormalities in the operating characteristics of the machine which require further investigation. It may not be practicable to include all of the instrument corrections in the provisional results.

5.1.3.1 Method A

This method shall be used when performance curves over a range of operating conditions must be obtained (see also Appendix D) or when the test conditions can be maintained constant (see 5.2.1) only for a short time. The test programme shall define:

a) the range of operating conditions to be covered by the test;

b) the number and sequence of operating points to be tested;

c) the guide vane/needle, runner/impeller blade and speed settings;

d) any supplementary index test to be made.

5.1.3.2 Method B

This method may be used only if the operating conditions can be maintained constant (5.2.1) over the whole test time necessary to establish the machine performance at the operating point specified (see also Appendix C).

The test programme shall define the minimum number of runs, but in no case shall the number be less than five at the same operating conditions. If tests at more than one operating condition are required, each of them shall have the same number of runs.

The test programme shall also define:

a) the number and sequence of operating points to be tested;

b) the guide vane/needle, runner/impeller blade and speed settings;

c) any supplementary index test to be made.

5.1.4 *Particular procedure for double regulated turbines*

Efficiency and power tests shall be made with the optimum relationship between guide vane and runner blade openings.

The optimum relationship can be established either during acceptance test or by previous index test. In this case, the optimum relationship must be established under the same hydraulic conditions as for the acceptance test, using for each of at least five blade openings, at least five different guide vane openings.

5.1.5 *Particular procedure for single regulated or double regulated pumps*

If possible, tests of these machines shall be carried out over the specified range of specific hydraulic energy and discharge. Efficiency and power tests shall be made with the openings of guide vanes and/or runner/impeller blades adequate to check the contract guarantees. These openings must be established under the same hydraulic conditions as for the acceptance test. In the case of a double regulated pump the relationship between guide vane and impeller blade openings can be established during the acceptance test or by a previous index test.

When adequate changes in water levels are not possible, discharge throttling and/or speed variation, if possible, may be used to obtain the necessary range of specific hydraulic energy.

5.2 *Test conditions to be fulfilled*

A run is considered valid if the following test conditions are fulfilled.

5.2.1 *Fluctuations and variations during a run* (see 2.1)

Fluctuations are defined as high frequency (more than 1 Hz) changes in the values of specific hydraulic energy, rotational speed, discharge or power about average values.

Some form of linear damping should be employed to eliminate the fluctuations and to read longer period changes (variations), which constitute the proper readings for the determination of the average value. In the case of sudden changes, the run cannot be considered valid. Variations of specific hydraulic energy, rotational speed and generator/motor power shall be such that the readings lie within the following limits during a run:

a) the variations of power shall not exceed $\pm 1,5$ % of the average value of power;

b) the variations of specific hydraulic energy shall not exceed ± 1 % of the average value of specific hydraulic energy;

c) the variations of rotational speed shall not exceed $\pm 0,5$ % of the average value of rotational speed.

5.2.2 *Deviations of average specific hydraulic energy and rotational speed from specified values during a run* (see 2.1)

A departure of the average values of specific hydraulic energy E and rotational speed n measured during a run from their specified values E_{sp}, n_{sp} is defined as deviation.

In all cases the deviations must lie within the limits defined under *a*) and *b*) below:

a)

$$0,97 \leq \frac{n/\sqrt{E}}{n_{sp}/\sqrt{E_{sp}}} \leq 1,03$$

In no case shall the values of $\frac{n}{\sqrt{E}}$ fall outside the values defining the operating range.

b)

$$0,80 \leq \frac{E}{E_{sp}} \leq 1,20$$

$$\text{and} \quad 0,90 \leq \frac{n}{n_{sp}} \leq 1,10$$

For conversion of test results to specified conditions see 6.1.2.

5.2.3 *Net positive suction specific energy* (see 2.3.6.9) *and tailwater level during the measurement of a point* (see 2.1)

5.2.3.1 For a reaction machine the net positive suction specific energy, *NPSE*, shall not fall below the value specified in the contract.

If the actual average specific hydraulic energy and/or speed deviate from the specified values, it is necessary to have the curve of minimum guaranteed value of *NPSE/E* as a function of *E*. The actual value of *NPSE/E* shall not fall below the curve (see Figure 12).

5.2.3.2 For impulse turbines, the highest tailwater level shall not exceed the maximum level specified in the contract.

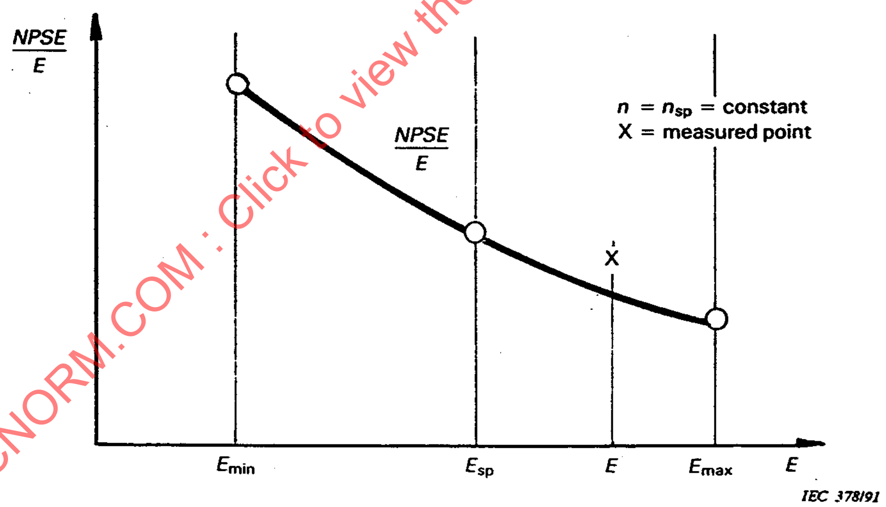


Figure 12 – Curve of minimum guaranteed value of *NPSE/E*.

6. Computation and analysis of results

6.1 *Computation of test results*

6.1.1 *Computation of a point*

For each run the arithmetic average value of the readings and recordings is computed for each measured quantity (n, Q, E, P); on the basis of these values the performance is calculated applying the necessary conversions and corrections (see 6.1.2).

In the case of multiple runs the performance results, obtained as indicated above, are averaged to establish the point.

6.1.2 *Conversion and correction of test results to specified conditions*

Figure 10 shows the guarantee curves. For the regulated turbine a guarantee curve is usually given for each specified specific hydraulic energy (Figure 10 a); on the contrary, for the non-regulated turbine and for the pump only a value for guaranteed quantities (efficiency for instance) is given for each specified specific hydraulic energy (Figures 10 b and 10 c). Provided that the conditions described at 5.2 are fulfilled, test results are valid. The method to calculate a point is explained at 6.1.1.

If the guaranteed discharge is referred to the ambient pressure (see 3.2.3), the measured value must be converted to this condition (see 2.3.4.5). If the average specific hydraulic energy E_n and/or rotational speed n deviate from specified values E_{sp} and n_{sp} during a run, a conversion must be made using affinity laws, assuming that the conditions of these laws are fulfilled. The following formulae and procedures can be adopted:

6.1.2.1 Non-regulated turbine and pump; if $n \neq n_{sp}$:

$$\frac{Q_{n\mathrm{sp}}}{Q_n} = \frac{n_{sp}}{n}; \qquad \frac{E_{n\mathrm{sp}}}{E_n} = \left(\frac{n_{sp}}{n}\right)^2; \qquad \frac{P_{n\mathrm{sp}}}{P_n} = \left(\frac{n_{sp}}{n}\right)^3; \qquad \eta_{n\mathrm{sp}} = \eta_n$$

Figures 13 a and 13 b represent the guarantee curves and the shifting of measured quantities Q, P, converted to n_{sp}.

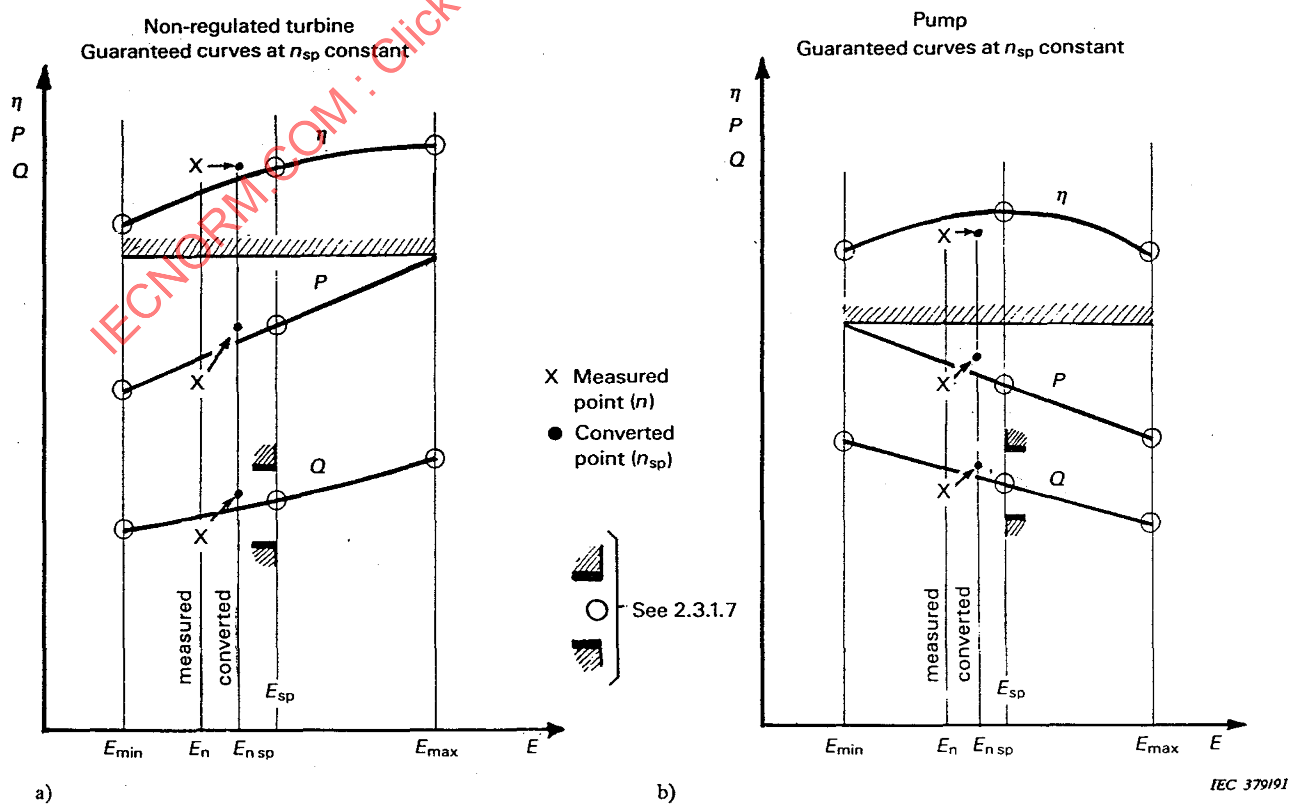


Figure 13 – Conversion of a measured point to the specified rotational speed

6.1.2.2 Regulated turbine: if $E_n \neq E_{sp}$ and/or $n \neq n_{sp}$, there are three possible cases:

a) in some rare cases it is possible to meet the relation $\frac{n}{\sqrt{E}} = \frac{n_{sp}}{\sqrt{E_{sp}}}$ and to avoid corrections outlined under *c)* by adjusting the speed if $E \neq E_{sp}$ and/or the specific hydraulic energy if $n \neq n_{sp}$.

Conversion formulae are:

$$\frac{Q_{E_{sp}}}{Q_E} = \left(\frac{E_{sp}}{E}\right)^{1/2}$$

$$\frac{P_{E_{sp}}}{P_E} = \left(\frac{E_{sp}}{E}\right)^{3/2}$$

$$\eta_{E_{sp},n_{sp}} = \eta_{E,n}$$

b) when the adjustment described above is not possible, and if $0,99 \leq \frac{n/\sqrt{E}}{n_{sp}/\sqrt{E_{sp}}} \leq 1,01$, no correction (see *c)*) is necessary and the conversion formulae given at a) are used.

c) when the adjustment described at *a)* is not possible and if $\frac{n/\sqrt{E}}{n_{sp}/\sqrt{E_{sp}}}$ is outside the range given at *b)*, it is necessary to make – in addition to conversion – a correction.

For this purpose it is necessary to have – in addition to the efficiency guaranteed curves corresponding to the different specified specific hydraulic energies – the relevant portion of the efficiency hill diagram (see Figure 14). In the case where the efficiency guarantees are given only for a specified specific hydraulic energy, it is necessary to have the portion of the efficiency hill diagram included between maximum and minimum specific hydraulic energies of the operational range. A previous agreement should be reached between purchaser and supplier on this matter.

If $n \neq n_{sp}$ and $E \neq E_{sp}$, the first thing to do is to convert point A_n into $A_{n_{sp}}$ using the formulae described in 6.1.2.1. As $E_{n_{sp}} \neq E_{sp}$, the next step is to shift $A_{n_{sp}}$ to the line corresponding to E_{sp} in Figure 14, following a constant opening method (A_2). Other modes of shifting (i.e. at constant discharge A_1, or at constant efficiency, A_3) may be agreed upon between the parties.

Efficiency shall be corrected by the formula:

$$\eta_{E_{sp},n_{sp}} = \eta + \Delta\eta$$

where η = measured value and $\Delta\eta$ = difference between efficiency in A_2 for instance, and efficiency in $A_{n_{sp}}$ according to efficiency hill diagram.

E_{sp} is known, $Q_{E_{sp},n_{sp}}$ and $\eta_{E_{sp},n_{sp}}$ are determined as explained before, $P_{E_{sp},n_{sp}}$ is consequently calculated.

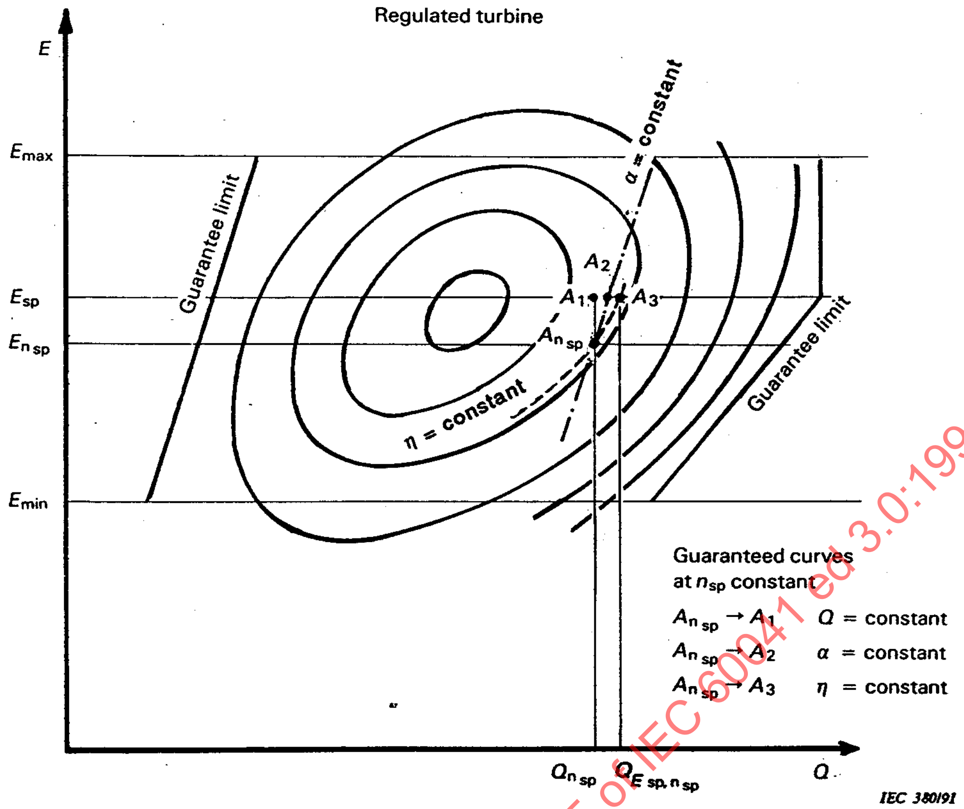


Figure 14 – Correction of a measured point to specified conditions

6.1.3 *Test curves*

– For regulated turbines:

values of η shall be plotted against $P_{E_{sp},n_{sp}}$ or $Q_{E_{sp},n_{sp}}$; values of $P_{n_{sp}}$ shall be plotted against $E_{n_{sp}}$.

– For non-regulated turbines and for pumps:

values of $Q_{n_{sp}}$, $P_{n_{sp}}$ and η shall be plotted against $E_{n_{sp}}$.

Conversion to specified values is given in 6.1.2.

6.2 *Uncertainties in measurements* and presentation of results*

6.2.1 *Definition of error*

The error in the measurement of a quantity is the difference between that measurement and the true value of the quantity.

No measurement of a physical quantity is free from uncertainties arising from systematic errors and random errors. Systematic errors cannot be reduced by repeating measurement since they arise from the characteristics of the measuring apparatus, the installation, and the operation conditions. However, a reduction in the random error may be achieved by repetition of measurements since the random error of the mean of n independent measurements is $\sqrt{n}$ times smaller than the random error of an individual measurement (see Appendix C).

6.2.2 *Definition of uncertainty*

The range within which the true value of a measured quantity can be expected to lie with a suitably high probability is termed the "uncertainty of the measurement". For the purposes of this standard, the probability to be used shall be 95 % level.

6.2.3 *Types of errors*

There are three types of error which must be considered:

- spurious errors;
- random errors;
- systematic errors.

6.2.3.1 Spurious errors

These are errors such as human errors, or instrument malfunction, which invalidate a measurement: for example, the transposing of numbers in recording data or the presence of pockets of air in leads from a water line to a manometer. Such errors should not be incorporated into any statistical analysis and the measurement must be discarded. Where the error is not large enough to make the result obviously invalid, some rejection criteria should be applied to decide whether the data point should be rejected or retained.

Unless otherwise agreed, the Grubbs test described in Appendix B is recommended for testing possible outliers; other tests, such as the Dixon test given in ISO 5168, may be used by agreement.

It is necessary to recalculate the standard deviation of the distribution of results after applying the outlier test if any data points are discarded. It should also be emphasized that outlier tests may be applied only if there is an independent technical reason for believing that spurious errors may exist: data should not be thrown away lightly.

6.2.3.2 Random errors

Random errors are caused by numerous, small, independent influences which prevent a measurement system from delivering the same reading when supplied with the same input value of the quantity being measured.

The measurements deviate from the mean in accordance with the laws of chance, such that the distribution usually approaches a normal distribution as the number of measurements is increased.

The random error is influenced by the care taken during measurements, the number of measurements and the operating conditions. The scatter of readings observed during a point results from the combination of the random error arising from the instrumentation and of the influence of the operating conditions.

* See ISO 5168.

6.2.3.3 Estimation of the uncertainty associated with random error

Statistical methods for estimating the uncertainty associated with random error are discussed in Appendices C and D.

When the sample size is small, it is necessary to correct the statistical results that are based on a normal distribution by means of Student's t values, as explained in these appendices. Student's t is a factor which compensates for the uncertainty in the standard deviation increasing as the sample size is reduced.

The uncertainty corresponding to a level of 95 % is written $(f_r)_{95}$.

An agreement prior to the test shall specify the maximum permissible value $\pm f_r$ of the uncertainty bandwidth due to random errors. If more than 5 % of the results are outside this range, an accurate analysis will be made and the measurements will be repeated or a new value of the uncertainty bandwidth due to random errors will be agreed.

6.2.3.4 Systematic errors

Systematic errors are those which cannot be reduced by increasing the number of measurements if the equipment and conditions of measurements remain unchanged.

The systematic error of a measurement depends partly on the residual error in the instrument or measuring system at the start of the test. At that time, all removable errors will have been eliminated by calibration, careful measurement of dimensions, proper installation, etc. The error still remaining is called systematic error (bias) and always exists, however small.

The systematic error is largely controlled by the choice of measuring method, and the operating conditions; for example, the value of the kinetic energy calculated with the mean velocity can differ from its true value if the velocity distribution at the measuring section is not sufficiently regular. Systematic errors do not affect the repeatability of measurements during a test.

Prior to any test, an agreement should be reached on an expected band of systematic uncertainty within the range given in the first column of Table AI, Appendix A. It must be emphasised that the values for systematic uncertainties listed in the second column are expected uncertainties when the measurements are made in normal conditions by experienced personnel with an apparatus of high quality, in accordance with the provisions of the standard. The actual value of systematic uncertainty usually depends on many factors, some of which can only be evaluated after the test. A review of these factors shall be made and an agreement between the parties concerned established whether the expected uncertainties have to be changed on technical grounds or not.

6.2.3.5 Estimation of the uncertainty associated with systematic errors

The uncertainty associated with systematic errors cannot be assessed experimentally without changing the equipment or conditions of measurement. This change can indicate an order of magnitude of the systematic error and should be applied whenever possible. The alternative is to make a subjective judgement on the basis of experience and consideration of the equipment involved.

The first step in the estimation of this uncertainty is to identify those aspects of the measurement that can affect its value; the second step is to allocate uncertainty limits to allow for each of these effects. This may be done, in part at least, by statistical analysis*.

* See for example ISO 5168.

If the error has a unique known value then this shall be added to (or subtracted from) the result of the measurement and the uncertainty in the measurement due to this source is then taken as zero. If the systematic error of a measuring device is unknown but its error limits (class of accuracy) are specified, the interval between them may be assumed as the systematic uncertainty of that device with a confidence level better than 95 %.

Systematic errors usually are considerably larger than random errors for the highest quality field test.

Actually, notwithstanding the difference exposed above between systematic and random uncertainties, the probability distribution of the possible values of each systematic component is essentially gaussian and the systematic uncertainty f_s is computed from the individual systematic uncertainties by the root-sum-squares method; for example, the systematic uncertainty of efficiency $(f_\eta)_s$ is computed from the individual systematic uncertainties in discharge $(f_Q)_s$, specific hydraulic energy $(f_E)_s$ and power $(f_P)_s$ by:

$$(f_\eta)_s = \pm\left[(f_Q)_s^2 + (f_E)_s^2 + (f_P)_s^2\right]^{1/2}$$

See also Clause A2 of Appendix A.

6.2.4 *Total uncertainty*

The total uncertainty in a measurement (f_t) is obtained by combining the systematic (f_s) and random (f_r) uncertainties (see 6.2.3.3 and 6.2.3.5). It defines a range within which the true value is assumed to have a probability of 95 % to lie, and any point in this range is equally valid.

Given the same type of probability distribution of the systematic and random uncertainties (see 6.2.3.5), they can be combined by the root-sum-squares method. The total uncertainty is thus given by:

$$f_t = \pm\left(f_s^2 + f_r^2\right)^{1/2}$$

6.2.5 *Analysis of results*

The method of analysis and presentation of results described hereafter with particular reference to comparison with guarantees is recommended. Appendix A contains estimates of systematic uncertainties; Appendices C and D provide enough information to make simple estimates of random uncertainties; Appendix B describes a method for rejecting outliers.

6.2.6 *Presentation of results*

Taking into account the total uncertainties calculated as explained in 6.2.4, each measured point should be represented on a diagram by an ellipse. The axes of this ellipse represent the total uncertainty, at a confidence level of 95 %, in the two quantities chosen as coordinates of the diagram. Any point within this ellipse is equally valid.

If a curve is guaranteed (guarantee given within a range of powers, for instance), an uncertainty band corresponding to the upper and lower envelopes of these ellipses is superimposed to the best fitted curve drawn through the test points (see Appendix D). All the points within this band are equally valid and thus this band constitutes an acceptable bandwidth for comparison with guarantees.

In some cases, for example, when the guarantee curve is plotted against specific hydraulic energy, the limits of the total uncertainty bandwidth can be obtained by reducing the ellipses to their principal axis.

6.3 *Comparison with guarantees*

The comparison with guarantees shall be made by the following methods using the total uncertainty bandwidth (see 6.2.6) and taking into account the contractual limits (see Figures 10 a, 10 b and 10 c).

6.3.1 *Power* (see 3.2.2)

6.3.1.1 Regulated turbine

Figure 15 shows the guaranteed curve of the power to be reached against the specified specific hydraulic energy. In this example, the guarantee for power is not fulfilled in the range A.

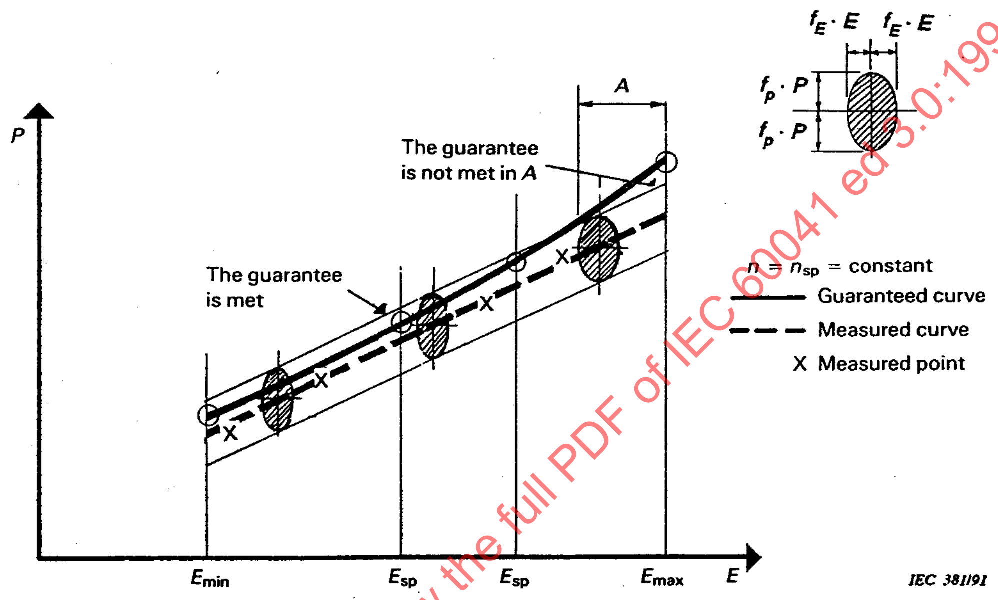


Figure 15 – Regulated turbine

6.3.1.2 Non-regulated turbine

Figure 16 shows the guaranteed curve of the power against the specified specific hydraulic energy and the result of the comparison with the measured curve, taking into account the bandwidth corresponding to the combination of total uncertainties.

As shown in this figure, the specified limits with regard to specified specific hydraulic energies are defined – if not otherwise agreed – by a lower limit kP_{sp} and a higher limit $(k + 0,1)P_{sp}$, k being a mutually agreed value lying somewhere between 0,9 and 1,0; normally the value of k is 0,95. The choice of k must be compatible with the power specified limits corresponding to E_{min} and E_{max}, if any. In Figure 16, the guarantee is not met in the range A.

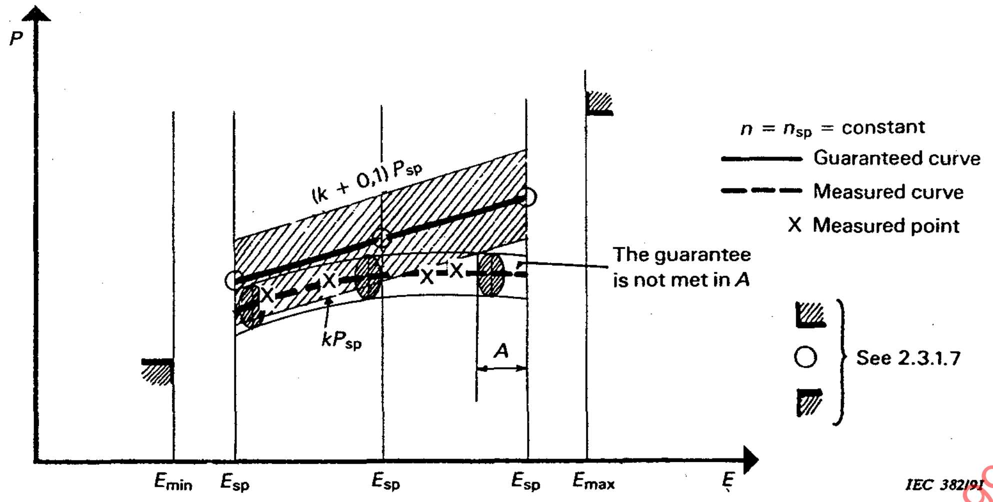


Figure 16 – Non-regulated turbine

6.3.1.3 Regulated/Non-regulated pump

Figure 17 shows the guaranteed specified limit of the power against the specified specific hydraulic energy and the result of the comparison with the measured curve, taking into account the bandwidth corresponding to the combination of total uncertainties. In this example, the guarantee for power is not fulfilled in the range *A*.

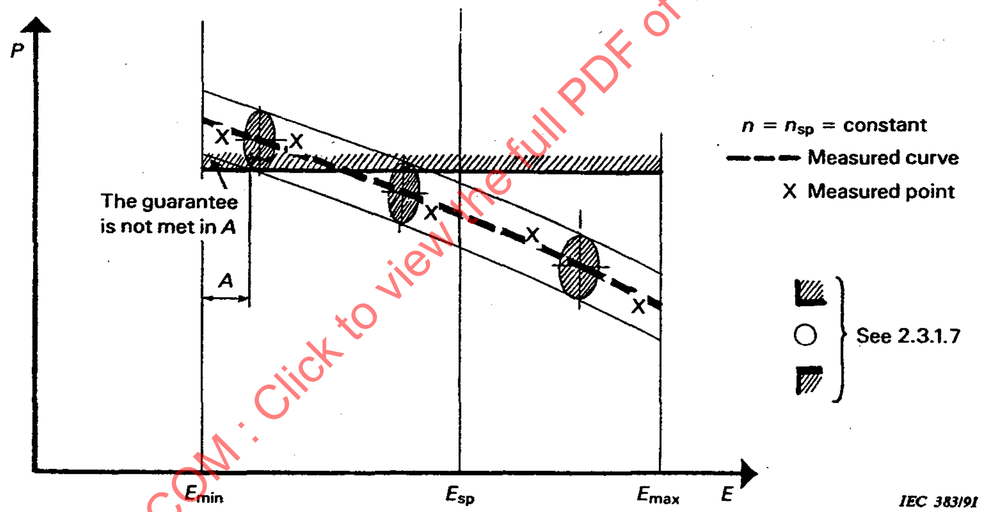


Figure 17 – Pump

6.3.2 *Discharge* (see 3.2.3)

6.3.2.1 Regulated turbine

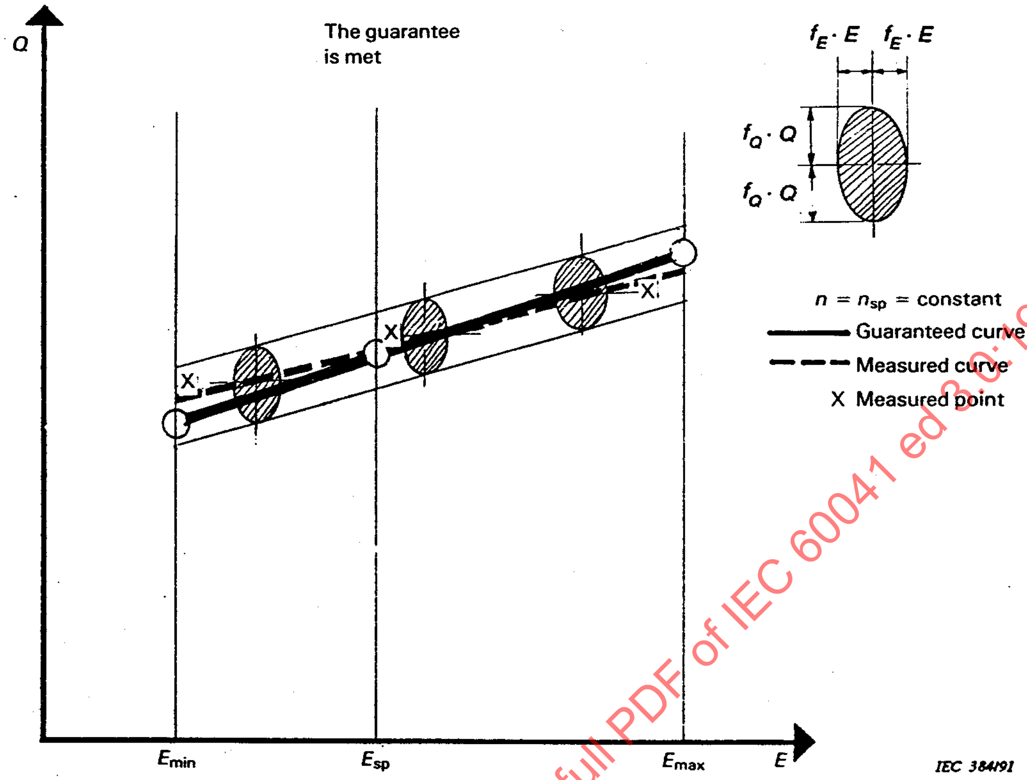


Figure 18 – Regulated turbine

6.3.2.2 Non-regulated turbine

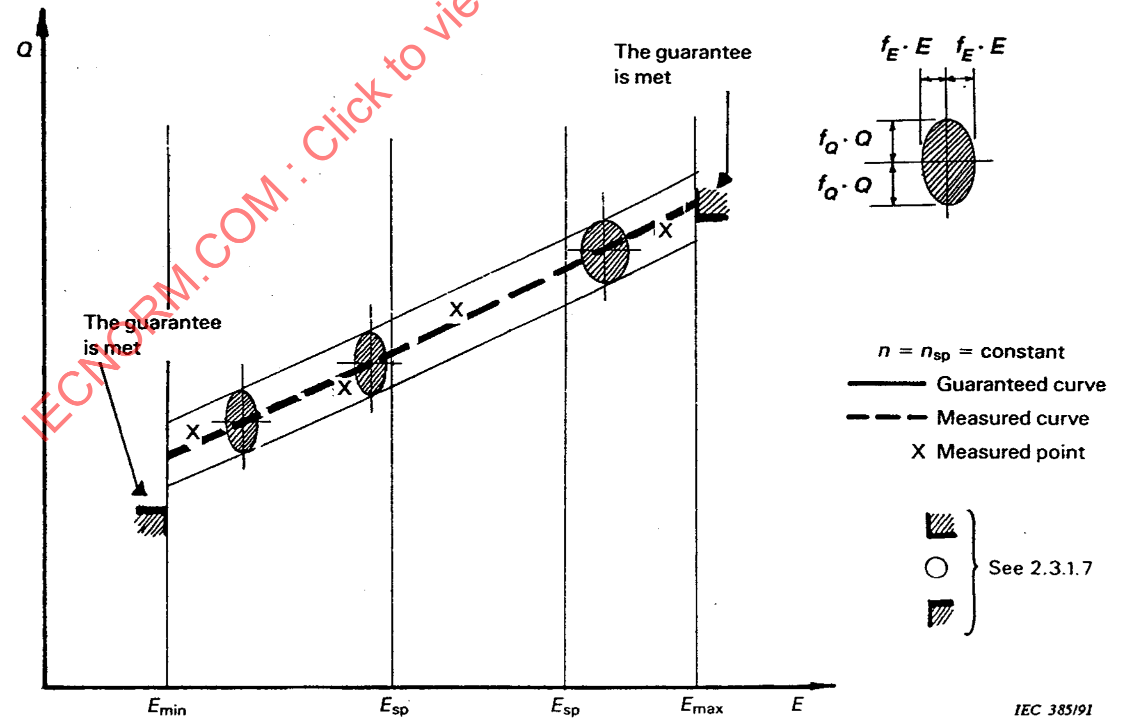


Figure 19 – Non-regulated turbine

6.3.2.3 Non-regulated/regulated pump

As shown in figure 20, the specified limits with regard to specified specific hydraulic energies are defined – if not otherwise agreed – by a lower limit kQ_{sp} and a higher limit $(k + 0,1)Q_{sp}$, k being a mutually agreed value lying somewhere between 0,9 and 1,0; normally the value of k is 0,95. The choice of k shall be compatible with the discharge specified limits corresponding to E_{min} and E_{max}, if any. In Figure 20 the guarantee is not met in the range A.

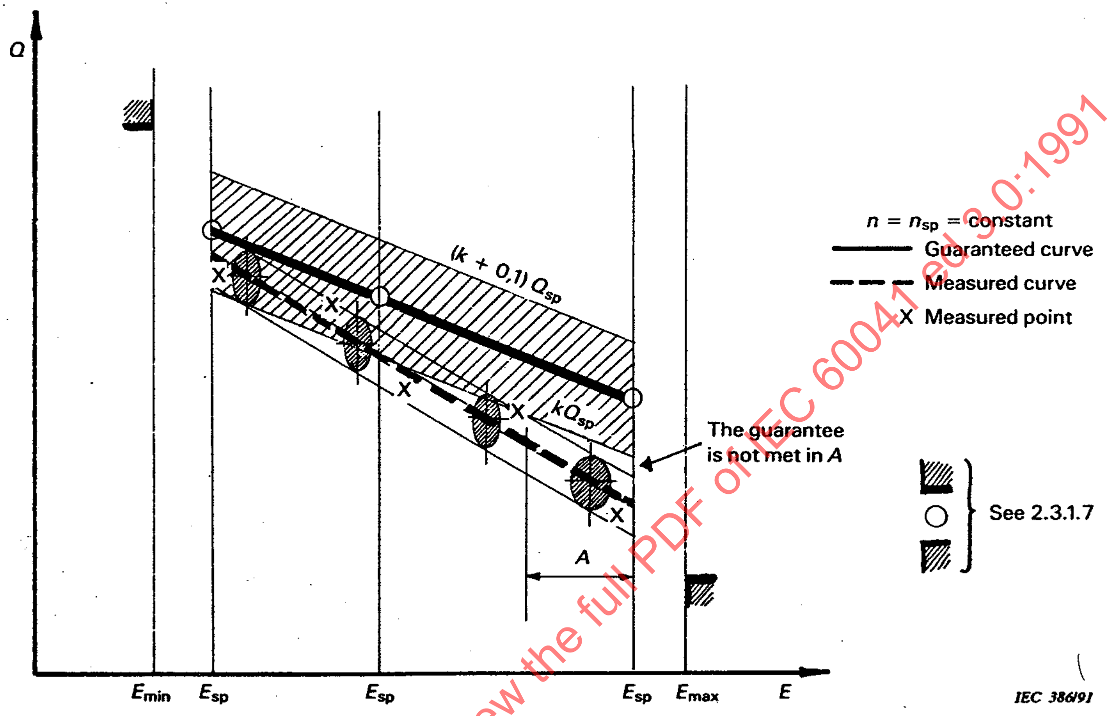


Figure 20 – Pump

6.3.3 *Efficiency* (see 3.2.4)

6.3.3.1 Regulated turbine

The measured efficiency η is plotted with the uncertainty bandwidth against the turbine power P or discharge Q (see 3.2.4.1) converted as necessary to correspond to the specified specific hydraulic energy and speed (see 6.1.2).

If the guaranteed power or discharge is exceeded on test, the supplier may have the option of naming a power or a discharge attained but not greater than 10 % above the guarantee power (see 6.3.1) or discharge (see 6.3.2) as a basis for determining the average efficiency (see Figure 21). This new reference power or discharge will be subject to any limitation specified in the contract. These newly chosen values of power or discharge may be used to reduce the amount of penalty, but not to increase the amount of premium. The newly chosen power or discharge shall be considered as reference power or discharge for all other guarantees (maximum momentary overspeed, maximum/minimum momentary pressure, cavitation pitting, etc.); the chosen rate of increase shall be applied to all the powers (discharges) corresponding to the other specified specific hydraulic energies, except those not tolerated by the electric machine.

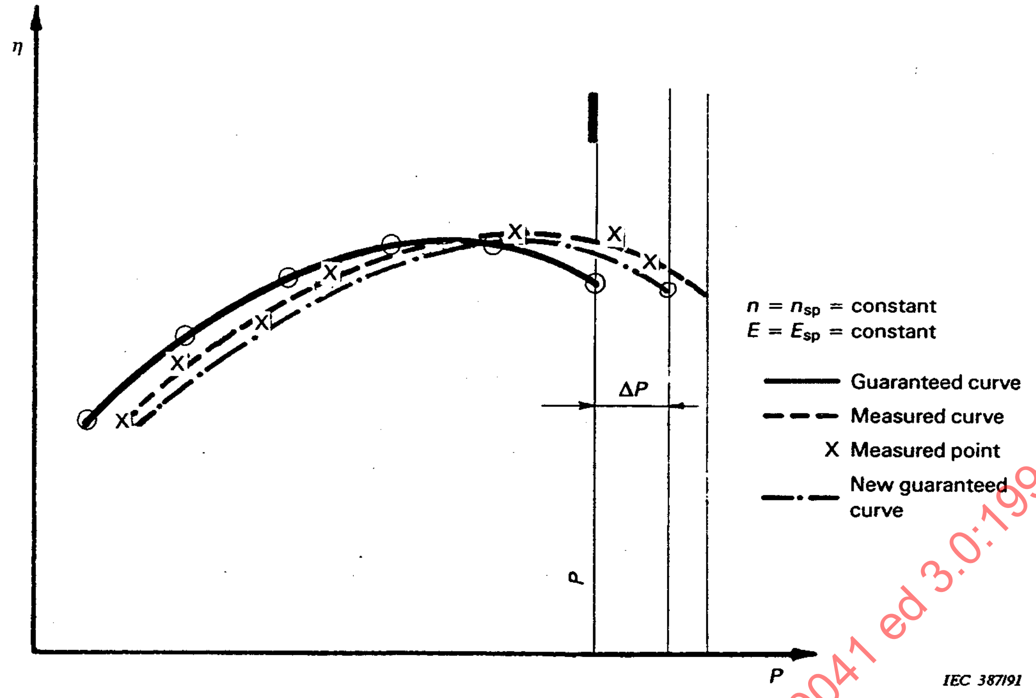


Figure 21 – Regulated turbine

a) If the guarantee is given at one or more individual specified powers or discharges or as a curve (see 3.2.4.1 *a)*) , it is met if, at the specified speed and specified specific hydraulic energy, the guaranteed single values or the guaranteed curve lie below the upper limit of the total uncertainty bandwidth over the specified power (or discharge) range (see Figure 21a), b) and c)).

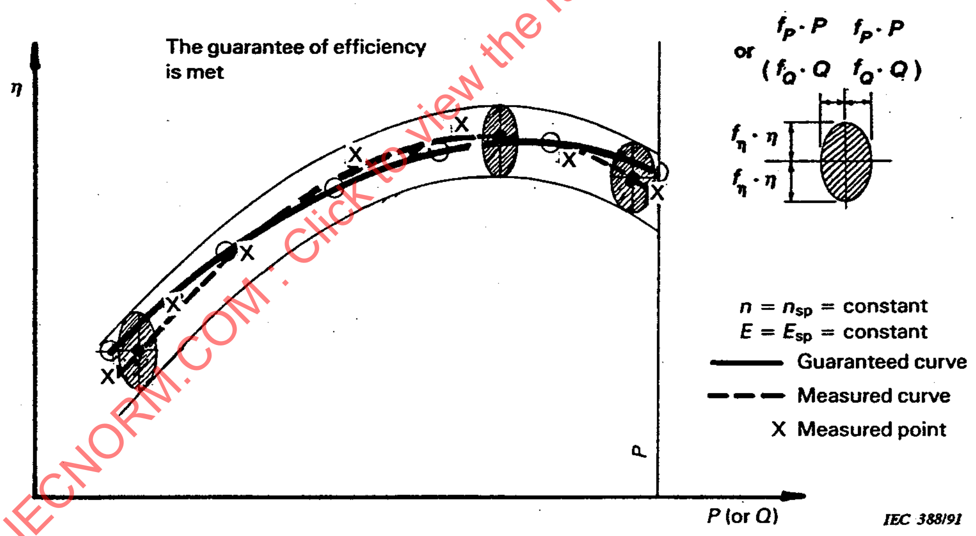


Figure 21 a – Regulated turbine

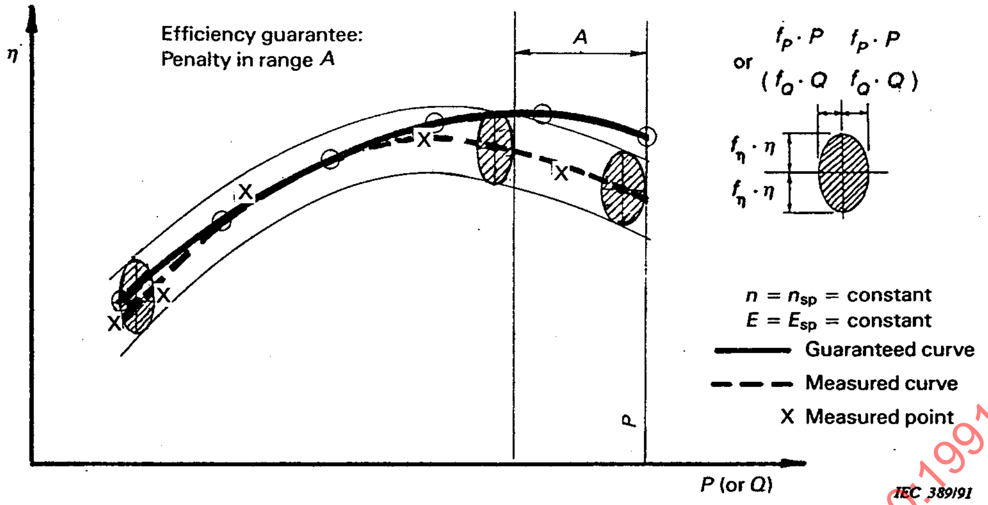


Figure 21 b – Regulated turbine

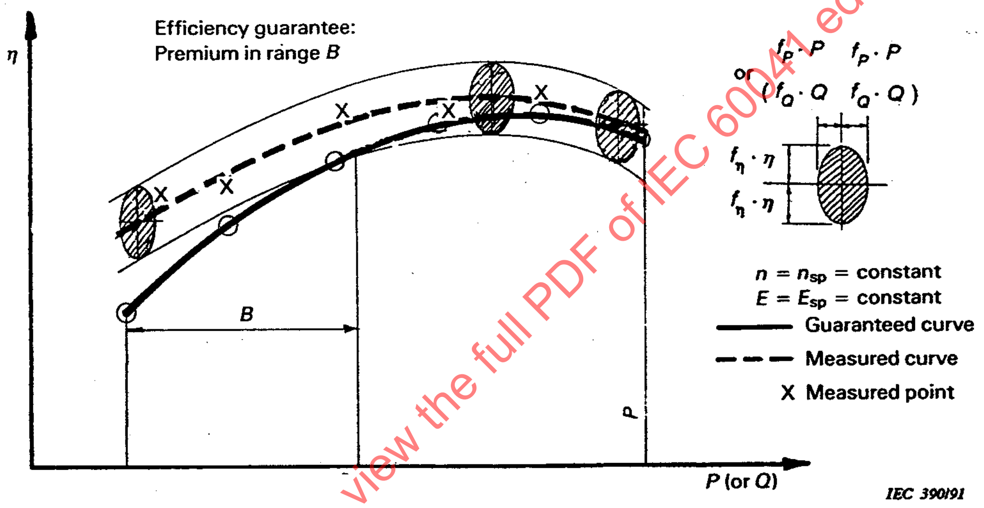


Figure 21 c – Regulated turbine

b) Alternatively, if the guarantee is given as a weighted or arithmetic average efficiency (see 3.2.4.1 *b*) and *c*)), the guarantee is met if, at the specified speed and specific hydraulic energy, the guaranteed average efficiency is exceeded by the average efficiency calculated at the same specified powers (or discharges), using the upper limit of the total uncertainty bandwidth.

6.3.3.2 Non-regulated turbine

The measured efficiency η is plotted with the uncertainty bandwidth against specific hydraulic energy E (see 3.2.4.2), converted – if necessary – to correspond to the specified speed (see 6.1.2).

a) If the guarantee is given at one or more individual specified specific hydraulic energies or as a curve (see 3.2.4.2 *a*)), it is met if, at the specified speed, the guaranteed single values or the guaranteed curve lie below the upper limit of the total uncertainty bandwidth over the specified specific hydraulic energy range (see Figure 22).

b) Alternatively, if the guarantee is given as a weighted or arithmetic average efficiency (see 3.2.4.2 *b*) and *c*)), the guarantee is met if, at the specified speed, the guaranteed average efficiency is exceeded by the average efficiency calculated at the same specified specific hydraulic energies using the upper limit of the total uncertainty bandwidth.

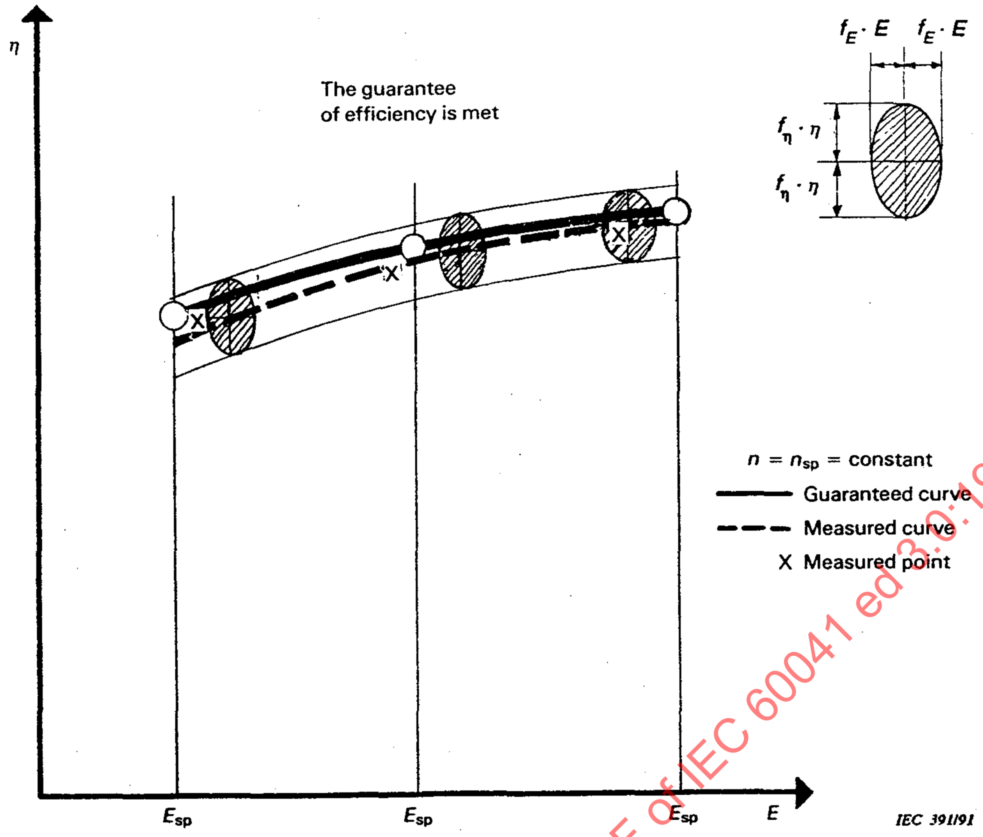


Figure 22 – Non-regulated turbine

6.3.3.3 Pump

The measured efficiency η is plotted with the uncertainty bandwidth against specific hydraulic energy E (see 3.2.4.2), converted – if necessary – to correspond to the specified speed (see 6.1.2).

a) If the guarantee is given at one or more individual specified specific hydraulic energies or as a curve (see 3.2.4.2 *a*)), it is met if, at the specified speed the guaranteed single values or the guaranteed curve lie below the upper limit of the total uncertainty bandwidth over the specified specific hydraulic energy range (see Figure 23).

b) Alternatively, if the guarantee is given as a weighted or arithmetic average efficiency (see 3.2.4.2 *b*) and *c*)), the guarantee is met if, at the specified speed, the guaranteed average efficiency is exceeded by the average efficiency calculated at the same specified specific hydraulic energies using the upper limit of the total uncertainty bandwidth.

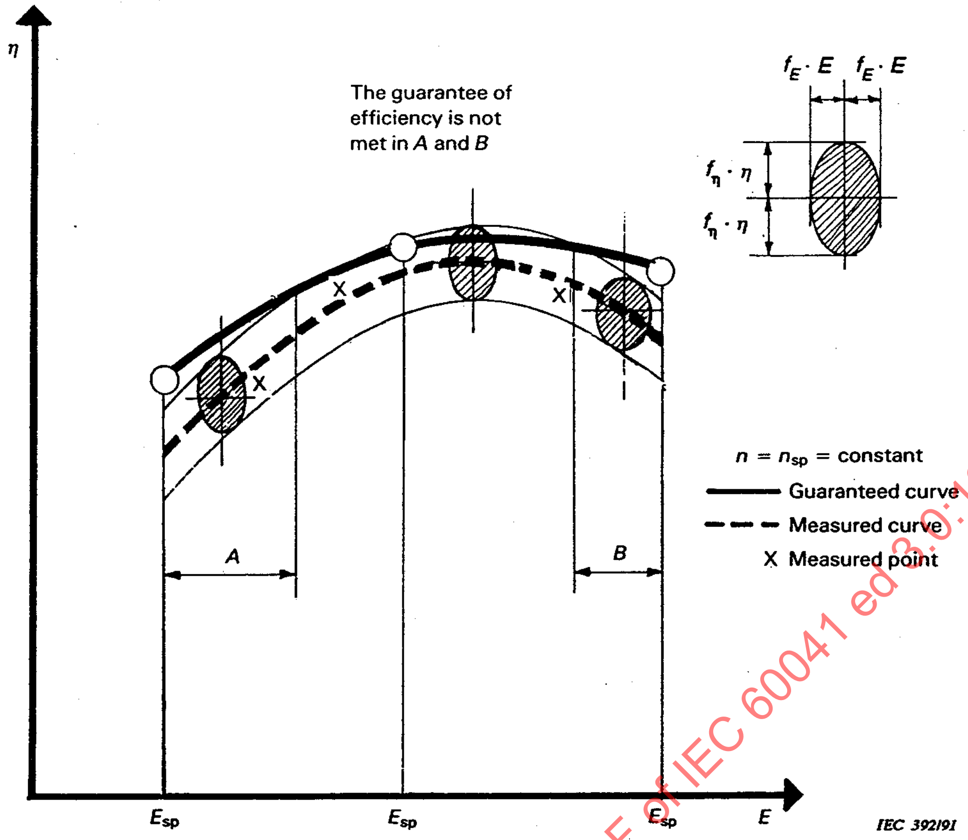


Figure 23 – Pump

6.3.3.4 Penalty and premium

If the contract provides for a penalty (or a premium) for lack (or excess) of efficiency, the amount of this penalty (or premium) shall be calculated from the difference between the guaranteed efficiency curve or guaranteed average value and the upper (or lower) limit of the total uncertainty band, this difference being taken into account in case of a guaranteed curve only within the range where the guarantee lies outside the uncertainty band (see zones *A* and *B* of figure 23).

SECTION THREE – EXECUTION OF TEST FOR THE DETERMINATION OF THE TRANSIENT CHARACTERISTIC OF THE MACHINE

7. Test conditions and procedure

7.1 *Test conditions*

7.1.1 *General*

Transient operating conditions (e.g. load rejections, power failure etc.) cause pressure and speed variations dependent on the type of machine and on the movement of the shut-off devices (i.e. guide vanes, needles and/or valves). In addition, superimposed pressure variations and fluctuations of significant magnitude, not directly attributable to operational changes, can occur in some applications (e.g. pump-turbines). In these cases, they should be the subject of a separate guarantee in the contract.

The test should be performed, if possible, under the specified worst conditions. For each plant the worst conditions should be determined carefully and agreed upon before the test.

7.1.2. *Speed variations*

7.1.2.1 Momentary overspeed

The definition is given in 2.3.4.13.

For most turbines, maximum momentary overspeed (see 2.3.4.14) will occur following sudden load rejection when power is being reduced to zero.

7.1.2.2 Steady state runaway speed

Regulated machines are normally protected from full runaway speed condition through an adequate closing device. Accordingly for most machines, steady state runaway speed is not normally reached and runaway speed therefore may be considered as an unusual or extraordinary condition.

Unless otherwise agreed, it is recommended not to carry out steady state runaway speed tests. If carried out they should be performed at reduced specific hydraulic energy in order to keep the physical stress of the machines – particularly of the electrical machinery – low in comparison with the stress which may occur at tests under the full specific hydraulic energy.

For non-regulated machines and for regulated machines with shut-off devices which have long closing times, steady state runaway speed will normally be exceeded during load rejection which is performed during commissioning. Therefore a separate steady state runaway test is not necessary.

7.1.3 *Pressure variations*

The maximum momentary pressure on the high pressure side and the minimum momentary pressure on the low pressure side of a turbine normally occur during the shut-down operation when a specified load is reduced to zero. The minimum momentary pressure on the high pressure side and the maximum momentary pressure on the low pressure side normally occur during the opening movement of the shut-off device beginning from zero or from no-load opening.

For pumps, the minimum pressure on the high pressure side and the maximum pressure on the low pressure side occur during a power failure.

Unless otherwise specified the momentary pressure shall be measured at the reference sections.

7.2 *Test procedure and instrumentation*

7.2.1 *General requirements*

Since the pressure and speed variations depend on the movement of the shut-off devices, all three quantities shall be recorded simultaneously.

7.2.2 *Measurement of speed variations*

Instrumentation for measurement of speed variations shall be capable of attaining a measurement total uncertainty of $\pm 1,0\%$.

7.2.3 *Measurement of pressure variations*

Electrical pressure transducers or spring-type indicators may be used for recording pressure variations. The measuring devices shall be insensitive to mechanical vibration and shall be connected directly (flush) to the penstock wall whenever this is possible. If the instrument cannot be directly connected to the penstock, the piping shall be as short and straight as possible and made of metal. Flexible tubes are not allowed.

Air shall be purged out of the piping before measurement. Purchaser and supplier shall agree upon an upper frequency limit up to which pressure fluctuations shall be accounted for. The measuring chain including transducer and piping shall reproduce fluctuations with frequencies lower than the limit without distortion by damping or resonance in the measuring tap. Fluctuations with higher frequency shall be removed by appropriate filtering.

The basis of the limiting frequency for the filter is given by the specific frequency characteristics of the hydraulic system.

The maximum permissible value of measurement total uncertainty shall be $\pm 100 \times p^{-0,25}\%$ (where p is in pascals).

8. Computation and analysis of results

8.1 *Conversion of results*

In those cases where it is not possible to perform the test under specified conditions, the measured values shall be converted by calculation. This conversion can be made in a simplified and approximate manner, if the following conditions are fulfilled:

a) for pressure variation:

$$0,9E_{sp} < E < 1,1E_{sp}$$

b) for speed variation:

$$0,9E_{sp} < E < 1,1E_{sp}$$

and

$$0,9P_{sp} < P < 1,1P_{sp}$$

c) the closing time is greater than 1,5 times the period of the pressure waves in the penstock;

d) the guide vane (needle) opening, the runner/impeller blade opening in case of a double regulated machine, and the closing time are approximately the same as for the specified conditions.

The following formulae shall be applied only for regulated reaction turbines excluding pump-turbines operating in turbine mode. For impulse turbines, only the formula for conversion of pressure rise is applicable.

If before measurement

$$E = K_E \cdot E_{sp} \quad \text{and} \quad P = K_p \cdot P_{sp}$$

the variations Δp_{sp} and Δn_{sp}, which are to be expected under specified conditions, can be calculated from the measured values of the pressure variation $\Delta p = p_m - p_i$ and speed variation $\Delta n = n_m - n_i$ (see Figures 4a, 4b and Figure 3) as follows*:

$$\Delta p_{sp} \approx \frac{\Delta p}{K_E^{1/2}} \quad \text{and} \quad \Delta n_{sp} \approx \Delta n \cdot \frac{K_E^{3/2}}{K_P^2}$$

8.2 *Comparison with guarantees*

8.2.1 *Nature and extent of guarantees*

Guarantees for the limits of the momentary pressure (see 2.3.5.6 and 2.3.5.7) and of the momentary overspeed (see 2.3.4.13 and 2.3.4.14) of the hydraulic machine are given for the whole range of specific hydraulic energy E under the worst operating conditions (see 3.2.6).

8.2.2 *Fulfilment of guarantees*

The guarantees are fulfilled if, taking into account the measurement total uncertainties (see 7.2.2 and 7.2.3) and tolerances, if any**:

a) the values measured under or converted to the specified worst conditions are within the guaranteed limits;

b) the measured values are within the limits obtained by interpolation from the guarantee.

In the case of superimposed pressure variations and fluctuations, (see 7.1.1) their interpretation and applicable tolerances have to be stated in the contract.

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*Basis for the formulae:
under steady state conditions the following relations are approximately valid within a narrow range:
for a Francis turbine for example:

$$Q \sim a_0 \cdot E^{1/2}; \quad T_s \sim a_0 \quad \text{(where } T_s \text{ is the closing time)}; \quad P \sim Q \cdot E \sim a_0 \cdot E^{3/2}.$$

For pressure variation $\Delta p \sim Q/T_s \sim E^{1/2}$.

For speed variation $\Delta n \sim P \cdot T_s \sim a_0^2 \cdot E^{3/2} \sim P^2 \cdot E^{-3/2}$.

The expressions of Δp_{sp} and Δn_{sp} are obtained from the above relations, combined with $E = K_E \cdot E_{sp}$ and $P = K_P \cdot P_{sp}$.

**The inexact prediction of the interaction between hydraulic machine and water ways may require a tolerance on the guarantees to be stated in the contract; otherwise this tolerance shall be zero.

Examples of tolerance are:

- momentary overspeed: 10% of the guaranteed speed variation, including the measurement uncertainty;
- momentary pressure: $\Delta(\Delta p_{sp}) = (K \cdot \Delta p_{sp})^{0,5}$

where:

$K = 5\,000$ Pa

$\Delta(\Delta p_{sp})$ = tolerance of the guaranteed pressure variation in pascals including the measurement uncertainty.

SECTION FOUR — METHODS OF MEASUREMENT

9. Introduction

9.1 *Efficiency*

A field acceptance test on a hydraulic machine in accordance with this standard aims at comparing the achieved hydraulic performance with the guarantees given by the supplier. This involves the evaluation of absolute values of specific hydraulic energy, discharge, mechanical power, rotational speed and efficiency.

Efficiency may be calculated from the mechanical power P exchanged with the electrical machine and the hydraulic power P_h exchanged with the water. According to the definition given in 2.3.9.3, the efficiency of the hydraulic machine is:

$$\eta = P/P_h \quad \text{for a turbine,}$$

$$\eta = P_h/P \quad \text{for a pump.}$$

The determination of the hydraulic power and of the mechanical power is dealt with in 9.2 and 9.3 respectively. This method involves the measurement of discharge (see Clause 10), specific hydraulic energy (see Clause 11), electrical or mechanical power (by direct method) (see Clause 12) and rotational speed (see Clause 13).

Efficiency may also be obtained in a more direct way from the water temperature increase due to the losses, using the thermodynamic method (see Clause 14). Efficiency is then expressed as:

$$\eta = \eta_h \cdot \eta_m = \frac{E_m}{E \pm \dfrac{\Delta P_h}{P_m} E_m} \cdot \frac{P}{P_m} \quad \text{for a turbine,}$$

$$\eta = \eta_h \cdot \eta_m = \frac{E \pm \dfrac{\Delta P_h}{P_m} E_m}{E_m} \cdot \frac{P_m}{P} \quad \text{for a pump.}$$

The basic advantage of the thermodynamic method is represented by the fact that it does not require the measurement of the discharge.

Besides these methods, an index test is often conducted on site. In normal conditions, such a test gives only relative information on the discharge and thus on the efficiency. However, when the relative discharge measuring method is calibrated by an absolute method of discharge measurement, the index method may be further used to extend an acceptance test to running conditions for which the uncertainty of the absolute measurements becomes too large. In such cases, the index test (see Clause 15) can be considered as a part of the field acceptance test.

9.2 *Hydraulic power*

9.2.1 *Definition*

The definition of hydraulic power is given in 2.3.8.1.

Its evaluation requires knowledge of the specific hydraulic energy of the machine and of the mass flow rate through the high pressure reference section (subscript 1).

The formula is: $P_h = E(\varrho Q)_1 \pm \Delta P_h$.

9.2.2 *Mass flow rate*

The mass flow rate (see 2.3.4.2) at reference section 1 may differ from that at the measuring section, due to the transfer of water to or from the system between these two sections. All transfers not necessary to the proper operation of the unit shall be stopped during the measurements (stilling period included) to avoid increased uncertainty and multiple measurements of discharge.

Account shall be taken of the remaining transfers.

9.2.3 *Hydraulic power correction*

9.2.3.1 Analysis of correction

The correction term ΔP_h will be evaluated after a relevant analysis of contractual definitions and local conditions. As a rule, hydraulic power transfer necessary to the proper operation of the hydraulic machine shall be charged to it.

This analysis shall be conducted taking into account:

- whether the auxiliary discharge is injected in or taken from the main circuit before or after the discharge measuring section and before or after the machine;
- whether the auxiliary discharge is used or not for the proper hydraulic machine operation;
- whether the machine operates as a turbine or as a pump.

For example, any water taken off between the discharge measuring section and a machine in turbine mode and not used for the turbine operation will induce a negative contribution to P_h.

9.2.3.2 Evaluation of correction

The mass flow rate of transferred water and the relevant specific hydraulic energy shall be used for evaluating each correction. This relevant specific hydraulic energy may differ from E, especially in multi-stage machines.

Since such transfers are generally a small fraction of the main discharge, a simple evaluation will be sufficient and will have no significant effect on the measuring uncertainty. It is recommended that all water transfers are specified in the contract and may be checked at time of test.

Since most transfers necessary to the correct operation of the machine are needed for specific purposes (for instance, cooling of the bearings), and therefore the relevant losses are measured or easily evaluated, a specific measurement for ΔP_h evaluation will then seldom be necessary.

An approximated value of transfer specific hydraulic energy may also be used.

9.2.3.3 Case of the thermodynamic method

Whenever the thermodynamic method is used, the hydraulic power is not needed for the evaluation of the efficiency. However, if there are water transfers, it is necessary to take them into account (see 14.5.3).

9.2.4 *Water density*

The density of water shall be determined for the pressure and the temperature prevailing in the discharge measuring section. Values of pure water density are tabulated in Appendix E, Table EII. In some cases, it may be necessary to measure the density of water, for example by a static method (see 11.4.7.1).

9.3 *Mechanical power*

Normally the power (mechanical power of the machine) is determined electrically by measuring the generator output (active output power) or motor input (active input power) and taking into account the mechanical and electrical losses in the electrical machine, and all the other losses specified in 2.3.8.3. This method is called indirect. In the case of small units of low capacity the direct method may be used; it consists of determining the power at the hydraulic machine shaft by means of devices measuring torque and rotational speed and taking account of the relevant losses (see 2.3.8.3). The direct method has to be used for hydraulic machines which are not directly coupled to an electrical machine.

Considering the development of torque measuring techniques, it is recommended that the Chief of test makes an analysis of the feasibility and of the expected uncertainty of the direct method.

All the elements necessary to determine the mechanical power by the indirect method are given in 12.1: electrical power measurement (12.1.1) and measurement or calculation of the various losses (12.1.2). The mechanical power measurement by the direct method is dealt with in 12.2.

10. Discharge

10.1 *General*

The measurement of discharge in a hydroelectric or pumped storage plant can be performed with the desired accuracy only when the specific requirements of the chosen method are satisfied. It is therefore in the interest of the parties involved to select the method (s) to be used for an acceptance test at an early stage in the design of the plant because later provision may be expensive or even impracticable. It is suggested that provision be made for two methods, for instance one method for gross discharge measurement and another giving information on the flow patterns.

10.1.1 *Choice of the method of measurement*

10.1.1.1 The choice of the method (s) for measuring discharge may dictate the conduct and duration of the performance test. Some of the factors that may affect this choice are:

a) limitations imposed by the design of the plant;

b) cost of installation and special equipment;

c) limitations imposed by plant operating conditions, for example draining of the system, constant load or discharge operation, etc.

10.1.1.2 The discharge measurement for an IEC acceptance test shall be made by an absolute method. Nevertheless, it may be useful to resort to relative methods (index methods) either to gain supplementary information or to make easier some operations (see 15.1.3).

The absolute methods described in this standard (see 10.2 to 10.8) are: the velocity-area method by means of current-meters or Pitot tubes, the pressure-time method (Gibson method), tracer methods either by transit-time or dilution measurement, standardized thin-plate weirs, standardized differential pressure devices, and volumetric gauging. In addition Appendix J describes the acoustic method which is optional. Moreover, the thermodynamic method of efficiency measurement (see Clause 14) permits discharge to be obtained as a derived quantity from efficiency, specific energy and power measurements.

Relative methods such as the Winter-Kennedy method, non-standardized differential pressure devices, non-standardized weirs or flumes, certain simple forms of acoustic method or local velocity measurement with a single current-meter may be used to obtain a relative value of the discharge or even an absolute value if they are calibrated in situ by comparison with an absolute method. Some of these relative methods are described in Clause 15.

10.1.1.3 Only the velocity-area method by means of current-meters or Pitot tubes and to some extent the acoustic method using several paths provide information on the flow pattern.

10.1.2 *Accuracy of measurement*

10.1.2.1 Clause 10 presents all the requirements for satisfactory measurements and estimates the systematic uncertainty to be expected when these requirements are satisfied.

A method of measurement is described in detail only when no standardized procedure exists elsewhere. Whenever possible, reference has been made to existing standards, especially to those published by the International Organization for Standardization (ISO) which are particularly suited to the precise requirements of this test standard. In some cases, the prescriptions of ISO Standards have been supplemented by a few additional requirements which appear necessary for the particular scope of this test standard.

10.1.2.2 The actual values of systematic and random uncertainties shall be evaluated taking into account the whole measuring system and the operating conditions. The total uncertainty shall be calculated in accordance with 6.2.

10.1.2.3 Frequently the accuracy achieved by the chosen method can be estimated only after the results of the tests at the given plant have been analysed (see 6.2.3.4). The numerical values of systematic uncertainty indicated in this clause are to be used only as guidance. They are valid only:

- with the best conditions of measurement;
- if all individual requirements are satisfied; and
- if the testing and analysis are carried out by qualified and experienced personnel.

If these conditions are not satisfied, there may be an unpredictable increase in both the systematic and random error of the discharge measurement.

10.1.3 *General requirements*

10.1.3.1 Steadiness of the flow

Whatever the method used, a discharge measurement for acceptance test is valid only if the flow is steady or nearly steady during each run. It may be assumed steady if the variations in generator or motor power, in specific hydraulic energy and in rotational speed are gradual and do not exceed the values stated in 5.2.1. If these requirements are satisfied, the mean value of the discharge calculated over the whole run shall be used; if they are not satisfied, the run shall be repeated, unless a sufficient period of time within the run duration may be found, during which the steadiness of all the quantities involved is satisfied.

As far as possible, the individual readings of the discharge should be plotted against time to assess the nature and the extent of possible pulsations.

10.1.3.2 Leakage, infiltration or diversion

As far as possible, leakage, infiltration or diversion of water shall be avoided between the measuring section or the measuring length and the relevant reference section. If this cannot be avoided, the incoming or outgoing flow shall be measured with an appropriate accuracy.

Whenever a surge tank is connected to the waterway between the measuring section and the machine, water level oscillations should normally be allowed to damp out before a run is initiated. Should this be difficult due to the length of the waterway (and accordingly to the settling time), discharge measurement can however be conducted, provided care is taken of the net volume of water exchanged between the duct and the surge tank within the duration of the measurement (for allowable variations of specific hydraulic energy, see 5.2).

10.2 *Current-meter method*

10.2.1 *Principle of velocity-area method*

The velocity-area method requires a number of propeller-type current-meters located at specified points in a suitable cross-section of an open channel or closed conduit. Simultaneous measurements of local mean velocity with the meters are integrated over the gauging section to provide the discharge. The water must be sufficiently clean, such that dissolved or suspended matter will not affect the accuracy of the meter readings during the test. Some integration techniques which may be used to compute the discharge assume velocity distributions that closely approximate known laws, especially in the neighbourhood of solid boundaries. If these techniques are used, it is essential to select a measuring section where this hypothesis is likely to be approximately fulfilled.

The method may be used at any suitable measuring section in:

- a closed conduit or penstock;
- an intake structure;
- an upstream or downstream open channel (headrace or tailrace).

If an open channel is to be used, it must be an artificial channel of well-defined cross-section. Natural streams are excluded for tests under this standard.

Test arrangements, procedures and limitations will depend to some extent on the characteristics of the selected measuring section. General requirements applicable to all measuring sections are given below.

10.2.2 *General requirements*

10.2.2.1 Duration of measurement

Measurements for each current-meter position shall last at least 2 min. If variations (see 5.2.1) in the water velocity are present, a run shall include at least four cycles of these variations. This may have an influence on the entire test programme. The duration of variations may be determined by observing the speed changes of the current-meters for 10 to 15 min for at least two typical conditions of operation.

10.2.2.2 Number of measuring points

The number of current-meters shall be sufficient to ensure a satisfactory determination of the velocity profile over the whole measuring section. A single-point measurement is not permitted under this standard. See also ISO 3354, 4.4.1 to 4.4.3.

At least 13 measuring points shall be used in a circular penstock, one of which shall be the centre point of the section. The number of measuring points per radius, Z, excluding the centre point, may be determined from $4\sqrt{R} < Z < 5\sqrt{R}$ where R is the internal radius of the conduit in metres. For any given number of current-meters, it is preferable to increase the number of radii than to increase the number of current-meters per radius, but care must be taken to avoid excessive blockage. Centre blockage can be reduced by cantilevering the radial supporting arms from the conduit wall. If this is done, only a single arm need extend to the centre of the conduit. Little advantage is gained by measurements on more than 8 radii or at more than 8 points per radius, excluding the centre point.

At least 25 measuring points shall be used in a rectangular or trapezoidal section. If the velocity distribution is likely to be non-uniform, the number of measuring points, Z, shall be determined from:

$$24\sqrt[3]{A} < Z < 36\sqrt[3]{A}$$

where:

A is the area of the measuring section in square metres

If the conduit or channel is divided into several sections, measurements shall be made simultaneously in all sections.

10.2.2.3 Types and general requirements of current-meters

Only propeller-type current-meters shall be used. The electrical impulses of the propeller rotation shall be transmitted by cables to the counting and recording device in such a way that the momentary speed of rotation of the propeller can be checked during and after the run. The current-meters shall fulfil the applicable requirements of ISO 2537. All meters shall be capable of withstanding the water pressure and the time of submergence without change in the calibration. It may be necessary to reduce the time of submergence where the water is hard.

Current-meter propellers shall be not less than 100 mm diameter except for measurements in the peripheral zone where propellers as small as 50 mm may be used. The distance from the trailing edge of the propeller to the leading edge of the mounting rod shall be at least 150 mm.

The angle between the local velocity vector and the axis of the current-meter should not exceed 5°. When larger angles are unavoidable, self-compensating propellers which measure directly the axial component of the velocity shall be used but only at angles for which they have been designed and calibrated (see 6.1.5 in ISO 3354).

The response of a current-meter can be affected by the axial and transverse components of the turbulence of the flow, and this effect cannot be taken into account during the calibration which is carried out in still water. Thus it is recommended to select the types of propeller which are the less sensitive to turbulence (propellers with a high moment of inertia).

10.2.2.4 Calibration of current-meters

Subject to the requirements stated below, all current-meters shall be calibrated in accordance with ISO 3455.

The current-meters shall be calibrated with the same type of mounting and mounting rod as that used during the test. If the current-meters are mounted on vertical rods during calibration, these shall extend at least 150 mm below the propeller shaft. It is desirable to calibrate several current-meters at the same time mounted at the same distance as will be used during the test.

The range of calibration velocities shall, if possible, cover the range of local velocities during the test. A normal calibration range is from 0,4 m/s to 6 m/s or even 8 m/s, the upper limit often being set by vibration. If extrapolation of the rating curve beyond 20% of the maximum calibration velocity is necessary, it shall be done only by mutual agreement and with the understanding that uncertainty in the measurement has been increased. Self-compensating propellers shall be calibrated at angles up to the maximum obliquity of the flow expected during the test and up to the maximum expected test velocity, the relative direction of the mounting rod and the oblique flow being respected; no extrapolation is permitted.

The estimated systematic uncertainty at 95% confidence level, due to current-meter calibration, should normally be less than 0,5% for velocities between 0,4 m/s and 6 m/s. Above and below those velocities, a greater uncertainty should be expected, depending on the characteristics of the calibration station and of the propellers.

Notwithstanding the fact that 4.6.2 requests calibration before a test, this may be considered as fulfilled if the current-meters are regularly calibrated showing consistent results. The time between calibrations depends on the duration and character of use of the current-meters. Three hundred hours of running time under favourable water conditions may be taken as a guide.

The Chief of test shall ascertain that no damage has occurred during the test, particularly deterioration caused by shocks, corrosion or abrasion. A calibration of a current-meter is imperative after the test only if it would seem to have been damaged.

10.2.3 *Measurements in closed conduits (penstocks)*

10.2.3.1 General

ISO 3354 shall apply subject to the restrictions given in 10.2.2 and 10.2.3.2.

10.2.3.2 Additional requirements

The accuracy required by this standard requires that specified subclauses of ISO 3354 be amended and supplemented as follows:

Subclause 4.3 of ISO 3354:	The direct measurement of signal frequency to obtain the rotational speed of the propeller is allowed, only if the resulting resolution meets the required accuracy.
Subclause 6.3.5 of ISO 3354:	A statistical calibration shall be permitted only if it is explicitly stated in the contract.
Subclause 7.2.3 of ISO 3354:	This subclause shall not be applicable for acceptance tests under this standard.
Annexes F and G of ISO 3354:	It may be expected that several components of error, as estimated in those annexes, could be slightly reduced owing to the stringent requirements of this standard and the care that must be exercised in making the measurements.

10.2.4 *Measurements in short penstocks or intake structures*

10.2.4.1 General

A penstock is defined as short if the straight length is less than 25 diameters.

No existing standard deals with discharge measurements in short penstocks or intakes, especially for low-head plants. ISO 3354 may be used as a guide especially the clauses stating general requirements and those dealing with rectangular cross-sections. Also applicable are the general requirements of 10.2.2 of the present standard. The main difficulty with this type of gauging arises from the fact that the measuring section may be located in a short converging conduit with uneven and/or unstable velocity distributions as well as oblique flow to the current-meters. Attempts should be made to remedy these difficulties either by a straightening device (see 10.2.4.2) or by special measuring techniques (see 10.2.4.3).

10.2.4.2 Bell-mouth nozzle

A temporary bell-mouth nozzle (see Figure 24) may be installed at the entrance to the intake structure. The advantages are:

– a straight and parallel flow;

– a more nearly uniform and stable velocity distribution;

– an increase in both the mean velocity and local velocities near the walls which increases the accuracy at low loads;

– a better measuring section than can be had in an open approach channel since the area is constant and depth measurements are eliminated.

The disadvantages are:

– the cost and difficulty of fabricating and installing such a structure;

– that the flow through the modified intake may change the performance of the machine. The available tests indicate this to be of little consequence;

– that the turbulent boundary layer thickness may be less than the distance from the wall to the outermost current-meter. This thickness shall be determined by test or calculation* and the discharge in the peripheral zone shall be computed with due regard to the actual velocity distribution.

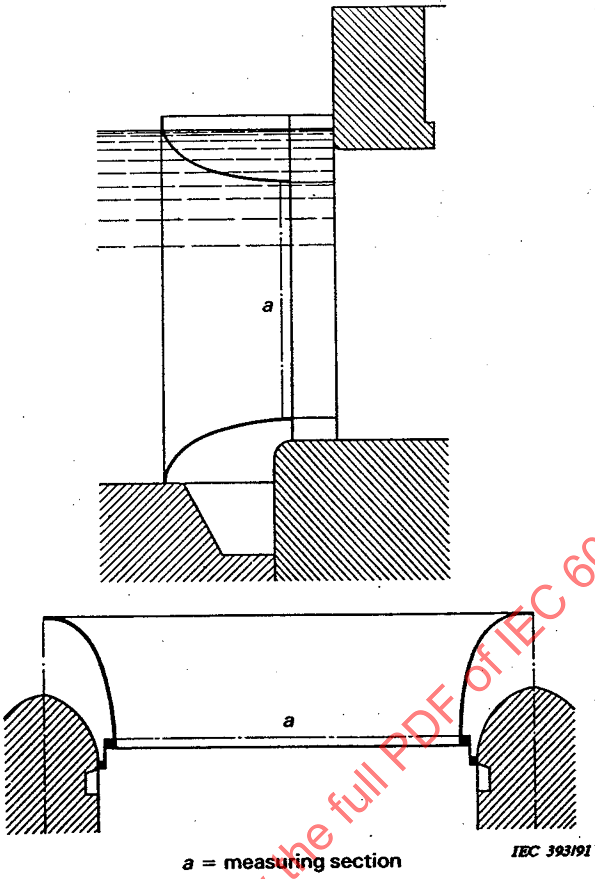


Figure 24 – Temporary nozzle or bell mouth placed in the intake of a low head turbine

10.2.4.3 Measurements in converging flow

Measurements in converging conduits with velocities oblique to the cross-section shall be allowed only by mutual agreement of the parties to the test. Gauging methods have been devised to improve the accuracy but they require highly-experienced personnel and it is difficult to predict the systematic and random errors which may arise.

In one method, the plane cross-section is replaced by an equipotential surface perpendicular to the streamlines. The surface may be determined by hydraulic or aerodynamic similitude or by electrical analogy. The current-meter axes are then aligned with the assumed velocity direction at each measuring point.

*The thickness, δ, of the turbulent boundary layer may be calculated by:

$$\delta = 0,37x/(vx/\nu)^{0,2}$$

where:

x is the distance along the conduit from inlet to measuring section
v is the mean velocity, and
ν is the kinematic viscosity

Another method uses a plane cross-section together with an exploration of the angularity of the velocity field. During preliminary tests, at each measuring position, the current-meter is aligned successively in two known directions and the velocities are measured. Caution shall be taken to keep the propeller closely to the same location. This may imply moving the supporting frame.

The actual direction of the velocity is calculated from these measurements and the angular response curve of the propeller. After that, each current-meter is aligned as closely as possible with the computed direction of the velocity at each position and the final measurement is made. Since individual adjustment of each current-meter may be difficult, some angularity may remain, that must be accounted for in the calculations.

The angular exploration is conducted for two load conditions of the machine, or more, if it appears that the velocity directions change with load.

Self-compensating propellers (see 10.2.2.3) are best suited for this method, provided they fulfil other requirements. Normal propellers may be accepted if the flow is two-dimensional in the converging section.

10.2.4.4 Direct integration method

This method is described in 7.2.2 and 7.3.2 of ISO 3354, and shall be allowed only by mutual agreement of the parties to the test. In a rectangular conduit, a vertical or horizontal row of meters is moved across the cross-section at constant speed (see Figure 25). Any influence of the transverse velocity on the measurements may be estimated by reversing the direction of motion of the supporting frame and by measurements with the frame at rest in several typical locations. These check runs should be made at several different flow rates. Special equipment is required for this method because the meters must be translated at constant speed and must also be free of vibrations.

Supplementary stationary measurements near the invert or ceiling may be required if these areas cannot be swept by the moving frame. Usually this method is advantageous only in conduits of very large cross-section.

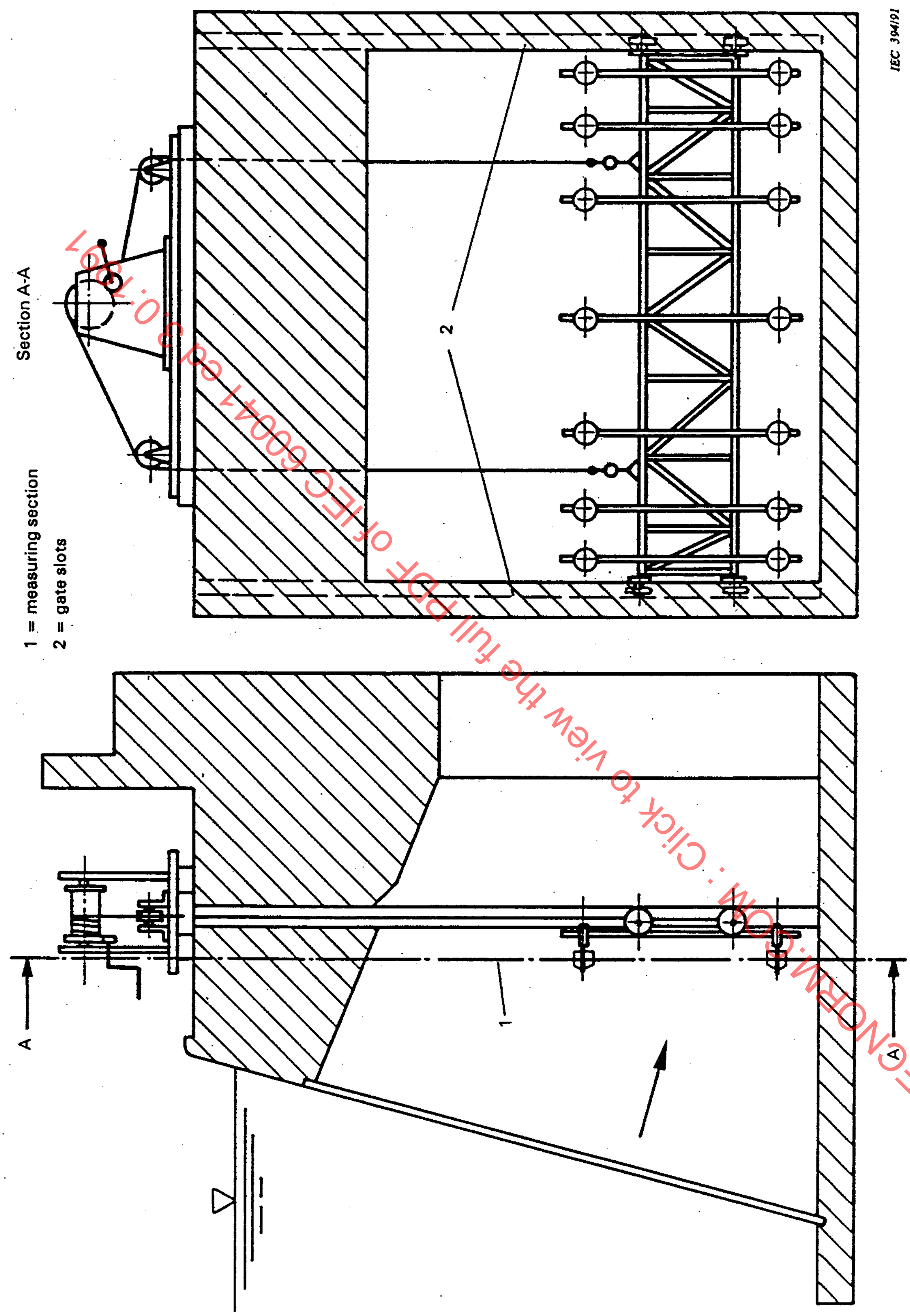


Figure 25 – Frame supporting current-meters for measuring discharge

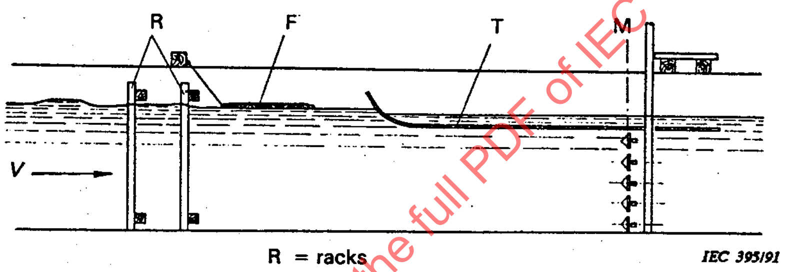
10.2.5 *Measurements in open channels*

10.2.5.1 General

Current-meter measurements may be made only in artificial channels (see 10.2.1). Usually these are rectangular or trapezoidal in cross-section. For this reason, ISO 748 is not applicable as it stands because it does not meet the standards of accuracy for tests under this standard. Specific sections which may be used are referenced below. In addition to the general requirements stated in 10.2.1, the following subclauses give the particular requirements that shall apply to measurements in open channels.

10.2.5.2 Choice of measuring section

In addition to the minimum requirements stated in 6.1 of ISO 748, the measuring section shall have both width and depth greater than 0,80 m or eight times the diameter of the propeller. If necessary, the flow pattern at the measuring section may be improved by the installation of one or more of the devices shown in Figure 26. The measuring section shall be at least ten times its hydraulic radius* downstream of the nearest device except the submerged roof whose main purpose is to better define the section. Some of these devices are effective in suppressing surface waves which increases the accuracy of the depth-measurement.



R = racks
F = rafts
T = submerged roof
M = measuring section

Figure 26 – Means for stabilizing flow in an open channel

10.2.5.3 Distribution of measuring points

The same requirements as for rectangular cross-sections in closed conduits shall apply (see 10.2.2.2 and 4.4 in ISO 3354), i.e. a minimum of 25 measuring points located at the intersections of 5 horizontal and 5 vertical lines.

Measuring points shall be closer to one another in the zones of steeper velocity gradient, i.e. near the walls, bottom and water surface. Points shall normally be spaced so that the difference in velocities between two adjacent points does not exceed 20 % of the greater of the two velocities. The minimum current-meter spacing shall not be less than $d + 30$ mm, where d is the outside diameter of the propellers. The distance from the axis of the nearest current-meter to any wetted surface shall be within 0, 75 d minimum to 200 mm maximum. The axis of the topmost current-meter in each row shall be at least one propeller diameter below the free water surface.

*Hydraulic radius is defined as the ratio of the wetted cross-sectional area to the wetted perimeter.

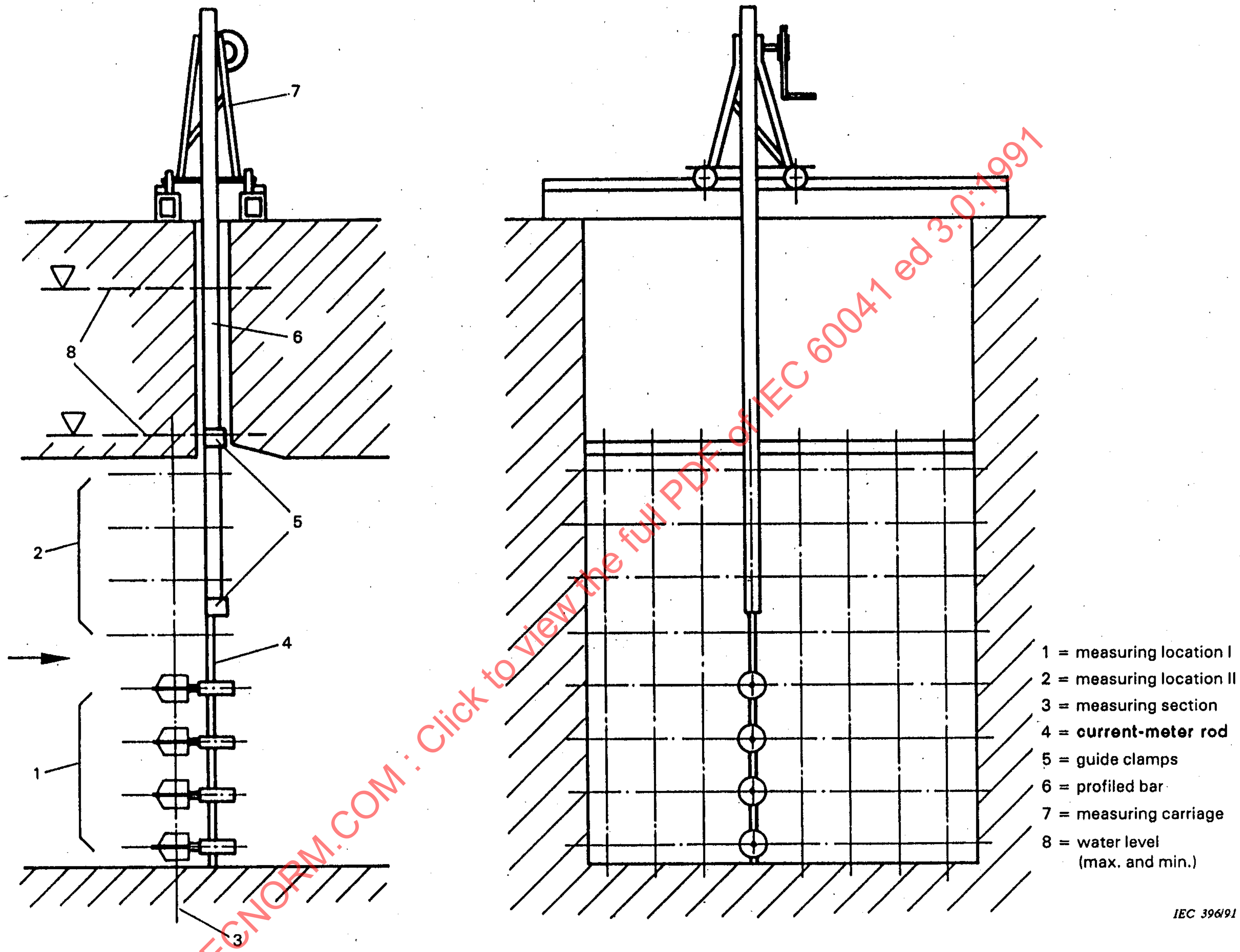


Figure 27 – Single vertical row of current-meters mounted on a travelling winch

10.2.5.4 Mounting of the current-meters

All current-meters shall be rigidly attached to the mounting rods with the propeller axes exactly perpendicular to the plane of the measuring section. The stiffness of the mounting structure shall be adequate to prevent meter vibrations. The structure shall also offer a minimum stable drag and minimum interference with the current-meter operation.

The current-meters may be used as a stationary battery mounted on a number of parallel rods over the whole measuring section. This may produce a significant blockage effect in channels of small cross-section. Alternatively, a single vertical row of meters mounted on a travelling winch (see Figure 27) or a horizontal row mounted on a frame (see Figure 25) may be moved to successive stations in the measuring cross-section. Since this requires steady flow (see 10.1.3.1) over a considerable length of time, any variations in the mean velocity shall be monitored over the whole run by at least one fixed current-meter or by an index measurement of discharge (see Clause 15).

10.2.5.5 Depth measurement

The water depth is determined using one of the methods described in 11.5. Variations in water depth shall not exceed ±1% of the average depth and shall be monitored over the whole duration of each run.

10.2.5.6 Computation of discharge

The general method of computation prescribed in 8.3 of ISO 3354 for the computation of discharge in conduits of rectangular cross-section shall be used with measurements in open channels. The extrapolation formula for velocities in the peripheral zone:

$$v_x = v_a (x/a)^{1/m}$$

where

v_x is the velocity at a distance "x" from the nearest wall

v_a is the velocity at the considered extreme measuring point (at a distance "a" from the nearest wall)

m is the coefficient depending on the wall roughness and on the flow conditions

is applicable near the sides and bottom but not near the free surface where the velocity profile shall be extrapolated by continuity. With trapezoidal cross-sections, the first integration shall always be made along the vertical lines and the second integration by plotting over the width the product $\overline{v}d$ (see Figure 28), where:

$\overline{v}$ is the mean velocity on a vertical line,

d is the water depth on the same vertical.

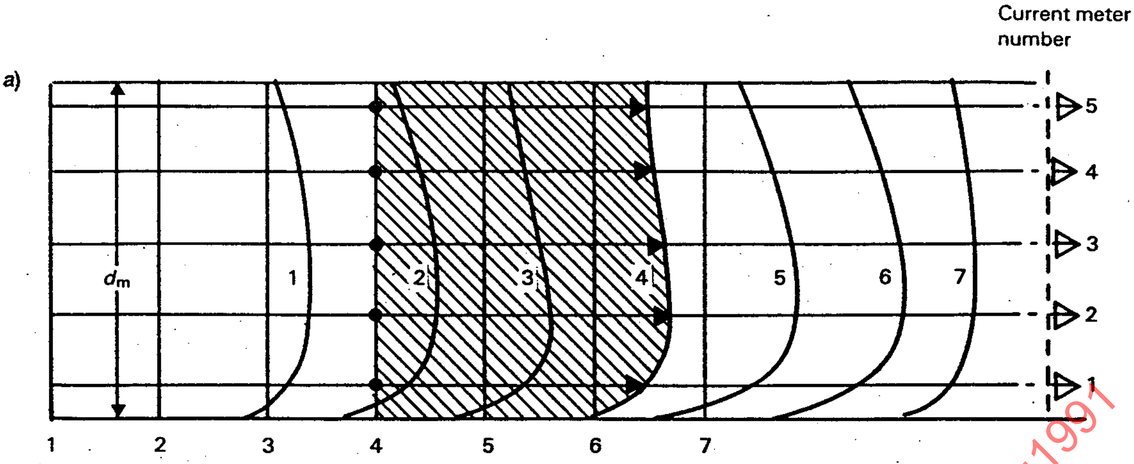


Figure 28a – Determination of partial discharges by graphical integration of the measured local velocities

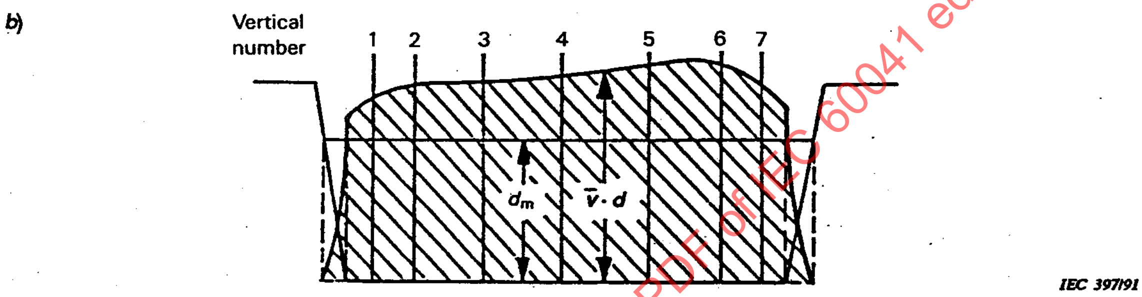


Figure 28b – Determination of total discharge by graphical integration of the partial discharges obtained in a)

Figure 28 – Example showing discharge measurement in a slightly trapezoidal canal

10.2.6 *Uncertainty of measurement* (see 10.1.2)

The accuracy in a discharge measurement made by current-meter gauging depends essentially on factors related to the flow (regularity of the velocity distribution, swirl or obliquity, turbulence, periodic fluctuations), the quality of the measurements (number and distribution of the measuring points and blockage effects) and method of discharge calculation. The uncertainty in current-meter calibration and uncertainties in all measurements shall be estimated and stated.

With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95% confidence level should be about:

– in closed conduits	±1 to ±1,5%
– in intakes with bell mouth	±1 to ±2%
– in intakes without bell mouth	±1,2 to ±2%
– in open channels with rectangular section	±1,2 to ±2%
– in open channels with trapezoidal section	±1,4 to ±2,3%

10.3 *Pitot tubes*

10.3.1 *General*

Pitot tubes may be used to measure the dynamic pressure, from which the local velocity may be obtained, at each of a sufficient number of points in the cross-section to permit computation of the discharge by the velocity area method. Since the dynamic pressure varies with the square of the velocity, the accuracy of measurement decreases rapidly with decreasing velocity. In practical terms this restricts the use of Pitot tubes to flow in closed conduits where the velocity is not too low and the water is free of suspended matter.

10.3.2 *Standardized Pitot tubes*

ISO 3966 covers the design, installation and use of standardized Pitot static tubes. Only the clauses relating to incompressible fluid shall be used for testing under this standard. Any significant blockage effect must be taken into account. The ISO standard gives all the necessary guidance for the selection and installation of Pitot static tubes, choice of measuring section, and the computation of the discharge and its uncertainty. ISO 3966 shall be used only with the standardized Pitot static tubes described therein which are equipped with a single total pressure tap and one or more static pressure taps. Such tubes may be used uncalibrated and the flow coefficient assumed to be unity. The local velocity v_i is given by:

$$v_i = \sqrt{2\Delta p_i/\rho}$$

where:

Δp_i is the difference between the total or stagnation pressure and the static pressure as measured with the Pitot tube located at point "i"

With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95% confidence level (see 10.1.2) should be about 1,5 to 2,5%.

Total uncertainty in discharge measurement may be estimated by annex G of ISO 3966.

10.3.3 *Non-standard devices*

Numerous devices are available that operate on the same general principle as the Pitot static tube. Among these are:

- The simple Pitot tube provided with a single total-pressure tap. The average static pressure shall be obtained from four equally-spaced taps in the conduit wall, so located that the frame supporting the Pitot tubes will not affect the static pressure measurement. Energy losses between the total and static pressure measurement planes must be taken into account.
- Devices in which the measured differential pressure is increased by locating one pressure tap in a region of low pressure, either pointing downstream or opening into the throat of a small Venturi tube.
- Tubular diametral rods which are self-supporting with the total, static or trailing taps bored in the rod itself.

The flow coefficients of all non-standard devices shall be established by careful calibration over the range of velocities encountered during the test. Usually the discharge may be obtained by the same method of integration as for current-meters or standardized Pitot static tubes. Larger measurement uncertainties may be expected due to limited knowledge of the effect on these devices of such phenomena as turbulence, obliquity of velocity, pressure and/or velocity gradients, blockage effect, etc.

10.4 *Pressure-time method*

10.4.1 *Principle of the method*

This method of discharge measurement (often called "Gibson method") is based upon Newton's law and the derived laws of fluid mechanics, which give the relation between the force due to the change of pressure difference between two sections and the acceleration or deceleration of the mass of water between these sections due to a gate* movement. Although this method is theoretically valid both for turbine and pump operation and for closure or opening of the gate, it is in practice only used in case of discharge cut-off in turbine operation.

The following is a simplified way of describing the pressure-time method principle.

In a fluid without friction, a change of velocity dv/dt in a conduit of constant cross-section A, of a mass of fluid ρLA would lead to a differential pressure Δp between the upstream (subscript u) and downstream (subscript d) cross-section of the considered length L:

$$\rho LA\frac{dv}{dt} = -A\Delta p \quad \text{where} \quad \Delta p = p_{\mathrm{d}} - p_{\mathrm{u}}$$

If t is the time during which the velocity changes and if ξ is the pressure loss due to the friction between the two sections, we obtain:

$$A\int_0^t dv = -\frac{A}{\rho L}\int_0^t (\Delta p + \xi)dt$$

Thus the discharge Q before the gate begins to close is given by:

$$Q = Av_0 = \frac{A}{\rho L}\int_0^t (\Delta p + \xi)dt + Av_{\mathrm{t}}$$

The discharge $q = Av_{\mathrm{t}}$ after the end of the closure is the leakage flowing past the gate and shall be determined separately with the machine running. This determination does not generally need a great accuracy, since it represents a small portion of the discharge Q to be measured.

A pressure-time graphical or numerical recording of the pressure wave passage is obtained by gradually closing the gate in a continuous movement and the change of pressure between two measuring cross-sections is integrated along the time scale.

Several variants of this method have been developed which differ only in instrumentation and computation technique of the pressure-time integral and by the use of separate or differential recordings (see 10.4.3 and 10.4.4).

* "Gate" is used here for any closing device (guide vanes, needles, valve, etc.).

10.4.2 *General requirements*

10.4.2.1 Conditions of validity

The general conditions to be fulfilled for the use of this method are:

a) No intermediate free surface shall exist between the two pressure measurement sections.

b) The leakage through the closed gate in the test conditions shall not be greater than 5% of the discharge being measured and shall be measured within an accuracy of 0,2% of that discharge.

c) In the multiple intake sections, simultaneous independent pressure-time recordings shall be taken.

d) Within the measuring reach the conduit shall be straight and have a constant cross-section and not present any significant irregularity. The distance between the two measuring sections shall not be less than 10 m.

e) The cross-sectional areas of the conduit and the length of the measuring reach between the two cross-sections shall be measured in the field with sufficient precision to determine the pipe factor F (see 10.4.3.2.2.*i*)) within an accuracy of 0,2%. Construction drawings may be used only as a check of field measurements.

f) The sum of the pressure loss between the two measuring sections and of the dynamic pressure, at the maximum discharge to be measured, shall not exceed 20% of the average change in differential pressure as recorded while closing the gate.

g) The differential pressure transducer or Gibson device should be located so as to have nearly equal lengths of connecting tubing to the upstream and downstream piezometer taps.

h) Pressure diagrams in which the running line A-A is above the static line 0-0 (in Figure 29 negative value of C) are considered dubious.

i) For each test run the determination of the discharge requires the measurement of the temperature of the water and of the mercury in the case where a Gibson apparatus is used, within an accuracy of ±1 °C.

10.4.2.2 Location of pressure taps

At least four pressure taps, between 3 and 6 mm in diameter, shall be installed at each measuring section in a plane normal to the axis of the conduit (in conduits less than 4 m in diameter, only two taps may be used). For circular conduits, the pressure taps shall be located at equal angles from each other and no tap shall be located near the top or the bottom of the measurement section. For rectangular conduits, the pressure taps shall be located at the quarter points of the vertical walls. All taps shall be constructed as specified in 11.4.3 and located as specified in 11.4.1. In no case shall a pressure tap be located at a distance less than $2D$ (D being the diameter of the conduit) from a significant irregularity of the conduit.

10.4.2.3 Connecting tubing

The pressure taps of each measuring section shall be connected through individual valves to a common header suitably located for connection to the pressure-time apparatus. To reduce the damping due to friction, all connecting tubing shall be as short as possible, non-elastic and of sufficient diameter (e.g. at least 18 mm for liquid-column manometers or 8 mm for pressure transducers).

All pressure connections and piping shall be verified to be tight against leakage and all piping between pressure taps and the pressure-time apparatus shall be free of air. Periodic inspections and flushing of the piping shall be performed before each run.

The general requirements given in 11.4.4 shall apply.

10.4.2.4 Checking of the pressure measurements

To ensure the necessary accuracy in the recorded pressure-time diagrams, flow conditions in the conduit shall be such that, at each measuring section, the difference between the pressure measured at any one tap and the average of the pressures measured at all taps shall not exceed 20% of the dynamic pressure. The average of the readings from any pair of opposite taps shall not differ from the average from any other pair of taps in the same cross-section by more than 10 % of the dynamic pressure. This may require consideration of such items as velocity distribution, length of straight run of the conduit and wall conditions at the individual taps. If any pressure tap appears to be in error, the source of the discrepancy shall be determined and removed. If this is not possible, the tap shall not be used for the measurements. A minimum of two taps shall be used in each measuring section.

These checks shall be carried out before the test begins. The special instrumentation required for that shall be immediately dismounted in order not to disturb the arrangement of the test apparatus and its connecting tubing (see 10.4.2.3).

10.4.3 *Differential pressure-time method*

10.4.3.1 Generalities

In this variant, the change in differential pressure between two sections of measurement, that is affected only by the changes in friction and in momentum between these two sections, is recorded. The effects of changes in friction outside of the test sections and in intake or surge tank water level are present at both measurement sections and are thus eliminated.

In addition to the requirements specified in 10.4.2.1, the product of the length between the two pressure measurement sections and the mean velocity in the pipe when the unit is carrying full load shall be not less than 50 m^2/s.

The discharge which is to be measured shall be fixed by means of the load limiting device or preferably by blocking the gates in the required position and waiting until stable conditions are established (see 4.4.2 *b*)). The pressure-time function can then be obtained by gradually closing the gates in one continuous movement and recording the resultant time dependent change in differential pressure.

The recording times before the beginning and after the end of the movement of the gate shall be not less than 20 s each.

Before the test a calibration of the measuring system has to be done. At each run the zero point of the measuring system and the calibration when using transducers have to be checked.

10.4.3.2 Differential mercury pressure-gauge (Gibson apparatus)

10.4.3.2.1 Principle of the apparatus

This was the first measuring system used for the pressure-time method. This apparatus delivers a pressure-time diagram in the form of a photographic record of the mercury level movement in a U-tube manometer. The integral $\int \Delta p \cdot dt$ is thus obtained by planimetry.

10.4.3.2.2 Evaluation of the diagram (see Figure 29)

All lengths, heights, distances and areas shall be in a coherent unit system.

a) Draw a horizontal line 0–0 representing the zero line of the apparatus and of the diagram.

b) Draw a horizontal line A–A representing the mean pressure loss under running conditions before the gate closure begins.

c) Draw a horizontal line F–F representing the mean final pressure loss due to leakage after the gate has been closed and coincident with the median line of the afterwaves following closure. (This line F–F is nearly identical to the line 0–0).

d) Measure on line F–F the distance B representing the half-period of the afterwaves and subtract from B a correction f taking into account the slot width of the photographic recorder.

e) Measure the heights H above line F–F of the peaks of two adjacent afterwaves and compute their ratio E:

$$E = \frac{H_j}{H_{j+1}}$$

f) Compute:

$$D = (B - f)\frac{\text{arctg}(2\pi/\ln E)}{\pi}$$

and subtract distance D from a point N where the falling edge of an afterwave intersects the line F–F. The point M so obtained defines the end of the diagram.

g) Draw a trial recovery line GPM as shown by the dotted line on Figure 29.

h) Measure with a planimeter the area A_T of the diagram referred to the line GPM. This area may be subdivided into several segmental areas $A_1, A_2, \ldots, A_n$ as shown in the figure. A slot correction determined by multiplying the vertical rise of each segmental area by the effective slot width shall be deduced from each of these areas.

i) Compute the discharge Q by:

$$Q = \frac{g}{sy}\frac{A_T}{F} + q$$

where:

s and y	are calibration constants of the diagram (respectively the length corresponding to 1 s and the height corresponding to a water column of 1 m)
F	is the pipe factor (ratio L/A of the length of the measuring reach to the cross-sectional area of the conduit)
q	is the leakage flow past the closing device

j) Determine a new recovery line assuming that at a given time t_i the remaining pressure loss is given by: $C_i = C(1 - r_i)^x$

where:

C	is the pressure loss before the beginning of the closure (difference between lines 0–0 and A–A)
x	is the exponential factor of Q in the pressure loss expression ($x = 2$ for pipes where the Reynolds number is greater than about 5×10^6; for lower values of Re, x shall be determined in each case)

$$r_i = \frac{a_i}{A_T + A_L} \quad \text{with} \quad a_i = \sum_{k=1}^{i} A_k \quad \text{and} \quad A_L = qF\frac{sy}{g}$$

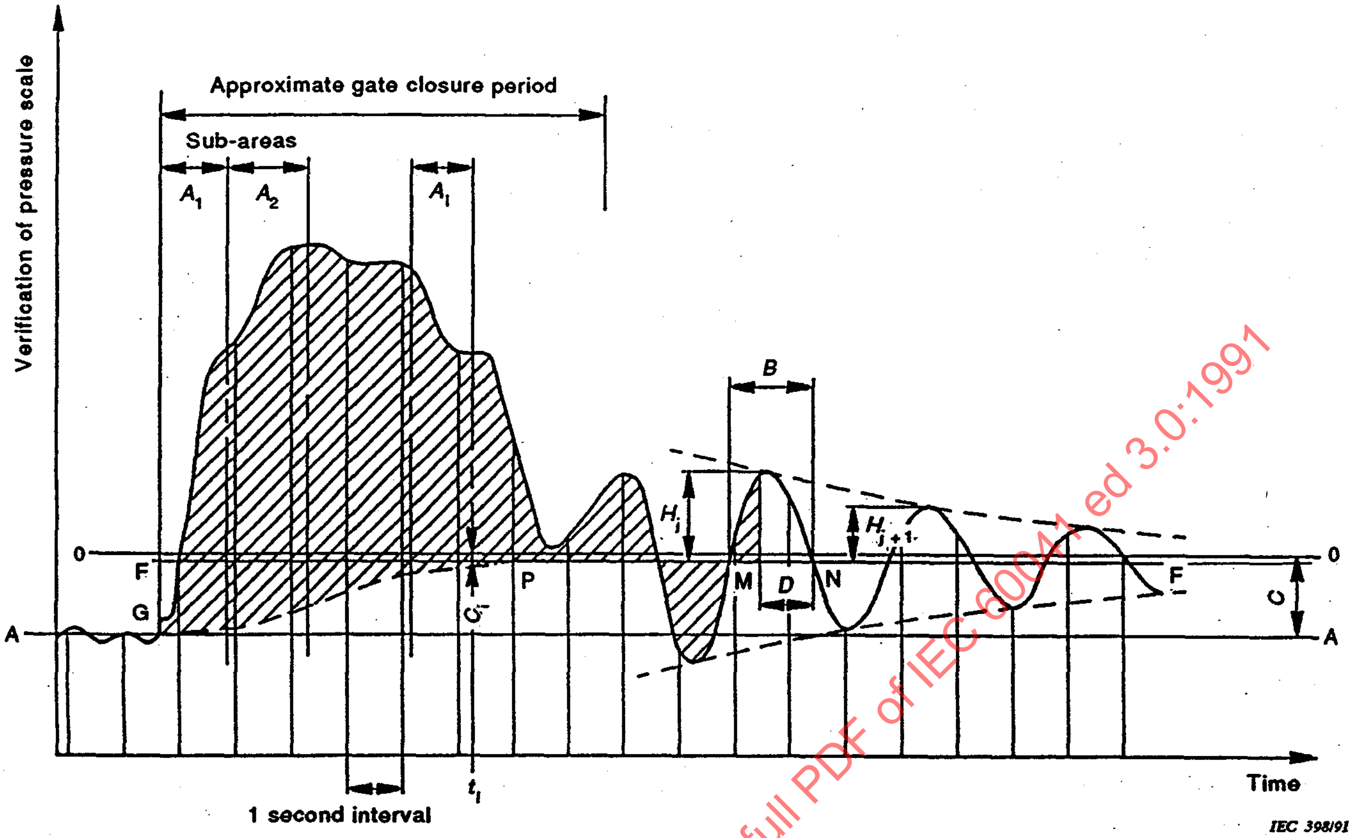


Figure 29 – Example of pressure-time diagram (Differential diagram method using Gibson apparatus)

k) Compute a new value of the discharge by the procedure described in *h*) and *i*). If two successive values of Q are within a relative difference of 0,1 %, stop the calculation and the last value found shall be taken as the total discharge at the moment the gates began to close. If not, go to *j*) and compute Q again.

10.4.3.3 Differential transducers

Differential transducers of small inertia permit recording of the pressure-time function more accurately and allow computer calculation.

10.4.3.3.1 Measuring system requirements

a) The measuring system natural frequency shall be ten times larger than the main frequency present in the pressure-time signal.

b) The time response of the measuring system shall be less than 10^{-2} s.

c) The linearity of the measuring system over the whole measuring range shall be better than 2×10^{-3}.

d) Digital recording of the pressure-time function requires a data acquisition frequency greater than or equal to 50 readings per second.

e) No overload of the measuring system shall be present in a pressure-time function record.

f) The measuring system shall be calibrated on the site under line pressure equal to mean static pressure at the highest measuring section at zero flowrate.

g) Low pass filters or pressure damping devices, if any are used to suppress high frequency fluctuations, shall not alter the integral of the differential pressure.

h) The data processing system shall not introduce errors greater than 0,05 % of the mean differential pressure and 1 ms.

i) The measuring system must not be temperature sensitive or must be maintained at constant temperature to avoid thermal shift and other problems.

10.4.3.3.2 Computation of discharge

The differential pressure measurements delivered by the transducers are numerically recorded and processed in a computer.

The discharge shall be computed by:

$$Q = \frac{A}{\rho L} \cdot \int_0^t (\Delta p + \xi)\, dt + q$$

The computer program, with all relevant information, shall be placed at the disposal of all the parties to the contract.

10.4.4 *Separate diagrams method*

10.4.4.1 Mode of operation

In this variant of the pressure-time method, the changes in pressure at two measurement cross-sections of the penstock are recorded separately. It is also possible to use only one measurement section referred to the intake free surface, but such a method can only be used where a surge chamber is not provided and where the length of the penstock, for which the calculation of the pipe factor is difficult (intake bell-mouth, etc.) does not exceed 2 % of the whole length.

In addition to the requirements specified in 10.4.2.1, the length of penstock between the two pressure measuring sections shall be not less than 50 m and the pipe factor F of the penstock from the surge chamber to the lower measuring section shall be not less than four times that from the surge chamber to the upper measuring section.

The mode of operation is practically the same as previously described in 10.4.3.

The equipment used in this case is shown schematically in Figure 30 and comprises:

- a water pressure measuring device at each measurement section;
- a calibration device for the pressure measuring device;
- a time measuring device;
- measuring devices of the water level and of its variation in the surge chamber;
- a recording device.

All parts of the pressure measuring and recording devices shall conform to the requirements stated in 10.4.3.3.1.

The following must be recorded on each run:

- the calibration diagrams of the measuring pressure device before and after the gate closure;
- the pressure-time diagrams before, during and after this closure (at least four pressure waves shall be recorded after the completion of the closure);
- the surge chamber water level-time diagram or the steady-state level after closure, when only one measuring section is used.

At least five recording measurements shall be made for each point.

10.4.4.2 Computation of discharge

a) Planimetric method: The discharge shall be calculated from the following formula:

$$Q = \frac{g}{F}\left(\frac{A_{T_d}}{y_d s_d} - \frac{A_{T_u}}{y_u s_u}\right) + q$$

where the symbols used are the same as in 10.4.3.2.2 and the subscripts u and d refer to the diagrams at the upstream and downstream sections respectively.

The total net areas A_{T_u} and A_{T_d} of the pressure-time diagrams in both measurement sections are obtained by planimetry, after determination of the recovery line accounting for the pressure loss by a process similar to that described in 10.4.3.2.2 and for the water level variation in the surge chamber if any.

b) Numerical method: In order to avoid planimetry, programs of calculation by digital computer are available which determine the recovery line, the total net area and thus the discharge. It is necessary to divide the diagrams into about thirty segments having equal time intervals, these intervals being the same for both the upstream and downstream diagrams. The computation shall be repeated a number of times until the difference between two successive approximations of the discharge becomes less than 0,1 %.

10.4.5 *Uncertainty of measurement*

The pressure-time method requires especially good instrumentation and a highly qualified staff of specialists to conduct the tests and to carry out the computations and estimate the uncertainty in the results. Under favourable conditions, an overall uncertainty, at the 95 % confidence level, of about ±1,5 % to ±2 % may be expected when using the computerized differential method and ±1,8 % to ±2,3 % in other cases.

There are some reasons to believe that applying the pressure-time method in conduits less than 1 m in diameter leads to overestimating the discharge.

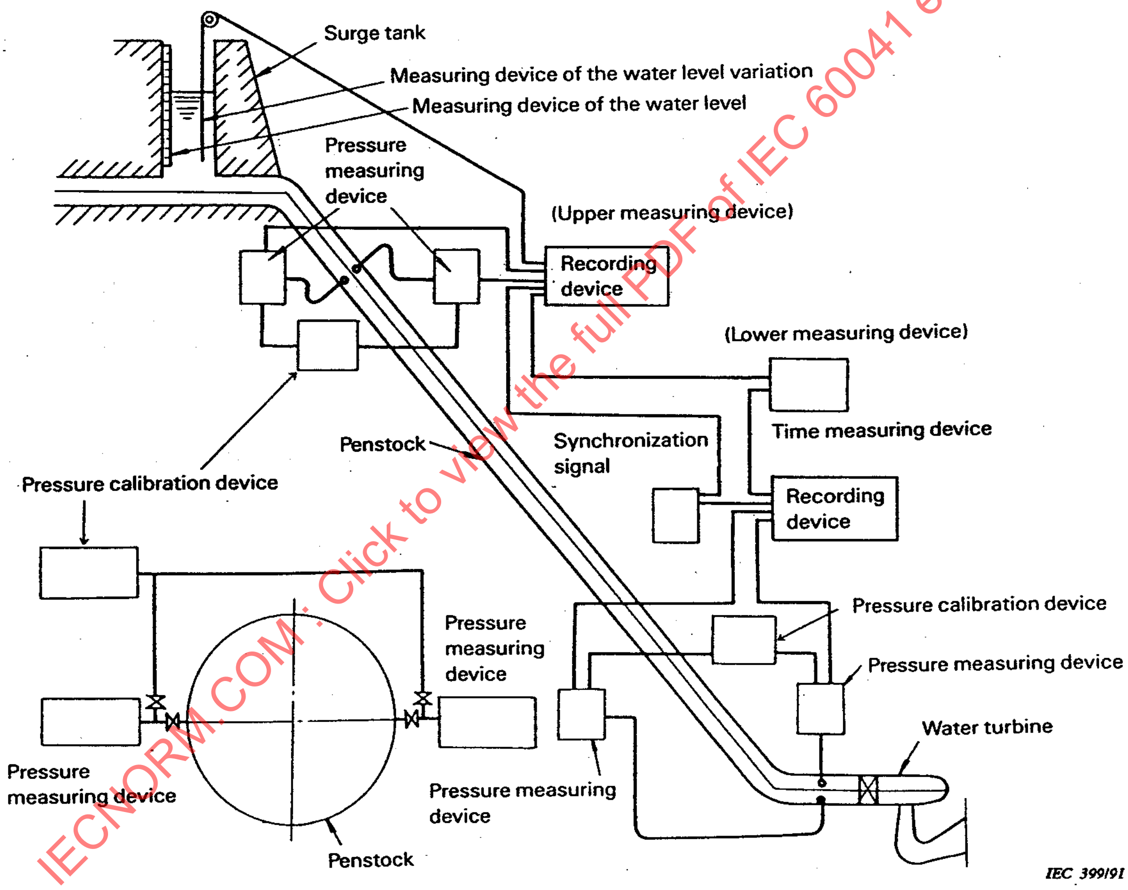


Figure 30 – Pressure-time measurement by separate diagrams method. Arrangement of apparatus

10.5 *Tracer methods*

10.5.1 *General*

Three basic methods exist: two, the "constant-rate-injection method" and the "integration (sudden injection) method", use the dilution principle and the third, known as the "transit-time method", is based on a measurement of the time taken for a tracer to travel a specified distance between two cross-sections in a pipe or in an open-channel. However, in the present state of knowledge, and for the purpose of this standard, only the constant-rate-injection method and transit-time method, in closed conduit, are recommended. Moreover, the transit-time method is to be preferred to the constant-rate-injection method, due to the spurious and random errors which can arise when using the latter.

Standards are available for these methods using both radioactive and non-radioactive tracers. Reference is made where appropriate in the sub-clauses below to those standards which can be used, within the limits given, for acceptance tests on hydraulic turbines and storage pumps. The methods are particularly suitable where there are relatively long lengths of penstock available or where additional mixing of the tracer may be obtained by inclusion of the machine in the measuring length or the installation of mixing promoters (e.g. turbulators), as the machine alone does not provide sufficient mixing.

10.5.2 *Constant-rate-injection method*

10.5.2.1 Principle of the method

The principle of this method of discharge measurement is the continuous injection of a tracer into the main water flow at a steady measured rate and the determination of the resulting concentration of tracer, relative to its initial concentration, at a point far enough downstream to ensure thorough mixing.

It is not necessary to know the geometric characteristics of the pipe but it is essential to ensure that reverse or side currents do not exist which could abort some of the tracer. Also, concentration of the tracer in natural water must be constant and not exceed 15 % of the concentration at the sampling point during injection of the tracer.

The discharge Q can be determined from:

$$Q = q\frac{C_1 - C_2}{C_2 - C_0}$$

where:
Q is the discharge to be measured
q is the discharge of tracer solution injected
C_0 is the initial concentration of tracer in natural water
C_1 is the concentration of tracer in the injected fluid
C_2 is the concentration of tracer at the sampling station

10.5.2.2 Application of the method

Radioactive and non-radioactive tracers can be used, provided the recommendations and procedures described in Parts 1, 2 and 3 of ISO 2975 are applied.

10.5.2.3 Uncertainty of measurement (see 10.1.2)

The ISO standard referred to in 10.5.2.2 gives all the necessary requirements for a successful measurement but does not give a specific limit on the uncertainty of the resulting measurement. It is required to estimate the individual sources of systematic errors in each of the component measurements and combine these with the random errors by the method given to obtain an estimate of the total uncertainty.

When applying these methods to the measurement of the discharge through hydraulic machines during acceptance tests, it is important that the strictest limitations given in the relevant standard are observed. Suitable tests must be carried out to check that the tracer and measurement equipment are suitable for the particular conditions of the installation and the flow distribution in the measuring length is acceptable.

With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95 % confidence level should be about ±1 % to ±2 %.

10.5.3 *Transit-time method*

10.5.3.1 Principle of this method

The transit-time method (formerly called the "Allen salt velocity method") is based on the measurement of the transit time of "labelled" fluid particles between two cross-sections of the conduit a known distance apart.

Labelling of the fluid particles is achieved by injecting a tracer into the flow a sufficient distance upstream of the two measurement cross-sections (i.e. detector positions) and the transit time is determined from the difference of the mean arrival times of the tracer at each of the detector positions. The discharge Q is then given by:

$$Q = \frac{V}{\bar{t}}$$

where:
V is the volume of the pipe between the detector positions
$\bar{t}$ is the mean transit time of the labelled particles

The geometric characteristics of the pipe must therefore be measured accurately to obtain the volume V. However, an advantage of the method is that the tracer concentration within the pipe need not be known; it is only necessary for the recorded signals of the passage of the "labelled" particles past each detector position to be proportional to the tracer concentration, the proportionality constant being immaterial.

10.5.3.2 Application of the method

Radioactive and non-radioactive tracers can be used, provided the recommendations and procedures described in Parts 1, 6 and 7 of ISO 2975 are applied.

All the requirements specified in that standard are necessary for the successful use of the methods for the measurement of discharge for acceptance tests on hydraulic turbines and storage pumps. In particular, Annex A of ISO 2975-6 sets out the detailed conditions for the use of a salt solution as the injected tracer together with specifications of the injection "pop" valves, the detector electrodes and the associated electrical circuits for detecting and recording the changes in conductivity of the water with the passage of the "labelled" particles.

10.5.3.3 Uncertainty of the measurement (see 10.1.2)

The ISO standard referred to in 10.5.3.2 gives all the necessary requirements for a successful measurement but does not give a specific limit on the uncertainty of the resulting measurements.

It is required to estimate the individual sources of random and systematic errors of the component measurements listed in the standard and combine these with the random errors by the method given to obtain an estimate of the total uncertainty.

With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95 % confidence level should be about ±1 % to ±1,5 %.

10.6 *Weirs*

10.6.1 *Principle of measurement*

The discharge is measured by interposing a thin plate weir in a free surface flow, by observing the head over the weir and by employing a unique functional relationship between the discharge and the head over the weir. In order to have the best known relationship, only rectangular weirs without side contraction sharp crested, with complete crest contraction and free overflow shall be used.

The basic formula for calculating the discharge is due to Poleni and can be written as:

$$Q = \frac{2}{3} C b \sqrt{2g}\, h^{3/2}$$

where:
Q is the discharge
C is the discharge coefficient
b is the length of the weir crest (perpendicular to the flow)
g is the acceleration due to gravity
h is the measured upstream head over the weir

10.6.2 *Description of the measuring device*

The plate constituting the weir shall be smooth and plain, particularly on its upstream face, and shall remain unaltered for the whole duration of measurements.

This weir plate shall preferably be made of metal which can resist erosion and corrosion. It shall be rigid, watertight and perpendicular to the walls and to the bottom of the channel.

The surface of the weir crest shall be a horizontal, flat and smooth surface, perpendicular to the upstream face of the plate: its intersection with the upstream face shall be straight and form sharp edges, free from burrs or scratches. Its edge width e perpendicular to the upstream face shall be within 1 mm and 2 mm. If the weir plate is thicker than the allowable crest width, the downstream edge shall be chamfered at a 45° angle.

Complete aeration of the nappe shall be secured. The ventilation must be sufficient to keep the air underneath the nappe at approximately atmospheric pressure. The cross-sectional area of the ventilation holes must be at least 0,5 % of the product of the length of the weir crest b times the height, s_1, of the weir above the water level in the downstream channel (see Figure 31).

During the test, the condition of the crest and the shape of the nappe shall be checked to avoid unsuitable conditions such as an adhering nappe, disturbed or turbulent flow or surging.

10.6.3 *Conditions of installation*

The weir is commonly located on the low pressure side of the machine, and care shall be taken to ensure that smooth flow (free from eddies, surface disturbances or significant amounts of entrained air) exists in the approach channel. There shall be no loss or gain of water between the machine and the weir.

When the weir is located on the outlet side of the machine being tested, it shall be far enough from the machine or the discharge conduit outlet to enable the water to release its air bubbles before reaching the weir. Stilling screens and baffles shall be used when necessary to give a uniform velocity distribution over the whole of the cross-section. Disturbed surface or undercurrents, or asymmetry of any kind, must be corrected by suitable screens.

The approach channel shall be straight and of a uniform cross-section and with smooth walls for a length of at least 10 times the length of the weir crest b. If stilling screens or baffles are used, they shall be located at a distance upstream of the weir greater than the length prescribed above. Along this length, the bottom slope must be very small ($< 0,005$). A desilting sluice can be installed if required, but it shall not disturb the regular flow of water along the upstream face of the weir.

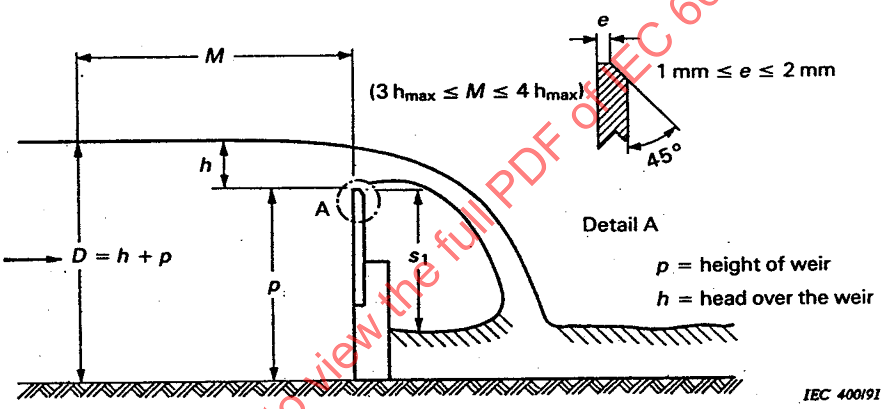


Figure 31 – Sketch of a rectangular sharp-crested weir

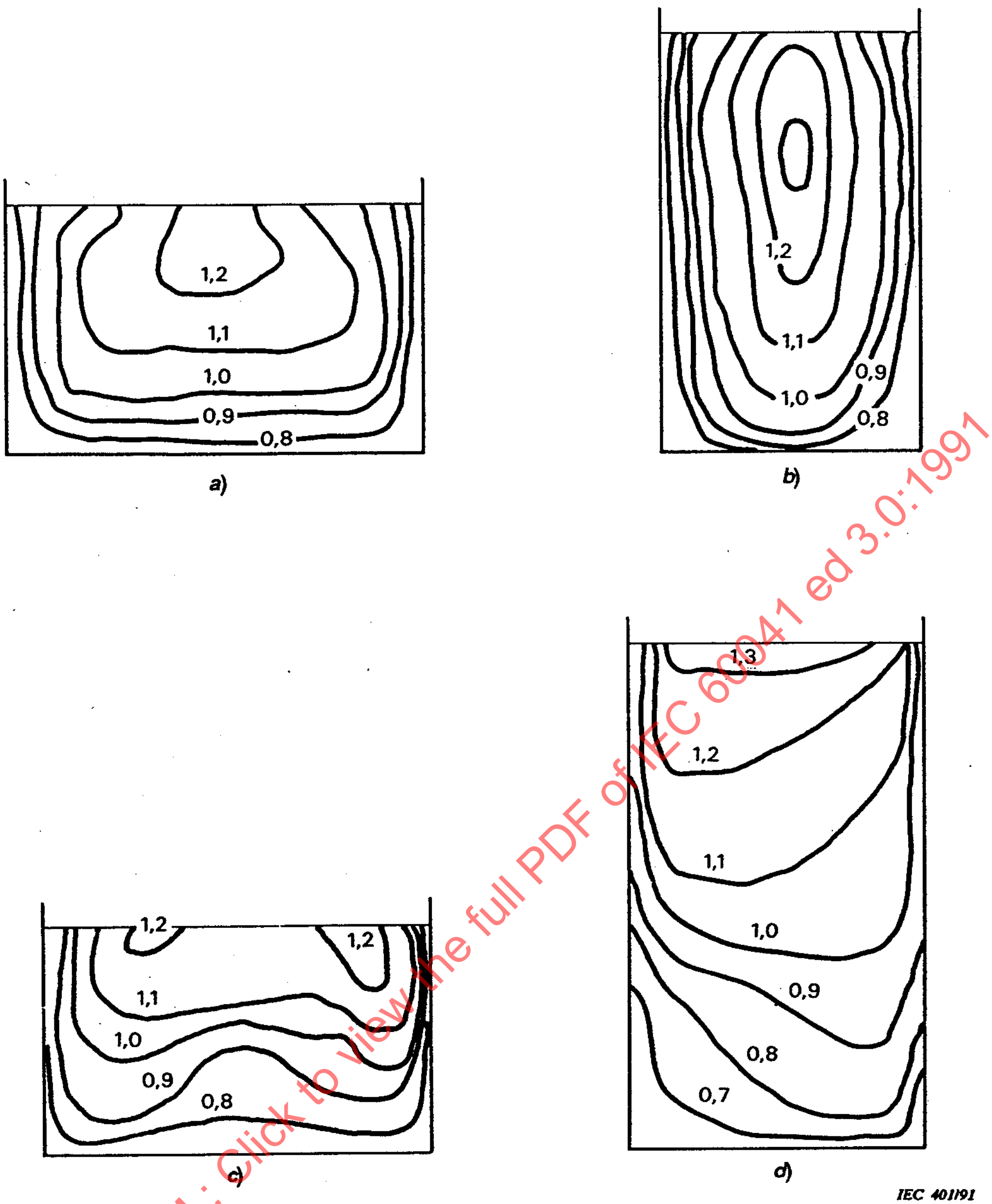
The sides of the channel above the level of the crest of the weir shall extend without discontinuity at least $0,3\,h_{max}$ downstream of the plane of the weir.

Before beginning the tests, it is advisable to check the velocity distribution in the approach channel by current-meter survey. Figure 32 shows some typical examples of velocity distributions.

10.6.4 *Measurement of head*

The head h above the crest shall be measured upstream of the weir at between three and four times the maximum head. For measuring h the number of measuring points uniformly spaced across the weir channel shall be as follows:

	Length of crest b	*Number of measuring points*
For	$b < 2$ m	2
	$2\text{ m} \leq b \leq 6$ m	3
	$b > 6$ m	4 at least



Note. – The velocity distributions a) and b) provide examples of observed normal distributions which are clearly acceptable.

The velocity distributions c) and d) show appreciable departure from normal distribution which can lead to results at the limit of the specified uncertainty.

Figure 32 – Examples of velocity distributions in the approach channel

However this number may be reduced to a minimum of 2, where approach velocities are small and the velocity distribution is particularly regular.

Measurements of the head at each point of measurement shall not differ by more than 0,5 %. If they do, every endeavour should be made to meet this requirement by installing screens, baffles or rafts. The arithmetic mean of all the head measurements shall be used for computing the discharge.

Head measurement may be made with point or hook gauges (see 11.5.4.2) with optical sighting or electrical contact or by floats (see 11.5.4.3). These devices shall be placed in stilling wells at the sides of the approach channel, communicating through special pressure connections terminating in taps that are flush with the channel wall, 3 mm to 6 mm in diameter and at least twice the diameter in length (see 11.5.4.8). The water in the stilling well shall be purged from time to time to ensure that its temperature is within ±2 °C of that in the approach channel. If it is not practicable to use stilling wells then pointe gauges may be used directly in the channel, but twice the number of measuring points given above shall be used and at least two independent observations made of each reading.

In all cases, several readings of the head at each measuring point shall be made at regular time intervals to check that steady flow conditions have been established.

Before and after each series of measurements, the zero height shall be accurately checked. For this purpose, a pointer shall be provided with its point set exactly level with the crest of the weir and fixed permanently in the approach channel or alternatively in the stilling or float well where provided.

When the flow may be interrupted the zero setting may be checked using either a dumpy level and a staff or a straight edge and a spirit level when the channel is empty (see Figure 33a) or using a special device directly fixed to the crest, the water level being reduced slightly under the crest level (see Figure 33b).

A zero check based on the level of the water at zero discharge is liable to serious errors from surface tension effects and shall not be used.

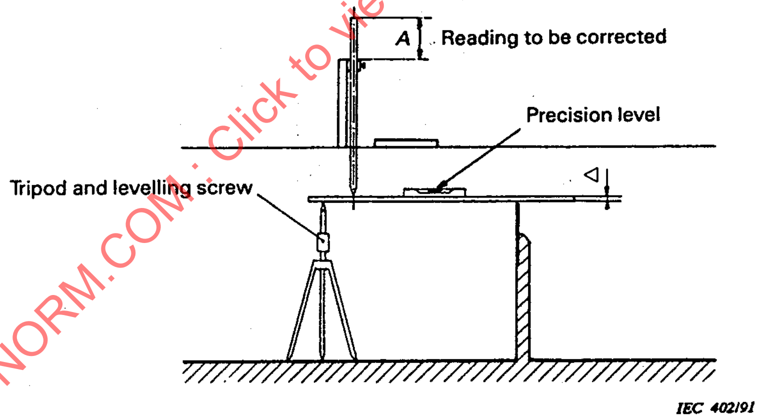


Figure 33 a – Weir zero setting with empty channel

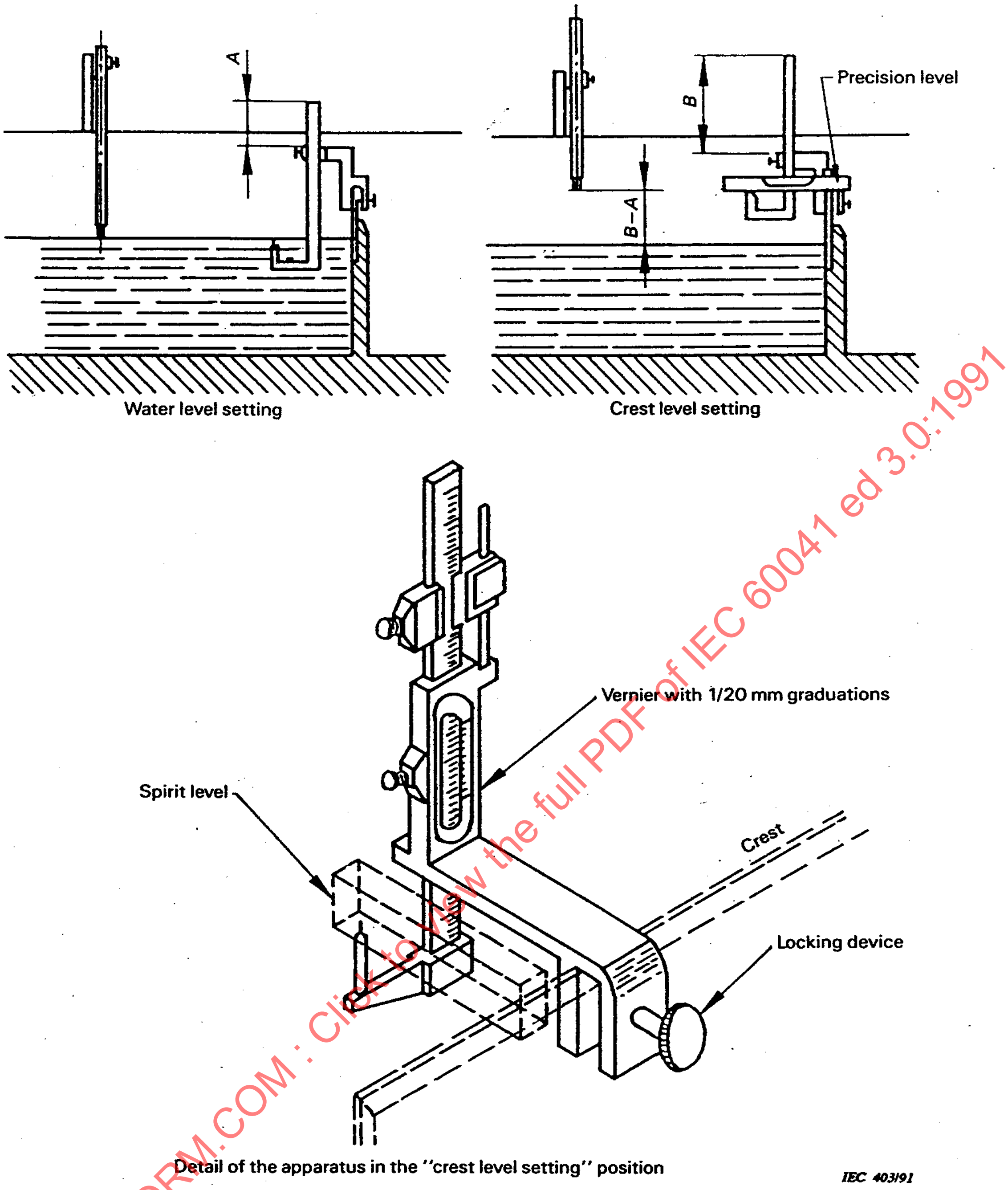


Figure 33 b – Weir zero setting in still-water condition

10.6.5 *Discharge formulae*

Among many empirical formulae which have been proposed to express the head-discharge relationship, the SIA formula (Swiss Society of Engineers and Architects – 1924), the Rehbock formula (1929), the Kindsvater-Carter formula (1959) and the IMFT formula (Fluids Mechanics Institute of Toulouse – 1967) appear to be preferred*.

Each of these was determined under special experimental conditions and shall be used only within the ranges covered by the experiments. Even then, the differences between the values of discharge calculated by the various formulae may be several per cent.

In such circumstances, the following average formula shall be used for calculating the discharge:

$$Q = \left(0,4077 + 0,0497\,\frac{h}{p}\right) b\sqrt{2g}\,h^{3/2}$$

within the following dimensional restrictions:

$$b \geq 0,40 \text{ m}$$
$$p \geq 0,30 \text{ m}$$
$$0,06 \text{ m} \leq h \leq 0,80 \text{ m}$$
$$0,15 \leq h/p \leq 1,00$$

The use of the limiting value of more than one parameter at the same time shall be avoided.

10.6.6. *Uncertainty of measurement* (see 10.1.2)

The accuracy of measurements made with a rectangular thin-plate weir depends on the accuracy of the head and crest length measurements and on the accuracy of the discharge coefficient used. It is therefore desirable that, whenever possible, the weir should be calibrated under the existing conditions of installation and use.

If such a calibration is not carried out and no mutual agreement has been made by the parties for using one of the experimental formulae given above, the discharge shall be computed by the average formula given in 10.6.5.

With the dimensional limitations prescribed above, this formula keeps the uncertainty (at 95 % confidence level) due to the discharge coefficient bias within ±1,5 %, providing the weir complies with the prescribed conditions throughout the duration of the tests.

Differences in approach velocity distribution, bluntness of crest, excessive roughness of the upstream face of the weir or imperfect ventilation under the nappe can seriously affect the head-discharge relationship.

Outside the range of the above limitations on b, p and h, the uncertainty of the discharge coefficient can increase greatly. This is especially true whenever h/p is below 0,25.

With good measuring techniques and flow conditions, the estimated systematic uncertainty at 95 % confidence level should be about ±1,7 % to ±3 %.

*These formulae can be consulted in ISO 1438-1.

10.7 *Standardized differential pressure devices*

10.7.1 *Principle of the method*

This sub-clause deals with the method of discharge measurement which consists in installing in the conduit a device (orifice plate, nozzle or Venturi tube) creating a constricted cross-section and measuring the pressure difference so generated. It does not deal with piezometric control devices, such as the Winter Kennedy method, which provide only a relative or index value of the discharge (see Clause 15).

10.7.2 *Field of application*

The method of discharge measurement by differential pressure devices is the subject of ISO 5167, supplemented by ISO 2186, concerning the pressure signal transmission.

These standards give all necessary directions concerning the design and the setting of the primary element, the choice of the section of measurement, the value of the flow coefficient, the computation of discharge and its uncertainty. These standards apply only in the range of pipe diameter D and Reynolds number Re_D specified in Table I. Annex B of ISO 5167 gives guidances on the applications of Venturi tubes outside this range.

TABLE I – Limiting dimensions and Reynolds numbers for differential pressure devices (Values extracted from ISO 5167)

Type of device		D (mm)		Re_D 2)	
		Minimum	Maximum	Minimum 1)	Maximum
Orifice plate	– with corner taps	50	1 000	5×10^3	∞
	– with D and D/2 taps or flange taps	50	1 000	3×10^3	∞
Nozzle	– ISA 1932	50	500	2×10^4	10^7
	– long radius	50	630	10^4	10^7
Classical Venturi tube					
	– with a rough-cast convergence	100	800	2×10^5	2×10^6
	– with a machined convergence	50	250	2×10^5	10^6
	– with a rough-welded sheet-iron convergence	200	1 200	2×10^5	2×10^6
Venturi-nozzle		65	500	3×10^4	2×10^6

1) For orifice plates, ISA 1932 nozzles and Venturi-nozzles, the actual minimum value of Re_D depends upon the diameter D and/or the diameter ratio d/D.

2) According to ISO 5167,

$$Re_D = \frac{v_1 D}{\nu_1}$$

where:

v_1 is the upstream mean flow velocity ($m \cdot s^{-1}$)

D is the upstream internal pipe diameter (m)

ν_1 is the kinematic viscosity of the fluid ($m^2 \cdot s^{-1}$)

10.7.3 *Uncertainty of measurement*

Whenever it is possible to satisfy the requirements of the ISO standards, it is unnecessary to calibrate the apparatus as the flow coefficients indicated in the standards may be used provided their resulting accuracy is considered sufficient. ISO 5167 gives all the data necessary to estimate the total uncertainty in the discharge measurement. For guidance, with good measuring techniques and flow conditions, the estimated systematic uncertainty at 95 % confidence level (see 10.1.2) should be about:

a) orifice plate, ISA 1932 nozzle or classical Venturi tube with a rough-cast convergence: $\pm 1\%$ to $\pm 1,5\%$;

b) other devices: $\pm 1,5\%$ to $\pm 2\%$.

10.8 *Volumetric gauging method*

10.8.1 *Principle of the method*

The conventional volumetric gauging method is confined to low discharges, because of the size of the tanks or reservoirs required. Therefore, it is unlikely to be applied to discharge measurements in the field.

Nevertheless, a variant of this method can be adopted for large-scale discharge measurements. It consists in determining the variation of the water volume stored in the headwater or tailwater pond on the basis of the variation of the water level. If necessary, provision shall be made for isolating the pond to ensure that there shall be no inflow to or outflow from it during the measuring time.

For such volumetric measurements. there is no limitation on the magnitude of the discharge provided that, during a run, the change of specific hydraulic energy is less than 1 % (if not otherwise agreed) and subject to conditions to be fulfilled (see 5.2); the measurement of the other quantities required for the determination of the efficiency must extend over the whole period during which the change in water level is measured. Therefore, any variations in the power and specific hydraulic energy during this time of measurement must be taken into account.

10.8.2 *Basins for volumetric measurements*

10.8.2.1 Type and shape of ponds

Artificial ponds best suited for volumetric measurements are concrete basins with vertical walls (e.g. headwater basins of pumped storage plants). With increasing size, the ponds are generally provided with inclined concrete walls; these ponds are particularly suitable for volumetric measurements if the slope of the walls remains constant over the whole of the measuring range. The shape of a basin and the slope of the walls should be considered carefully in the planning stage of the plant if the basin is to be used for volumetric measurements.

Natural basins are very rarely suitable for volumetric measurements, since they cannot provide the same accuracy as artificial ponds. Nevertheless, their accuracy can be improved by completely grubbing the banks and smoothing them as far as possible over the expected measuring range. According to the nature of their banks, the actual volume is larger than the geometrical volume, due to absorption or resorption of water by the banks while filling or emptying the ponds.

10.8.2.2 Volume of ponds

The volume of the pond as a function of the water levels can be determined more accurately the simpler the plan view of the pond and the steeper the walls. The volume can be determined by geometrical measurement or by photogrammetry.

At the gauging stations, suitable non-corroding level markers shall be provided and their elevations referred to the main bench mark (see 4.4.3).

10.8.2.3 Choice of water-level range

With a pond having sloping walls and an asymmetric cross-section, it is good practice to use a mathematical interpolation formula and an electronic data-processing system to determine the calibration values at regular height intervals. A plot of the calibration will indicate the range of elevations best suited for a discharge measurement. The tests should be confined to this range and the duration of each run should be such that the uncertainty in the change in volume is less than ±1 %.

10.8.2.4 Number and arrangement of measuring points

Water level measurement in the pond will be made easier and more accurate by giving careful consideration to the arrangements for the measuring points and their approaches at the time the pond is built.

The water level shall be measured simultaneously at least at four points judiciously located. In irregularly shaped ponds, it is recommended that the number of measuring points should be increased sufficiently to achieve an average value representative of the mean water level, particularly if wind occurs or if the flow velocities in the pond are not negligible.

At each measuring point, a suitable arrangement shall be made for the intended measuring device. In most cases, stilling pipes or wells shall be established, in which the water gauge or float is installed (see 11.5.4.8 and 11.5.4.3). The use of a bubbler gauge using compressed air requires only minimum arrangements (see 11.5.4.7). Staff gauges (see 11.5.4.4) may also be used either vertical (attached to the walls or fastened on step frames according to the circumstances) or inclined along the slope of the bank; it is then necessary to ensure an accurate reading of the levels by providing either adjustable observation stands or flights of stairs. It is also necessary to provide fixed level marks, as mentioned in 10.8.2.2, allowing the gauges to be correlated with each other and with the main bench mark and eventually to convert the oblique measurements along the banks to vertical heights. Details of water level measurements are given in clause 11.5.

10.8.3 *Operation of measurement*

10.8.3.1 Disturbing effects

Depending on location and size of the pond and the water level chosen for the measurements, the influence of the wind on the actual water level may be such an important factor that measurements can be conducted only during a calm period. With the gates and/or shut-off valves of all machines closed, it is possible and advisable to assess this influence by making a comparison of the water levels measured at various points.

The arrangements prescribed in 10.8.2.4 may be sufficient to obviate errors due to small waves, but in the event of a heavy swell or swell with a long period the measurements must be suspended until the swell subsides.

The influence of rainfall or evaporation must be assessed, and if necessary, the measurements must be suspended until favorable conditions exist.

Leakage through the walls of an artificially formed pond or through the bed of a natural basin can seriously affect the measurements. An assessment of the amount of leakage shall be made by measuring the change in water level over extended periods of time with all machines shut down. This assessment shall be made at a number of different heights of water in the pond or basin under conditions as nearly as possible identical to those for the actual tests, particularly with regard to the water saturation in the surrounding earth. For artificial ponds, it is also possible to measure directly the leakage from the pond.

All the above considerations also apply to the possible inflow into the pond.

Due to all the disturbing effects indicated above, the elevation of the datum of each level indicator cannot be ascertained through elevation of the water surface with all gates closed. A careful levelling between each datum and reference bench mark is recommended.

10.8.3.2 Duration of measurement

The duration of measurement is the time taken by the water level to cover the measuring range specified in 10.8.2.3.

If the desired water level variation can only be obtained with an excessively long duration of measurement, the uncertainty in the determination of the mean power and head will probably be increased.

The number of readings within the duration of a run must be so chosen that a well-defined graphical record of the water level variation as a function of time can be prepared; these readings shall be closer near the beginning and the end of the run. To achieve this, simultaneous measurements at all points are imperative.

10.8.3.3 Measurement of quantities other than discharge

The pressure or water level measurements used for the determination of specific hydraulic energy, the readings of the wattmeters for power measurement and the measurements of speed (the latter are particularly important in pump operation) must be carried out simultaneously with the water level measurements in the pond.

It is recommended that a series of volumetric gaugings be made for calibrating a secondary discharge measuring device over a range of loads (see Clause 15). Index tests may be used to augment parts of the general test programme, to check the constancy of the discharge over the duration of a volumetric gauging or to determine its variation during a run where the change in specific hydraulic energy is significant.

10.8.4 *Analysis of the test results*

The average water levels are computed from the simultaneous measurements made at the various locations.

The mean discharge over the duration of the run is obtained from the variation of the water volume given by the calibration table (see 10.8.2.3) between the water levels at the beginning and the end of the run and the relevant measuring time.

The constancy of the flow rate over the duration of measurement shall be checked by determining the discharge within shorter intervals of time included in the whole duration. These check values shall be compared to the corresponding values deduced from the index test during the same intervals of operation.

All individual readings shall be recorded in order to provide data to determine the random uncertainty.

10.8.5 *Uncertainty of measurement* (see 10.1.2)

For discharge measurements by the volumetric method, the uncertainty of measurement depends primarily on the pond area or volume determination. For large ponds, only approximate values can be given which may vary, depending on size and shape of the ponds and completeness of the methods used for the area and elevation determinations. Therefore, it is imperative that these approximate values be checked in consultation with those in charge of the pond calibration.

Approximate values of the uncertainty of the volume determination:

a) concrete pond with vertical walls: $\pm 0,5$ % to $\pm 0,8$ %;

b) concrete pond with sloping banks: $\pm 0,7$ % to $\pm 1,0$ %.

In case *b)* the pond requires surveying by means of triangulation, established survey system, photogrammetry and supplementary tacheometry.

For natural ponds, no information can be furnished (see 10.8.2.1).

In addition to the uncertainty due to the pond calibration, consideration shall be given to:

a) the uncertainty of the measurement of filling or emptying time;

b) the uncertainty of the water level determination, to be assessed for each run on the basis of the measurement conditions and of the various sources of error listed in 10.8.3.1.

With good conditions, the estimated systematic uncertainty at 95% confidence level should be about ±1% to ±2%.

In the acceptance test of a pump-turbine, if the contractual guarantees give an equal weight to the turbine and pump efficiencies, the uncertainty due to the determination of the pond areas may be to a large extent ignored for the evaluation of the total uncertainty, provided all the measurements are carried out in the same range of water levels.

11. Specific hydraulic energy of the machine

11.1 *General*

11.1.1 *Object*

The specific hydraulic energy of the machine is a main characteristic and it must be calculated in any test of a hydraulic machine.

The formula enabling its evaluation is given in 2.3.6.2. Appendix F explains the derivation of this formula.

The net positive suction specific energy is also an important characteristic and should normally be determined. The formula is given in 2.3.6.9.

11.1.2 *Method of determination*

To determine the specific hydraulic energy of the machine, it is necessary to evaluate the specific energy of water in the high pressure and low pressure reference sections. In practice it is not always possible to measure the pressure at the reference sections. The absolute pressure, the mean velocity and the elevation are then determined as near as possible to the corresponding reference sections and chosen so as to achieve measurements of high accuracy.

Whenever possible direct pressure measurements shall be used, in particular on the low pressure side where the measuring section should be located within the draft tube. In some cases, this method has to be replaced by free water level measurement.

11.1.3 *Steady-state conditions and numbers of readings*

Readings required to determine the specific hydraulic energy shall be taken only when steady-state conditions prevail as defined in 5.2.1 and at regular intervals, as prescribed in 4.7.2. The number of readings and the intervals between them shall be as specified in 5.1.2. If the measurements are recorded (graphs, punched tape, magnetic tape, etc.), at least two direct readings for each run should be taken for the purpose of checking.

11.2 *Determination of the specific hydraulic energy*

11.2.1 *Measuring sections*

11.2.1.1 General

The basic conditions to achieve an accurate determination of the specific hydraulic energy are mentioned in 11.1.2. Requirements for a pressure measuring section are given in 11.4.1.

11.2.1.2 Shifted measuring sections

The main reason for shifting the measuring section away from the reference section at the design stage is flow perturbation from the machine itself or from the conduit and its accessories. Such a shift may also be mandatory at the time of the test by an absence of adequate provision for testing.

The high pressure reference section of a pump is a typical case since the pressure and velocity distribution may be such that the calculation of specific hydraulic energy from the mean values would result in significant errors. A measuring section located some conduit diameters away from the pump will generally increase the reliability of the measurement.

A butterfly valve close to the high pressure reference section of a turbine is another difficult situation, since the loss due to the valve is as difficult to assess as its effect on the measurement.

Another difficult case occurs when the high pressure side measuring section in the case of a turbine cannot be located downstream of the intake trash racks. In this case the calculation of the specific hydraulic energy losses has to be agreed upon prior to the test.

When pressure taps have not been provided, and cannot be added for the test, it is necessary to locate the measuring sections in places with access to the flow; this results quite often in using sections with a free surface flow. In particular, if it is not possible to measure the pressure inside the draft tube, the tailwater level shall be measured directly above the draft tube outlet (turbine)/inlet (pump) or as close to it as possible in the tailrace (see Figure 40).

11.2.1.3 Specific hydraulic energy correction for shifted measuring sections

When the measuring section is not the reference section, the loss of specific hydraulic energy between the measuring section and the reference section shall be taken into account, due consideration being given to the flow direction and distribution, the relative position of the two sections and the actual kinetic energy recovery which may take place between them. Evaluation of this loss may be based on theoretical knowledge and practical experience.

Before a decision is made to use a shifted measuring section, due consideration shall be given to the uncertainty introduced by the loss calculation as compared to that arising from unsatisfactory measuring conditions at the reference section.

11.2.2 *Reference levels*

11.2.2.1 Reference datum

The elevations shall be referred to a reference datum such as mean sea level.

11.2.2.2 Bench marks

A fixed elevation reference point called the main bench mark shall be chosen or provided at each hydraulic machinery installation. The elevation of this bench mark shall be determined in relation to an established reference datum (see 11.2.2.4).

An official bench mark is usually available for instance as part of a national survey of elevations above mean sea level.

The main bench mark (see 4.4.3) must be clearly labelled to avoid any possibility of error.

If there is no bench mark available, the reference level of the machine may be chosen as the main bench mark.

The elevations of auxiliary bench marks defining the reference levels of all the gauges shall be accurately determined in relation to the main bench mark prior to starting the test.

All bench marks shall be retained undisturbed until the final test report has been approved.

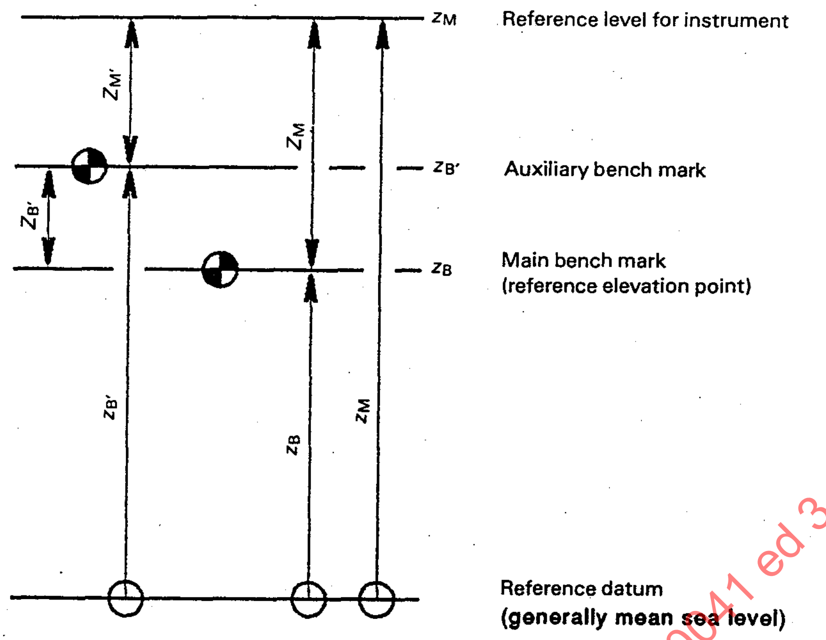
11.2.2.3 Reference level for instrument

Each of the pressure or free water level measuring instruments shall have a mark fixed permanently to it. The elevation of this mark z_M is called the reference level for instrument. The difference between the reference level for instrument and the bench mark is $Z_M = z_M - z_B$ (see Figure 34a).

An example of main elevations and heights is shown in Figure 34b.

11.2.2.4 Differences of elevations

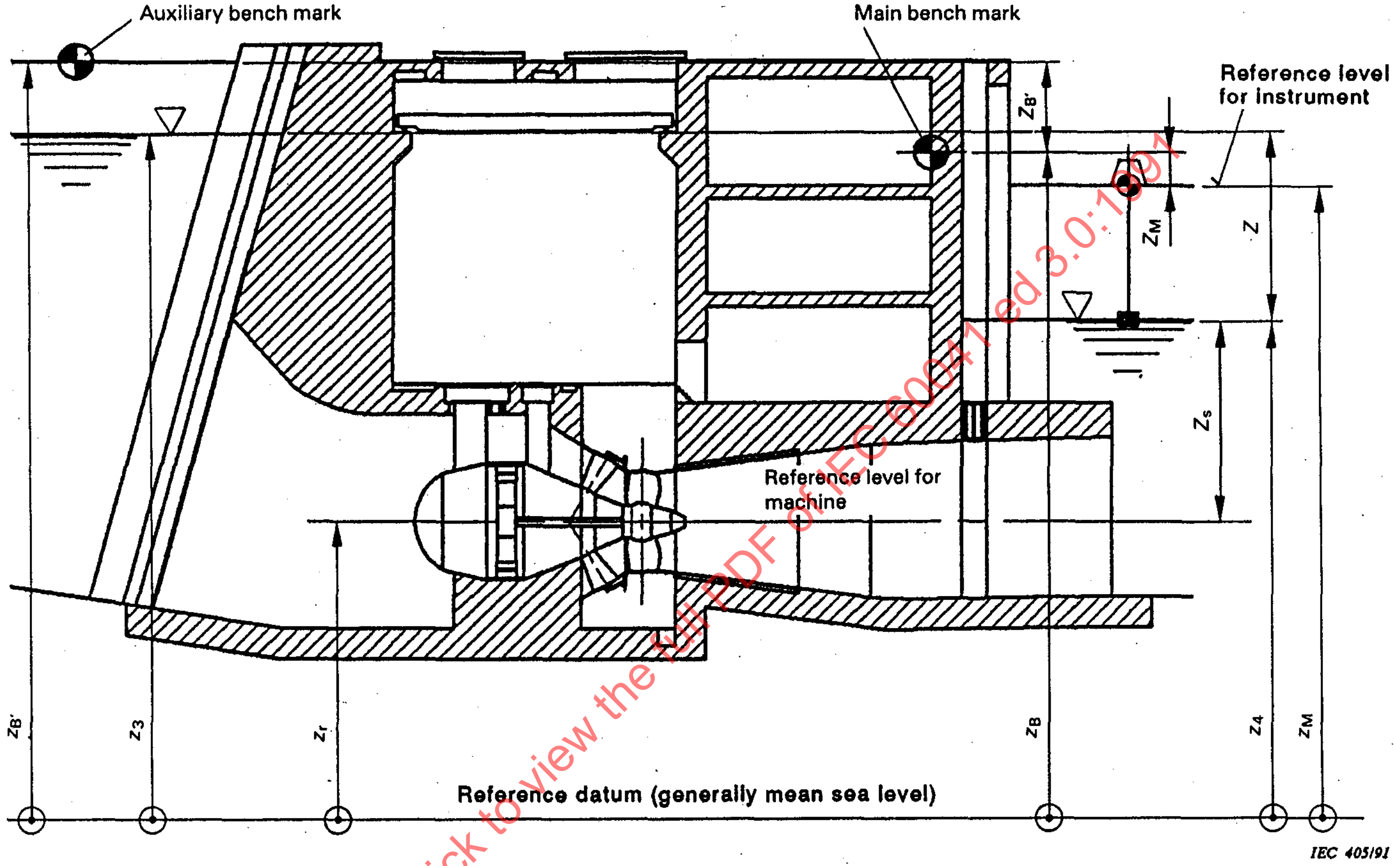
It is only important to establish accurately the differences of elevations. The exact elevation of the main bench mark is of secondary importance. To measure differences in elevation (height), levelling instruments of adequate precision may be required; for small heights measuring tapes may also be used.



z is the elevation of a point in the system above reference datum (see 2.3.2.5)
Z is the difference of elevations

$$Z_M = z_M - z_B$$
$$Z_{M'} = z_M - z_{B'}$$
$$Z_{B'} = z_{B'} - z_B$$

Figure 34 a – Definition of reference level for instrument



z_r	is the reference level for machine (see 2.3.7.10)	Z	$= z_3 - z_4$	(geodesic height of plant, see 2.3.7.1)
z_B	is the elevation of the main bench mark (see 11.2.2.2)	Z_s	$= z_r - z_4$	(suction height, see 2.3.7.8)
z_B	is the elevation of an auxiliary bench mark (see 11.2.2.2)	$z_{B'}$	$= z_{B'} - z_B$	(see Figure 34 a)
z_M	is the reference level for instrument (see 11.2.2.3)	Z_M	$= z_M - z_B$	(see Figure 34 a)
		▽		is the water level

Figure 34 b – Example showing main elevations and heights

11.2.3 *Water density*

From the definition in 2.3.6.2, mean water density shall be calculated as the mean of densities at the two reference sections.

As the temperature difference between the inlet and outlet of the machine is small, the temperature of the water at the low pressure reference section may be used for calculating the densities involved in the evaluation of $\overline{\varrho}$ (see 9.2.4).

11.2.4 *Specific kinetic energy*

The specific kinetic energy term is determined in any section, from the mean velocity of the water in that section. The mean velocity v is the actual volume discharge passing through the measuring section divided by the area of that section. This area shall be measured or may be deduced from construction drawings, if the specific kinetic energy term is a small part of the specific hydraulic energy.

By convention the specific kinetic energy in a reference section is taken as $e_c = \frac{v^2}{2}$.

The same convention is applied when the measuring section is shifted from the reference section within the limits of the machine.

When the measuring section in the low pressure side has to be located outside of the draft tube (see Figure 40), the calculation of mean velocity in the measuring section is explained in 11.2.5.3.2.

11.2.5 *Simplified formulae*

11.2.5.1 General

As indicated in Appendix F, the general formula given in 2.3.6.2 is a convenient approximation of the exact value of the specific hydraulic energy of the machine. The relative error due to the approximation is less than 0,02%.

For the specific hydraulic energy of the machine, variation of g with elevation is generally negligible and can be calculated for the reference level of the machine z_r (see 2.3.7.10). Further simplifications are possible in each specific case and approximations may be introduced, for example, when the water compressibility or the difference in ambient pressure between sections 1 and 2 can be neglected.

The simplified formulae established in this sub-clause are typical for the described measuring installations. Only the most common installations are reviewed. A simplified formula shall not be used for a differing installation without a careful examination of its adequacy.

11.2.5.2 Measurements using pressure taps

11.2.5.2.1 Measurement of differential pressure

Figure 35 shows schematically the measuring installations of the specific hydraulic energy of the machine whenever a differential pressure device is used. This solution is specially suitable for low head machines but can be applied to the range of head for which instruments of sufficient accuracy and sensitivity are available.

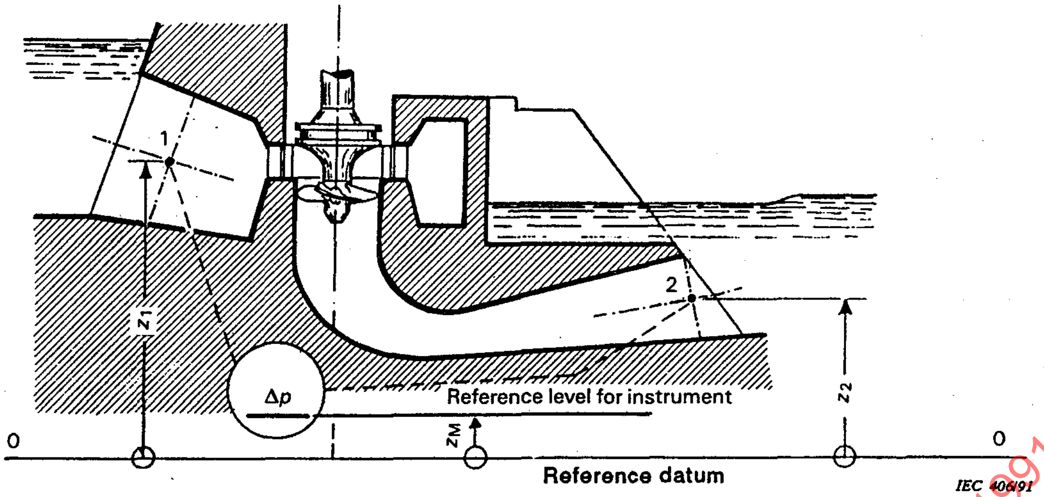


Figure 35 – Determination of specific hydraulic energy of machine through differential manometer

$$E = \overline{g}H = \frac{p_{abs_1} - p_{abs_2}}{\overline{\varrho}} + \frac{v_1^2 - v_2^2}{2} + \overline{g}(z_1 - z_2)$$

From the pressure difference measurement, one gets:

$$\frac{p_{abs_1} - p_{abs_2}}{\overline{\varrho}} = \frac{\Delta p}{\overline{\varrho}} + \overline{g}\left[(z_2 - z_M)\frac{\varrho_2}{\overline{\varrho}} - (z_1 - z_M)\frac{\varrho_1}{\overline{\varrho}}\right]$$

When applied to low head machines ($\Delta p < 400\,000$ Pa), the compressibility of water is neglected and it is assumed:

$$\varrho_1 = \varrho_2 = \overline{\varrho} \qquad \text{(see 11.2.3)}$$

Therefore the simplified formula is:

$$E = \frac{\Delta p}{\varrho_2} + \frac{v_1^2 - v_2^2}{2}$$

11.2.5.2.2 Separate measurement of pressures

a) Low head machines

Figure 36 identical to Figure 5a refers to low head machines, where the pressure is measured in both sections with water column manometers.

An approximation is introduced in this case: the compressibility of water is neglected since pressure differences are less than about 400 000 Pa. Ambient pressure may be assumed in calculating air density.

b) Medium and high head reaction machines

Medium and high head reaction machines are dealt with in Figure 37 identical to Figure 5b, pressure being measured separately in each reference section by a pressure gauge. In this case, the difference in elevation of the gauges contributes to a small extent in E and therefore the effect of ambient pressure can be neglected.

c) Pelton turbines (impulse turbines)

Other simplifications are introduced when the general formula is applied to Pelton turbines (see Figures 38 and 39; the first one is identical to Figure 5 c).

By convention, v_2 is taken as zero, elevation z_2 of the low pressure reference section is the mean elevation of all contact points of the jet axis with the Pelton jet pitch diameter and the pressure inside the housing is assumed equal to the ambient pressure, provided the housing is not pressurized.

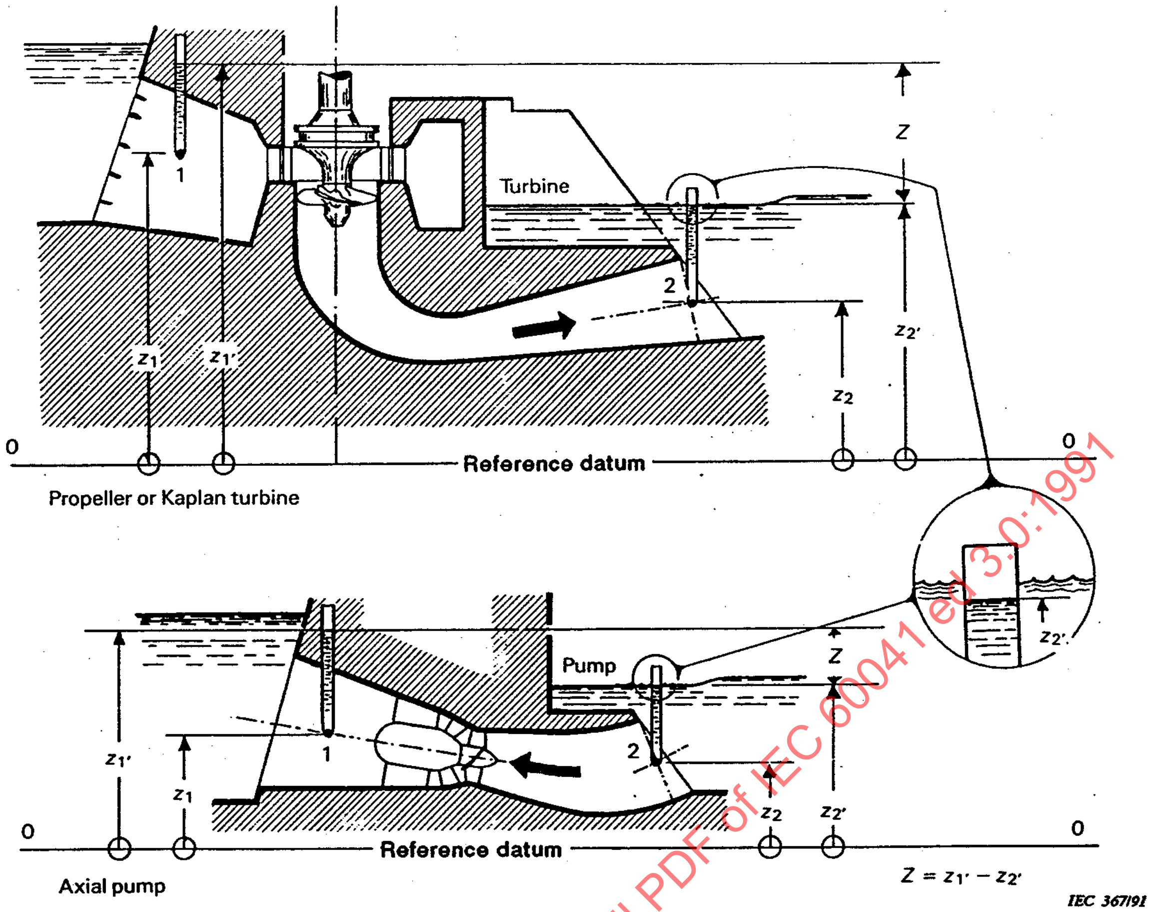


Figure 36 – Low-head machines – Determination of specific hydraulic energy of machine

Water column manometers are applied at points 1 and 2.

$$E = \overline{g}H = \frac{(p_{abs_1} - p_{abs_2})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g}(z_1 - z_2)$$

The compressibility of water is neglected because the difference of pressure between 1 and 2 is small, therefore:

$$\varrho_1 = \varrho_2 = \overline{\varrho}$$

and:

$$p_{abs_1} = \overline{\varrho} \cdot \overline{g}\,(z_{1'} - z_1) + p_{amb_{1'}}$$

$$p_{abs_2} = \overline{\varrho} \cdot \overline{g}\,(z_{2'} - z_2) + p_{amb_{2'}}$$

$$p_{amb_{1'}} - p_{amb_{2'}} = -\varrho_a \cdot \overline{g}\,(z_{1'} - z_{2'})$$

and therefore the simplified formula is:

$$E = \overline{g} \cdot (z_{1'} - z_{2'}) \cdot \left(1 - \frac{\varrho_a}{\overline{\varrho}}\right) + \frac{(v_1^2 - v_2^2)}{2} = \overline{g} \cdot Z \left(1 - \frac{\varrho_a}{\overline{\varrho}}\right) + \frac{(v_1^2 - v_2^2)}{2}$$

The water density at ambient pressure may be assumed as $\overline{\varrho}$.

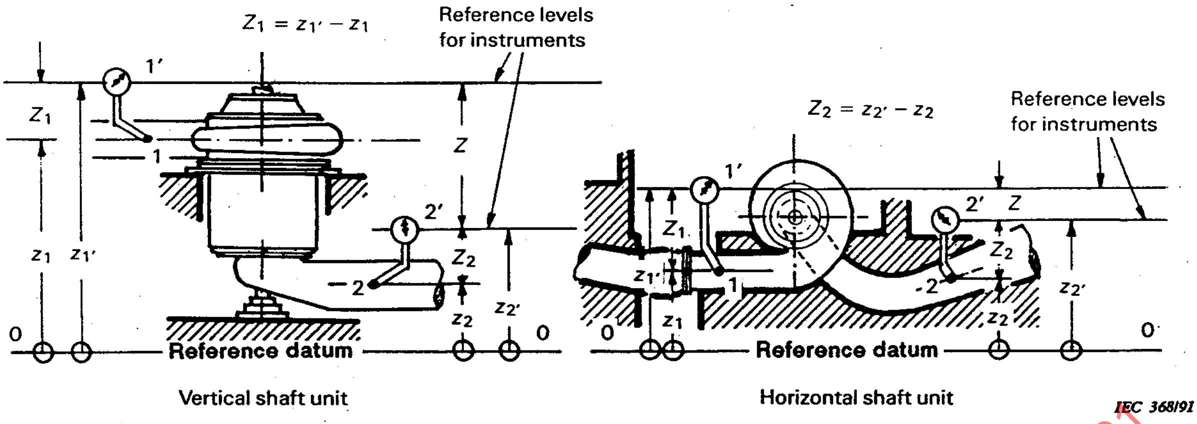


Figure 37 – Medium and high-head machines – Determination of specific hydraulic energy of machine

Pressure gauges are applied at points 1 and 2.

$$E = \bar{g}H = \frac{(p_{abs_1} - p_{abs_2})}{\bar{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \bar{g}\,(z_1 - z_2)$$

The difference in ambient pressure between 1′ and 2′ is neglected because Z is small compared to H, therefore:

$$p_{amb_{1'}} = p_{amb_{2'}} = p_{amb}$$

Since both Z_1 and Z_2 are small compared to H, it may be assumed that:

$$Z_1 \cdot \frac{\varrho_1}{\bar{\varrho}} = Z_1 \qquad Z_2 \cdot \frac{\varrho_2}{\bar{\varrho}} = Z_2$$

hence:

$$p_{abs_1} = p_{1'} + Z_1 \cdot \varrho_1 \cdot \bar{g} + p_{amb}$$ where $p_{1'}$ is the gauge pressure measured at 1′

$$p_{abs_2} = p_{2'} + Z_2 \cdot \varrho_2 \cdot \bar{g} + p_{amb}$$ where $p_{2'}$ is the gauge pressure measured at 2′

and therefore the simplified formula is:

$$E = \frac{(p_{1'} - p_{2'})}{\bar{\varrho}} + \bar{g} \cdot (z_{1'} - z_{2'}) + \frac{(v_1^2 - v_2^2)}{2} = \frac{(p_{1'} - p_{2'})}{\bar{\varrho}} + \bar{g} \cdot Z + \frac{(v_1^2 - v_2^2)}{2}$$

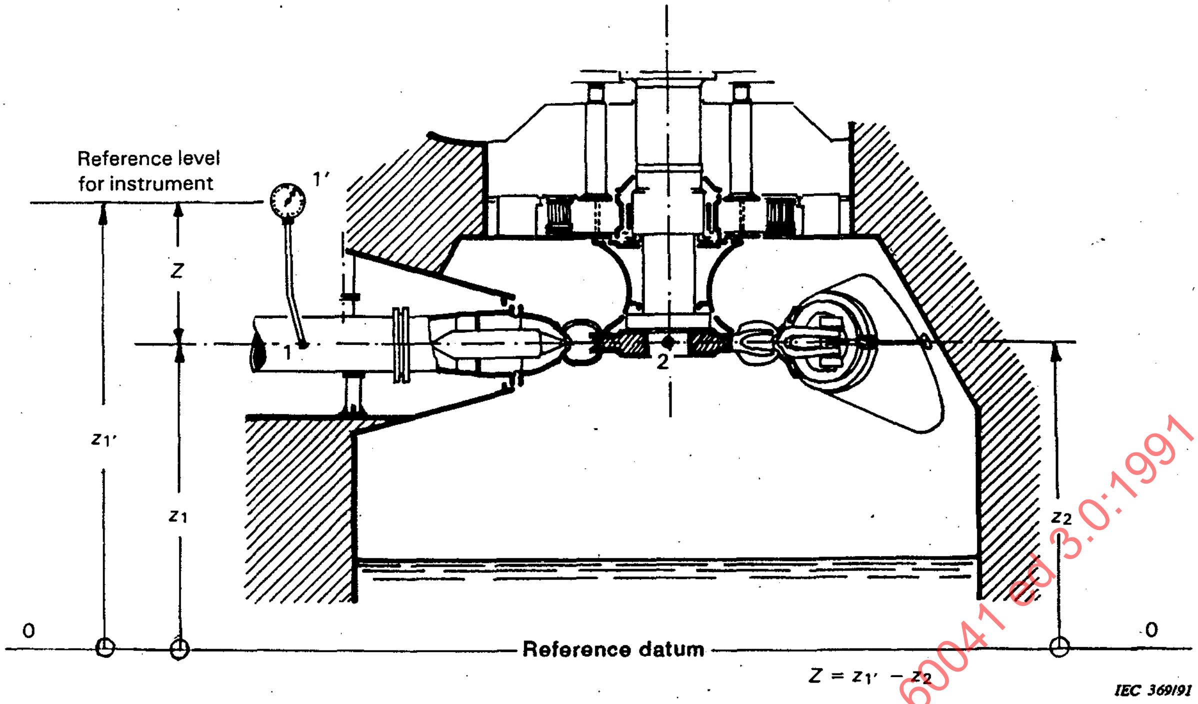


Figure 38 – Pelton turbines with vertical axis – Determination of specific hydraulic energy of machine

Case of non-pressurised housing.

It is conventionally assumed that the low pressure reference section corresponds to the plane at elevation z_2 and that the pressure inside the housing is equal to the ambient pressure in case of non-pressurised housing.

$$E = \overline{g} \cdot H = \frac{(p_{abs_1} - p_{abs_2})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g} \cdot (z_1 - z_2)$$

The difference in ambient pressure between 1′ and 2 is neglected because Z is small compared to H, therefore:

$$p_{amb_{1'}} = p_{amb_2} = p_{amb}$$

For the same reason it is assumed:

$$Z \cdot \frac{\varrho_1}{\overline{\varrho}} = Z$$

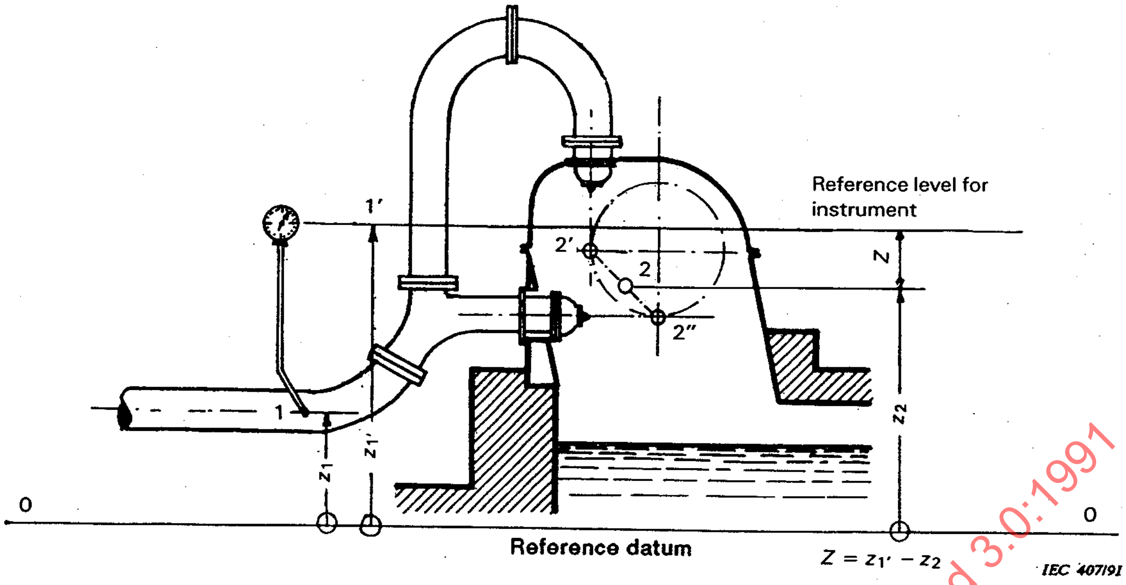
hence:

$$p_{abs_1} = p_{1'} + Z \cdot \varrho_1 \cdot \overline{g} + p_{amb}$$ where $p_{1'}$ is the gauge pressure measured at 1′

$$p_{abs_2} = p_{amb}$$

As $z_1 = z_2$ and assuming $v_2 = 0$, the simplified formula is:

$$E = \frac{p_{1'}}{\overline{\varrho}} + \overline{g} \cdot (z_{1'} - z_2) + \frac{v_1^2}{2} = \frac{p_{1'}}{\overline{\varrho}} + \overline{g} \cdot Z + \frac{v_1^2}{2}$$



Note. – In case of multiple nozzles the reference elevation z_2 is chosen as the average of the elevations of the points of contact (2' and 2" in the sketch).

Figure 39 – Pelton turbines with horizontal axis – Determination of specific hydraulic energy of machine

Case of non-pressurised housing: the pressure inside the housing is conventionally assumed as equal to the ambient pressure.

$$E = \overline{g} \cdot H = \frac{(p_{abs_1} - p_{abs_2})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g} \cdot (z_1 - z_2)$$

The difference in ambient pressure between 1' and 2 is neglected because Z is small compared to H, therefore:

$$p_{amb_{1'}} = p_{amb_2} = p_{amb}$$

For the same reason it is assumed:

$$Z \cdot \frac{\varrho_1}{\overline{\varrho}} = Z$$

hence:

$$p_{abs_1} = p_{1'} + (z_{1'} - z_1) \cdot \varrho_1 \cdot \overline{g} + p_{amb}$$ where $p_{1'}$ is the gauge pressure measured at 1'

$$p_{abs_2} = p_{amb}$$

Assuming $v_2 = 0$, the simplified formula is:

$$E = \frac{p_{1'}}{\overline{\varrho}} + \overline{g} \cdot (z_{1'} - z_2) + \frac{v_1^2}{2} = \frac{p_{1'}}{\overline{\varrho}} + \overline{g} \cdot Z + \frac{v_1^2}{2}$$

11.2.5.3 Measurements using water levels

11.2.5.3.1 Measuring installation

Whenever the lack of pressure taps prohibits the measurement of pressure, other measuring sections must be chosen. This situation may happen at the low pressure side of any machine, but only to low head machines at the high pressure side.

Figure 40 referring to low head machines shows the evaluation of the specific hydraulic energy from a measurement of the water levels. Gate chambers may be used as water column manometers. In this case, the requirement for the size of pressure taps is not met and errors may arise from dynamic effects. When this measuring technique is used, it shall be checked that the free water surface is not affected by high velocities or level fluctuations. Measurement of water level shall be made at two or more locations and the results shall comply with the requirements of 11.4.2.

11.2.5.3.2 Restrictions

The flow between the reference section and the corresponding section, where the water level is measured, shall be free of perturbing structures, such as a trash rack. If this is not possible, the calculation of the specific hydraulic energy has to be agreed upon, prior to the test.

The low pressure side measuring section 2′ should be as close as possible to the draft tube opening (see Figure 40).

For such measurement the water level should be measured directly above 2′ and the surrounding water surface should be free of jump, vortex and heavy back current. Water level fluctuations may be damped by measuring wells or stilling boxes (see 11.5.4.8). To evaluate the mean velocity, the walls of the draft tube are supposed to extend up to section 2′, delineating the fictitious area of the section.

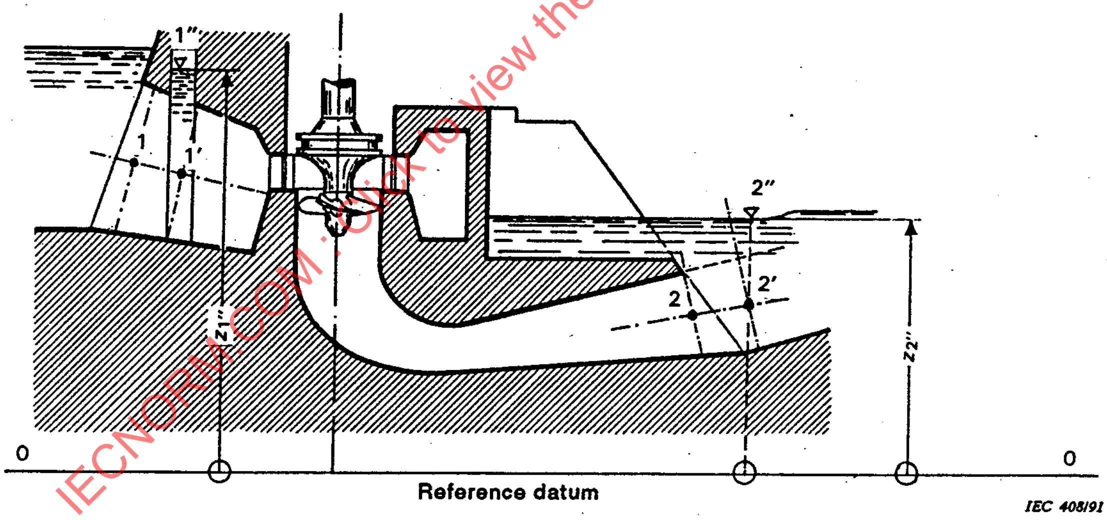


Figure 40 – Low-head machines – Determination of specific hydraulic energy of the machine using water levels

$$E = \overline{g} \cdot H \frac{(p_{\text{abs}_1} - p_{\text{abs}_2})}{\overline{\varrho}} + \frac{(v_1^2 - v_2^2)}{2} + \overline{g} \cdot (z_1 - z_2)$$

Sections 1′ and 2′ are chosen as measuring sections.

$$E = \overline{g} \cdot H = \frac{(p_{\text{abs}_{1'}} - p_{\text{abs}_{2'}})}{\overline{\varrho}} + \frac{(v_{1'}^2 - v_{2'}^2)}{2} + \overline{g} \cdot (z_{1'} - z_{2'}) \pm E_{\text{L}1-1'} \pm E_{\text{L}2-2'}$$

The loss between 1 and 1′, $E_{\text{L}1-1'}$, is added for a turbine and subtracted for a pump with the situation described in the sketch above. The contrary is valid for the loss between 2 and 2′, $E_{\text{L}2-2'}$.

The compressibility of water is neglected because the difference of pressure between 1′ and 2′ is small. Therefore:

$$\varrho_{1'} = \varrho_{2'} = \overline{\varrho}$$

The simplified formula becomes:

$$E = \overline{g} \cdot (z_{1''} - z_{2''}) \left(1 - \frac{\varrho_a}{\overline{\varrho}}\right) + \frac{(v_{1'}^2 - v_{2'}^2)}{2} \pm E_{\text{L}1-1'} \pm E_{\text{L}2-2'}$$

The water density at ambient pressure may be assumed as $\overline{\varrho}$.

11.3 *Determination of the net positive suction specific energy*

11.3.1 *Definition*

The net positive suction specific energy is referred to the low pressure side of the machine and it is in direct relation with the cavitation phenomenon. Its definition and the general formula for its determination are given in 2.3.6.9.

Its measurement may be affected by practical circumstances, in the same way as the specific hydraulic energy of the machine. Requirements in 11.2 shall also be considered for measurement of the net positive suction specific energy.

11.3.2 *Simplified formulae*

As long as the pressure can be measured in the low pressure reference section, the general formula is of immediate application and valid for both operating modes, pump and turbine (see Figure 7).

When the measuring section is shifted from the low pressure reference section, requirements in 11.2.1.3 shall be carefully considered in the case of a low-head machine since the kinetic energy, and eventually correlated losses, are significant.

Under particular circumstances, one may be forced to evaluate net positive suction specific energy from tailwater level measurements, see Figure 41. In this case, requirements in 11.2.5.3 shall be applied.

Figure 41 shows the determination of the net positive suction specific energy when the pressure in section 2 cannot be measured and the energy losses between sections 2 and 2′ cannot be neglected.

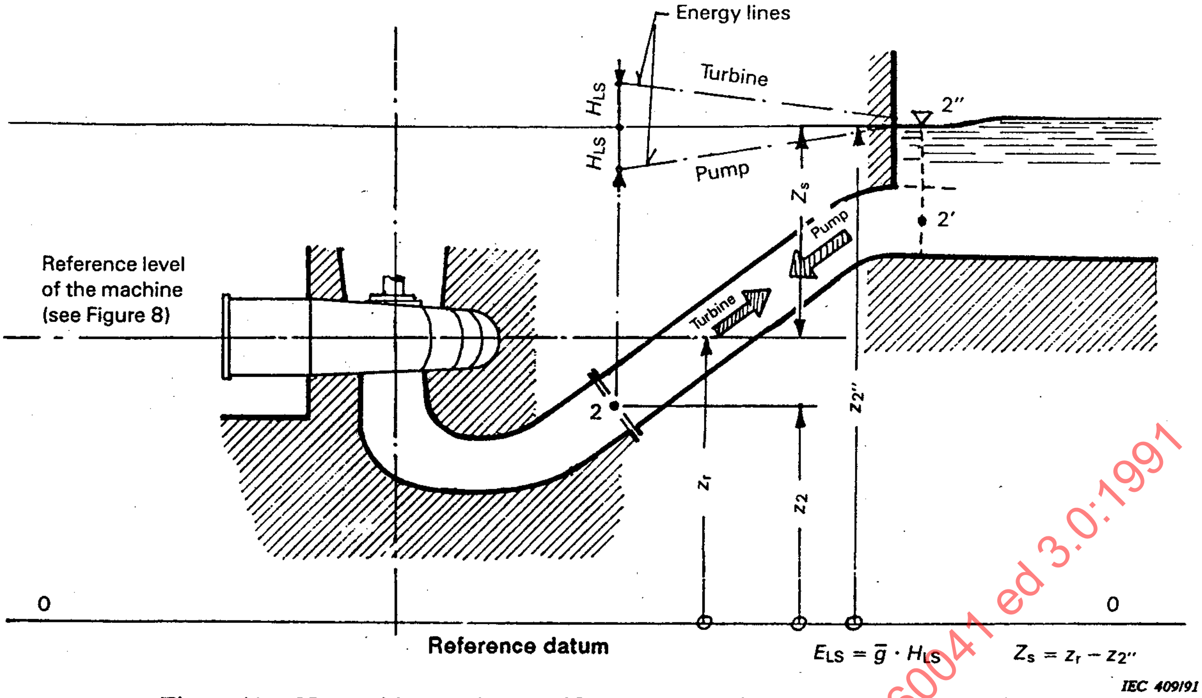


Figure 41 – Net positive suction specific energy, $NPSE$, and net positive suction head, $NPSH$ ($E_{LS} \neq 0$)

$$NPSE = g_2 \cdot NPSH = \frac{(p_{abs_2} - p_{va})}{\varrho_2} + \frac{v_2^2}{2} + g_2 \cdot (z_r - z_2)$$

The pressure should be measured inside the draft tube (point 2) (see 2.3.6.9); in this case the above formula is valid for both turbines and pumps.

If it is not possible to measure the pressure inside the draft tube, the net positive suction specific energy, $NPSE$, can be calculated from the tailwater level (see 11.2.5.3).

Taking into account the specific hydraulic energy losses between sections 2 and 2′, the formula becomes:

$$NPSE = g_2 NPSH = \frac{(p_{amb_{2''}} - p_{va})}{\varrho_2} + \frac{v_{2'}^2}{2} - g_2(z_r - z_{2''}) \pm E_{LS}$$
$$= \frac{(p_{amb_{2''}} - p_{va})}{\varrho_2} + \frac{v_{2'}^2}{2} - g_2 \cdot Z_S \pm E_{LS}$$

+ for turbines, – for pumps

11.4 *Pressure measurements*

11.4.1 *Choice of pressure measuring section*

Special attention must be given to the location of the measuring section. There should be a minimum of disturbance to the flow. Sections where the velocity pattern is distorted by an elbow, valve or other flow disturbances outside of the hydraulic machine should be replaced if possible by other measuring sections with better flow conditions.

The plane of the measuring section shall be normal to the average direction of flow. Its area, which is required for computing the mean water velocity, must be readily measurable.

The measuring section should preferably be arranged in a straight conduit section (which may also be slightly convergent or divergent) extending three diameters upstream and two diameters downstream from the measuring section and free from any water extraction or injection active during the test. Closed branches shall be more than five times their diameter away from the measuring section.

11.4.2 *Number and location of pressure taps*

Generally, for any form of section at least two pairs of opposite pressure taps shall be used. With favourable conditions the number of taps can be reduced by mutual agreement. In the case of circular sections the four pressure taps shall be arranged on two diameters at right angles to each other. The taps shall no be located at or near the highest point of the measuring section in order to avoid air pockets and not near the lowest point because of the risk of dirt obstructing the taps. In the case of non-circular, in most cases rectangular sections, the taps shall not be located near the corners. If taps have to be arranged at the top or bottom of a section special care has to be observed to avoid disturbances due to air or dirt.

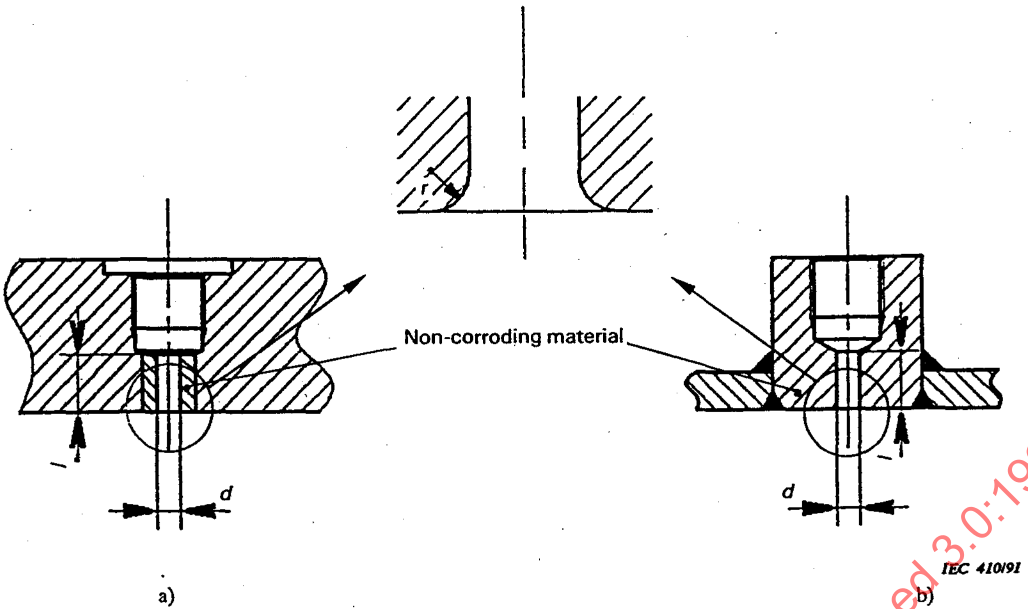
Individual mean pressure measurements around the measuring section should not differ from one another by more than 0,5% of the specific hydraulic energy of the machine or 20% of the specific kinetic energy calculated from the mean velocity in the measuring sections. If this requirement is not fulfilled and if it is not possible to correct the faulty tap, a mutual agreement should be reached to eliminate the faulty tap or to select another location or to accept this deviation.

11.4.3 *Pressure taps*

Pressure taps should be located in inserts of non-corroding material. Figure 42a and 42b show typical inserts which must be installed flush with the wall of conduit.

The cylindrical bore of the pressure tap shall be 3 mm to 6 mm in diameter and have a minimum length of at least twice the diameter. It must be perpendicular to the conduit wall and free of all burrs or irregularities which could cause local disturbances. Preferably the edges of the openings should be provided with a radius $r \leq d/4$ smoothly joining the flow passage. The only purpose of this rounding is to eliminate any possible burrs.

The surface of the conduit shall be smooth and parallel with the flow in the vicinity of the bore for at least 300 mm upstream and 100 mm downstream. In concrete passageways, the pressure taps shall be at the centre of a stainless steel or bronze plate at least 300 mm in diameter flush with the surrounding concrete.



d = 3 mm à 6 mm $\ell \geq 2d$ $r \leq d/4$

Figure 42 – Examples for pressure taps

11.4.4 *Gauge piping*

Pressure taps may be manifolded (see Figure 43), but each tap shall be separately valved so that it can be read individually. The diameter of the connecting piping shall be at least twice that of the tap, not less than 8 mm and not more than 20 mm. The diameter of the manifold shall be at least three times the diameter of the tap. Special precautions shall be taken when pipes are embedded in concrete. Connection pipes should, if possible, be of equal length, slope upward to the gauge or manometer with no intermediate high spots where air may be trapped. Valved shall be provided at all high points for flushing out air. Transparent plastic tubing is available for a wide pressure range and is useful in disclosing the presence of air bubbles. No leaks shall be permitted in the gauge connection.

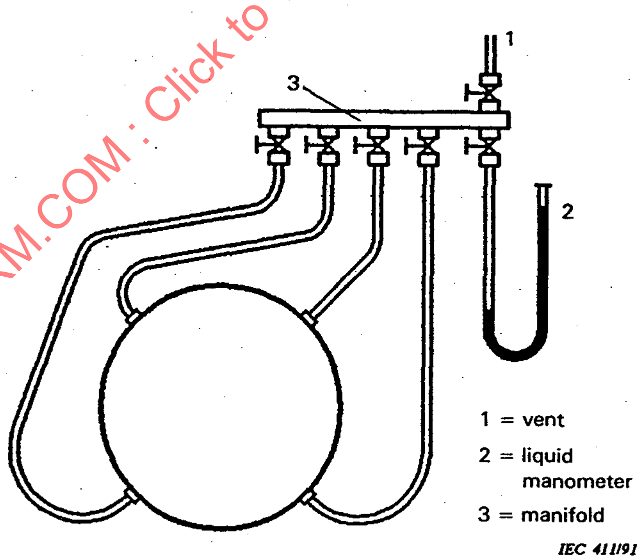


Figure 43 a – Pressure taps connected through separate connecting pipes to manifold

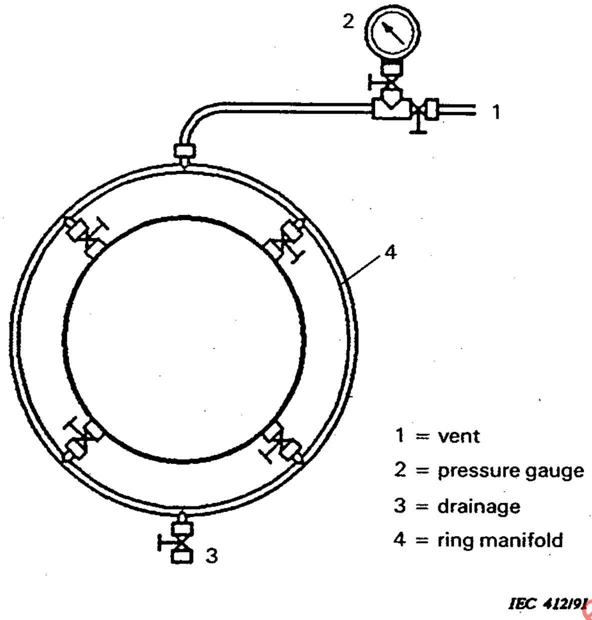


Figure 43 b – Pressure taps connected through ring manifold to pressure gauge

11.4.5 *Damping devices*

When the pressure to be measured is fluctuating (see 5.2.1), it may be difficult to obtain correct readings on a pressure manometer. In order to improve such conditions, suitable damping shall be provided. However, this requires special care, because a proper damping device depending on viscous resistance should be fully symmetrical with equal resistance to flow in both directions. A capillary tube with a 1 mm bore and a suitable length (e.g. 50 mm to 150 mm) is recommended for this purpose because it provides linear damping of irregular pressing pulsations. Additional damping may be obtained from an air or surge chamber connected to the pressure line ahead of the gauge. Using an orifice plate is not recommended because it may introduce an error due to non-linear damping. A valved bypass around any damping device should be provided an kept open except for the short time during which readings are taken. Bending or pinching the connecting pipes or inserting any non-symmetrical throttling device is not permitted.

11.4.6 *Measuring apparatus*

Liquid column manometers and dead weight manometers are considered as primary instruments.

11.4.6.1 Liquid column manometers

Liquid column manometers are used to measure small pressures or small pressure differences (less than 3×10^5 Pa). In field tests mostly water or mercury column manometers are used (see Figure 44a, b, c and d). In some cases other liquids of known density may be used.

The tube of a water column manometer shall have a minimum inside diameter of 12 mm in the measuring range to minimize capillary effects. With mercury manometers, this diameter shall be at least 8 mm.

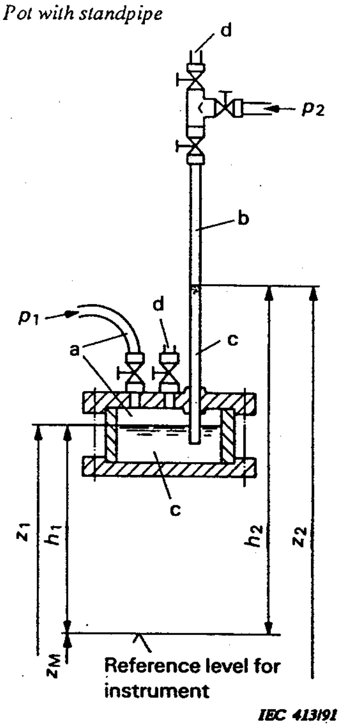
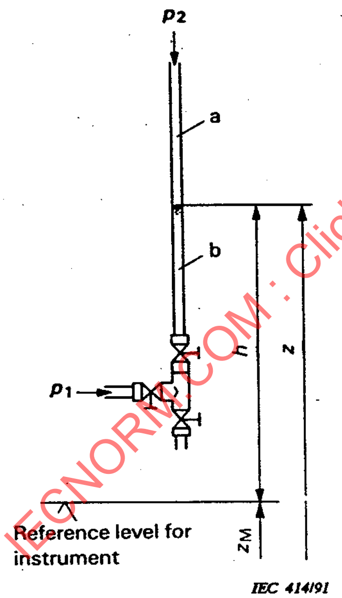
Manometer	Gauge pressure $p_2 = p_{amb}$	Differential pressure $p_2 \neq p_{amb}$
	$p = p_{abs} - p_{amb}$	$\Delta p = p_1 - p_2$
a) *Pot with standpipe* 	p_M = pressure at the reference level of instrument $p_M = g[\varrho_{Hg}(h_2 - h_1) + \varrho h_1]$ $h_1 = z_1 - z_M$ $h_2 = z_2 - z_M$ a = water b = air c = mercury d = vent	$\Delta p = g(\varrho_{Hg} - \varrho) \cdot (h_2 - h_1)$ $\Delta p = g(\varrho_{Hg} - \varrho) \cdot (z_2 - z_1)$ a = water b = water c = mercury d = vent
b) *Water column (standpipe)* 	$p_M = g \cdot \varrho \cdot h$ $h = z - z_M$ a = air b = water	Not applicable

Figure 44 a and b – Liquid column manometers (values of ϱ, ϱ_{Hg} and ϱ_a are given in Appendix E)

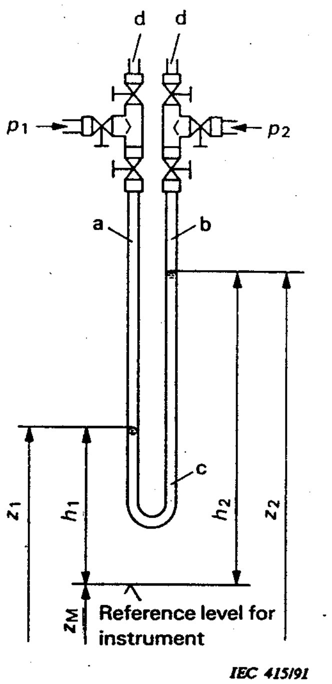
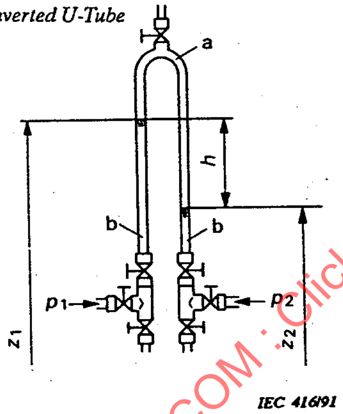
Manometer	Gauge pressure $p_2 = p_{amb}$	Differential pressure $p_2 \neq p_{amb}$
	$p = p_{abs} - p_{amb}$	$\Delta p = p_1 - p_2$
c) *U-Tube* 	p_M = pressure at the reference level of instrument $p_M = g[\varrho_{Hg}(h_2 - h_1) + \varrho h_1]$ $h_1 = z_1 - z_M$ $h_2 = z_2 - z_M$ a = water b = air c = mercury d = vent	$\Delta p = g(\varrho_{Hg} - \varrho) \cdot (h_2 - h_1)$ $\Delta p = g(\varrho_{Hg} - \varrho) \cdot (z_2 - z_1)$ a = water b = water c = mercury d = vent
d) *Inverted U-Tube* 	Not applicable	$\Delta p = gh \cdot (\varrho - \varrho_a)$ $h = z_1 - z_2$ a = air, compressed air or vacuum b = water

Figure 44 c and d – Liquid column manometer (values of ϱ, ϱ_{Hg} and ϱ_a are given in Appendix E)

11.4.6.2 Dead weight manometers

Dead weight manometers are commonly used for pressure higher than 2×10^5 Pa. Dead weight manometers may be of the simple or differential piston types. The effective piston diameter d_e of the former may be determined as the arithmetic mean value of the piston diameter d_p and bore diameter d_b and used for pressure calculation without further calibration:

$$d_e = \frac{d_b + d_p}{2} \quad \text{if} \quad \frac{d_b - d_p}{d_b + d_p} \leq 0,001$$

The pressure p measured at the lower end of the piston of a dead weight manometer loaded with mass m is:

$$p = \frac{4gm}{\pi d_e^2}$$

Dead weight manometers must fulfil the following conditions:

- The effective piston diameter d_e must be determined within the relative uncertainty

$$f_{de} \leq 5 \times 10^{-4}$$

For example, the effective piston diameter d_e of 10 mm must be determined with an accuracy of at least 5×10^{-3} mm.

- The friction between piston and bore must be eliminated by rotating the piston slowly ($0,25\ s^{-1} \leq n \leq 2\ s^{-1}$).
- The cylinder must be filled with a suitable fluid, commonly by oil of low viscosity ($\nu \simeq 10^{-5}\ m^2s^{-1}$).
- An oil reserve of sufficient volume in connection with the cylinder to replenish the unavoidable oil losses between bore and piston must be provided.
- If the weight plate is rotating with the piston the weights imposed on this plate must be balanced to avoid oscillation of the piston.
- The dead weight manometer is to be placed on a solid base. The axis of the piston must be vertical.
- All the acting masses (weights, piston, weight plate, etc.) must be calibrated.

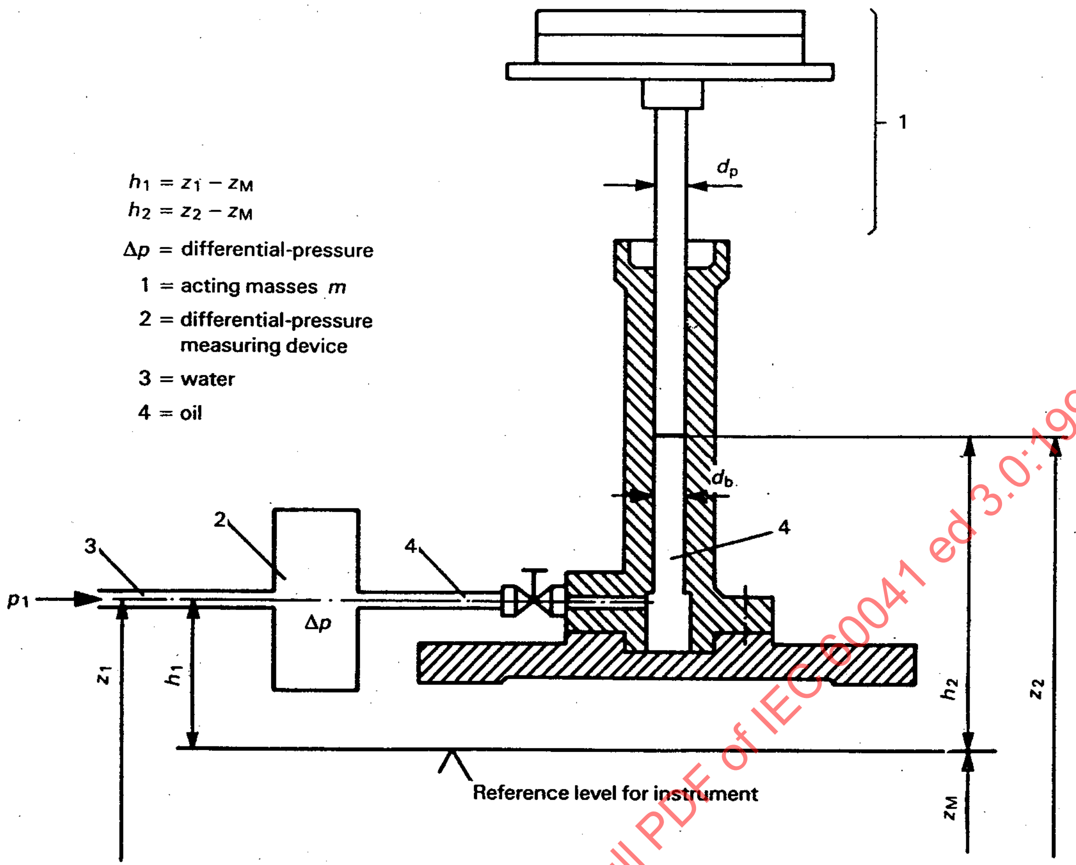
It is good practice to determine the effective piston area indirectly by checking against a static pressure at zero discharge (see 11.4.7.1).

For stabilisation of the dead weight manometer it is recommended to use a setup with a compensating device, such as:

- A dead weight manometer, which is connected in series with a differential-pressure measurement device (e.g. transducer or liquid manometer), see Figure 45 a.
- A dead weight manometer which is connected in parallel with a force measurement device (e.g. liquid column, spring, load cell), see Figure 45 b.

The correction curve due to these setups shall be determined either by checking them against a calibrated dead weight manometer without compensating devices or by loading the weight plate at constant pressure additionally with small weights of appropriate mass, so that the indicator of the compensator shows zero.

The sensitivity of a dead weight manometer in good condition is less than 100 Pa.

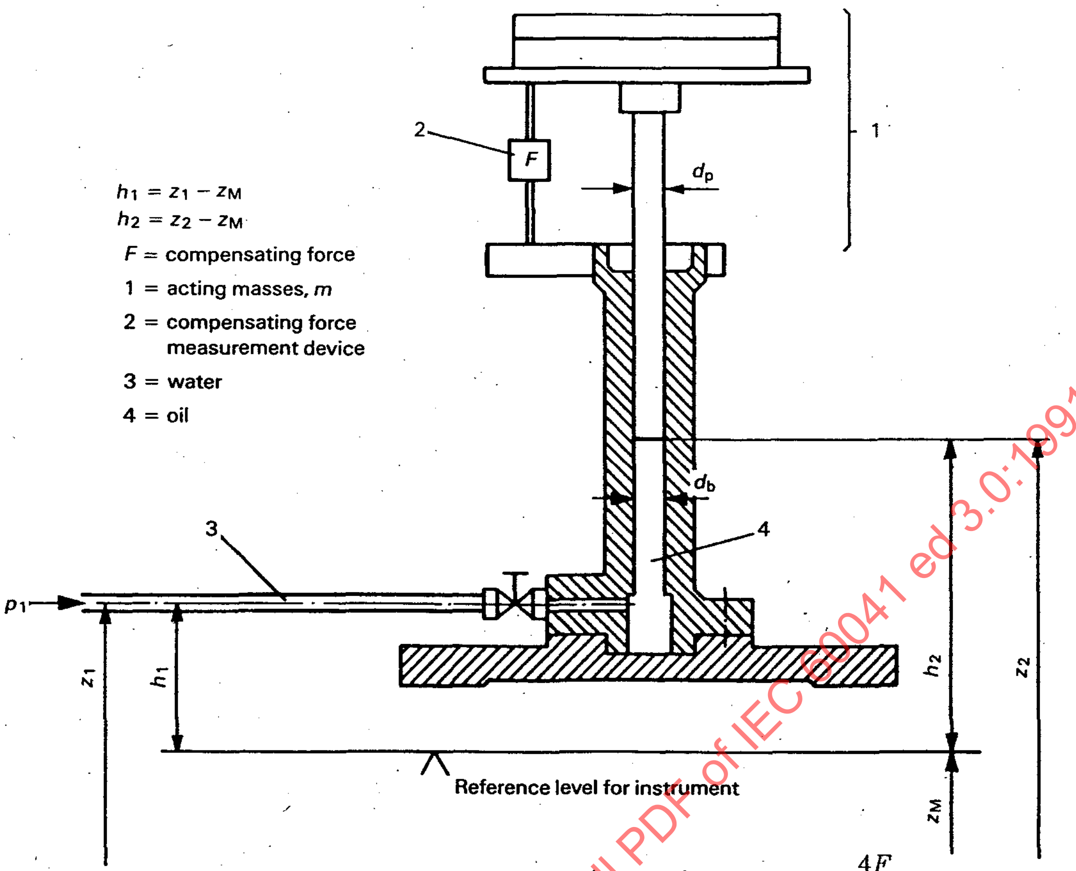


$$p_M = p_1 + \varrho \cdot g \cdot h_1 = p + \varrho_{oil} \cdot g \cdot (h_2 - h_1) + \varrho \cdot g \cdot h_1 + \Delta\Delta p$$

where:

$$p = \frac{4 \cdot m \cdot g}{\pi \cdot d_e^2} \quad \text{with:} \quad d_e = \frac{d_b + d_p}{2}$$

Figure 45 a – Dead weight manometer with stabilization by differential pressure measurement (transducer or liquid manometer)



$$p_M = p_1 + \varrho \cdot g \cdot h_1 = p + \varrho_{oil} \cdot g \cdot (h_2 - h_1) + \varrho \cdot g \cdot h_1 + \frac{4F}{\pi d_e^2}$$

where:

$$p = \frac{4 \cdot m \cdot g}{\pi \cdot d_e^2} \quad \text{with:} \quad d_e = \frac{d_b + d_p}{2}$$

Figure 45 b – Dead weight manometer with stabilization by force measurement (liquid column, spring, load cell, weighbeam)

11.4.6.3 Spring pressure gauge

This type of gauge uses the mechanical deflection of a loop of tubing (plain or spiral) or a diaphragm to indicate pressure. Depending on the pressure to be measured the corresponding range for a spring pressure gauge has to be selected. It may be used by mutual agreement provided the gauge is of suitable precision and used within its optimum measuring range (usually from 60 % to 100 % of full scale) as well as calibrated on site against a reliable standard before and after the test.

11.4.6.4 Pressure transducers

Pressure transducers are electromechanical devices in which mechanical effects produced by pressure are converted into electrical signals.

Depending on the pressure to be measured the corresponding range for the pressure transducer has to be selected.

Some advantages in using pressure transducers are:

- Ease of integration into electronic data acquisition systems.
- They usually require negligible fluid flow through pressure taps thus providing rapid and accurate response.
- Average values of fluctuating pressures or pressure differences as well as records of transient phenomena are easily obtained using readily available electronic equipment.

The pressure transducers should have the following characteristics:

- sufficient calibration stability;
- high repeatability, negligible hysteresis;
- low zero shift and low temperature sensitivity.

Operation with and without filters on the electronic equipment should be conducted to ascertain the absence of bias when filters are operating.

The complete pressure transducer system must be calibrated on site under the pressure to be encountered during the test. The accuracy of a transducer will be determined by the accuracy of the calibration. The calibration can be done by a suitable pressure gauge, for example a dead weight manometer, provided for checking the measurements by the transducer systems at any time during the test (see 11.4.7.3).

Another possibility is to install two similar transducer systems in parallel and to take simultaneous readings during the test. The transducer systems are checked before and after the test and when the two systems show different readings, a comparison with a suitable pressure gauge is recommended.

Whenever a fast response of the pressure transducer is needed, the instrument shall be connected directly to the pressure line and all the calibration system shall be shut off during the measurements to preserve the dynamic quality of the transducers.

11.4.7 *Checking of pressure gauges*

11.4.7.1 Comparison of the gauge pressure with the static pressure at zero discharge

Before and after the acceptance test, the readings of the pressure gauge p_M shall be compared with the static pressure for zero discharge. If there is a surge tank, several hours may be required to stabilize the system.

The checking system is made by comparing (see Figure 46):

a) the absolute static pressure

$$p_{abs_1} = p_{amb_0} + \overline{\varrho}\,\overline{g}\,(z_0 - z_1) = p_{amb_0} + \overline{\varrho}\,\overline{g}\,Z_0$$

and

b) the pressure measurement

$$p_{abs_1} = p_M + p_{amb_M} - \varrho_1 g_1 (z_1 - z_M) = p_M + p_{amb_M} - \varrho_1 g_1 Z_1$$

where:

p_M is the gauge pressure indicated by the manometer

$\overline{\varrho} = (\varrho_0 + \varrho_1)/2$

$\overline{g} = (g_0 + g_1)/2$

It is generally assumed that $\overline{g} = g_1$.

In the case where $p_{abs_1} \leq 4 \cdot 10^5$ Pa, it can be written: $\overline{\varrho} = \varrho_1$.

The difference between the two above mentioned pressure measurements *a*) and *b*) of p_{abs_1} shall be less than 0,1 %.

The accuracy depends almost entirely on the accuracy with which the elevation z_o and z_1 and the mean water temperature have been determined. The physical properties of water (mean density, etc.) are taken from data given in Appendix E except when density is determined by measurement at site.

With the use of an already calibrated pressure measuring device the procedure given in this paragraph can be used to determine the water density (see 9.2.4).

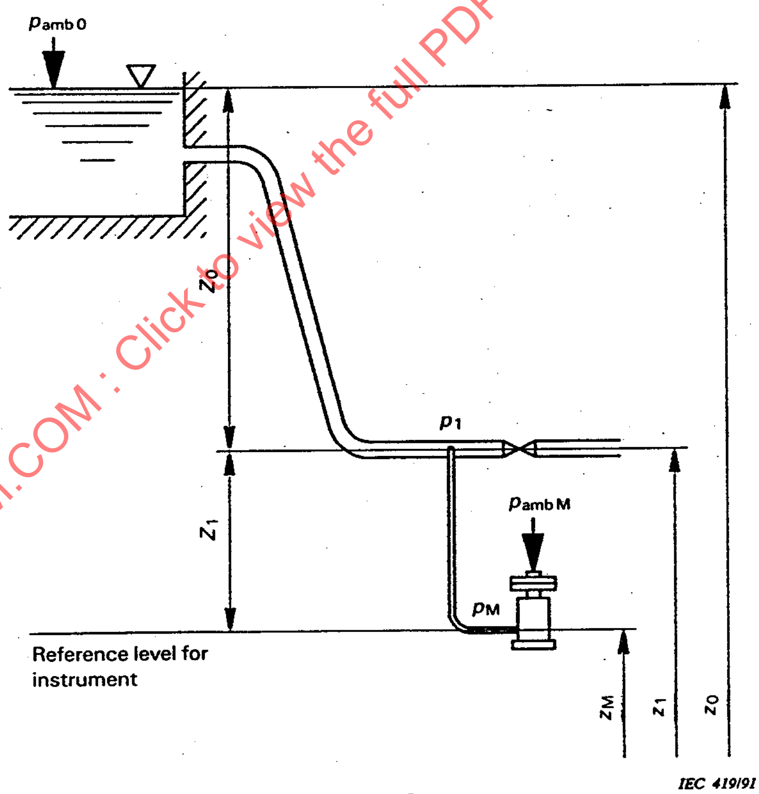


Figure 46 – Checking of a manometer

11.4.7.2 Comparison with primary measuring instruments

Spring gauges and pressure transducers must be checked at least over the measuring range during the test against primary instruments (see 11.4.6) or by comparison with water levels.

11.4.7.3 Running calibration

A possibility of comparison with primary instruments between each run with a permanent installation, the so-called running calibration, is shown in Figure 47.

The spring pressure gauge or the pressure transducer to be calibrated is connected in parallel with a deadweight manometer (or with any other primary device) to the penstock through an interface vessel, so that before and after any run during the test, all parties may check that the gauge readings or recorded measurements are in agreement with the primary device. The interface vessel permits operation of the dead weight manometer with oil as required while providing for operation of the gauge or the transducer with a medium (oil) at constant temperature.

The two modes of operation, pressure measurement with the gauge or the transducer and calibration of the instruments with the dead weight manometer, are obtained by switching valves. For pressure measurement, valves A and C are open, valves B, D, E and F are closed. For instrument calibration, valves A, C and D are closed and E is open, valve F and sight glass are only used for checking the point of zero gauge pressure. Valve D can be used to either release any trapped air from the interface vessel or fill the vessel and pressure line with oil from a portable tank and valve B to either relieve pressure in the vessel or adjust the interface level to the reference elevation.

If:

p_T is the test pressure,

p_L is a pressure just below expected test pressure,

p_H is a pressure just above expected test pressure,

therefore: $p_L < p_T < p_H$.

The procedure to be followed is:

1) Pre-calibrate the gauge/transducer immediately before the test run. This calibration does not need to include the point of zero gauge pressure, or to cover the full instrument range; it must, however, include pressure p_L and pressure p_H. The applied weights and respective gauge readings are recorded, but the gauge/transducer is not adjusted.

2) Measure the test pressure p_T recorded in the usual way.

3) Post-calibrate the gauge/transducer. This is a repeat of the procedure of step 1 immediately following the measurements.

If the elapsed time between consecutive runs is short, step 3 of the previous run can be considered to be step 1 of the next run.

The true test pressure is determined by linear interpolation between the average values of p_L and p_H obtained in steps 1 and 3.

Should the differences between the averages obtained in step 3 and the ones in step 1 exceed acceptable limits (see 11.6), the causes of such differences shall be determined and eliminated, and the run repeated.

The estimated uncertainty of this method is of the same order as for the primary instrument.

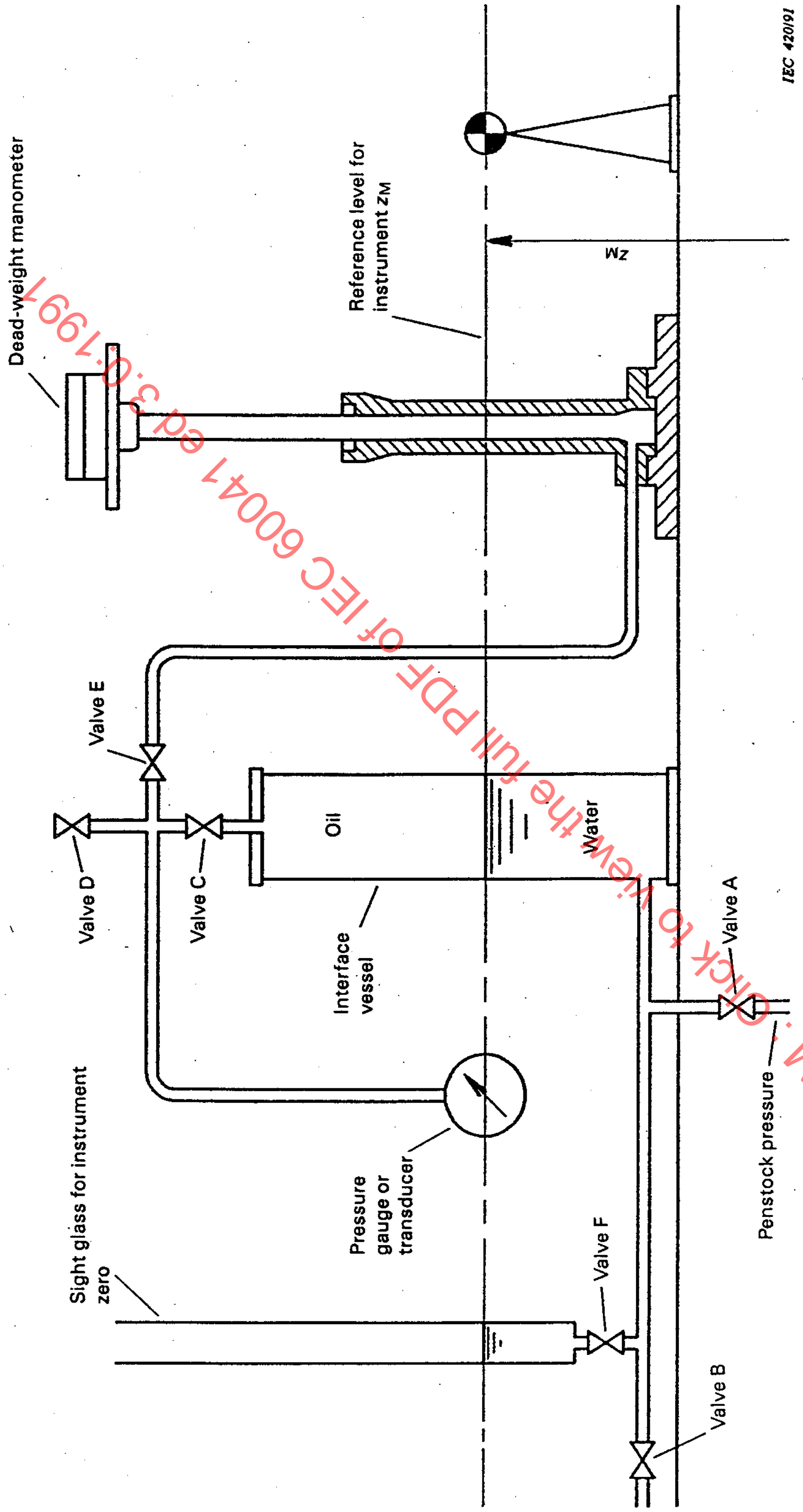


Figure 47 – Running calibration of spring pressure gauge or pressure transducer

11.4.8 *Vacuum measurements*

11.4.8.1 General

For tests carried out on hydraulic machines, vacuum measurements are rarely required. Such measurements may, for example, be required in installations without a characteristic draft tube.

11.4.8.2 Gauge piping for vacuum measurements

The gauge piping shall either be completely filled with water or, if air is used, shall be transparent to permit observation of the water level, if present. Such pipes, when filled with water, shall be flushed carefully and frequently between runs, to remove any air coming out of the solution or entering through the pressure tap and to maintain the water in the gauge piping at the same temperature as in the conduit. All piping and connections shall be airtight. Flexible pipes may be used as gauge pipes only if they cannot be collapsed by ambient pressure.

11.5 *Free water level measurements**

11.5.1 *General*

If it is not possible to measure the pressure in a closed section in agreement with 11.4 at the high and/or low pressure side of the machine, free water level measurement is necessary (see 11.2.5.3)

Free water levels have to be measured also in case of discharge measurements by:

- current-meters in open channels (see 10.2);
- weir (see 10.6);
- volumetric method (see 10.8).

11.5.2 *Choice of water level measuring sections*

The measuring section for the determination of a free water level shall be chosen to satisfy the following requirements:

a) The flow shall be steady and free of disturbances. Sections where the flow velocity is influenced by an elbow or by other irregularities should be avoided.

b) The area used to determine the mean water velocity shall be accurately defined and readily measurable.

11.5.3 *Number of measuring points in a measuring section*

Measurement of free water levels shall be obtained for at least two points in every measuring section or in each passage of a multiple passage measuring section and the average of the readings is to be taken as the free water level**.

*See also ISO 4373.

**In the case of current-meter measurements in multiple passages the average of the readings for each passage has to be taken separately as the area of each passage depends on the free water level.

11.5.4 *Measuring apparatus*

Commonly, free water levels are measured from a reference level for the instrument z_M.

If the measuring section is inaccessible, the free water level can be measured by means of pressure measuring apparatuses or column manometers (see 11.5.4.6).

11.5.4.1 Plate gauge

A plate gauge, consisting of a metal disk suspended from a flexible steel tape, will be found convenient to determine the level in relation to the reference level for the instrument z_M, at the measuring section (Figure 48).

11.5.4.2 Point or hook gauge

Point or hook gauges may be used to determine the level of calm water, for example, inside stop-log grooves, measuring wells or stilling boxes (Figure 49).

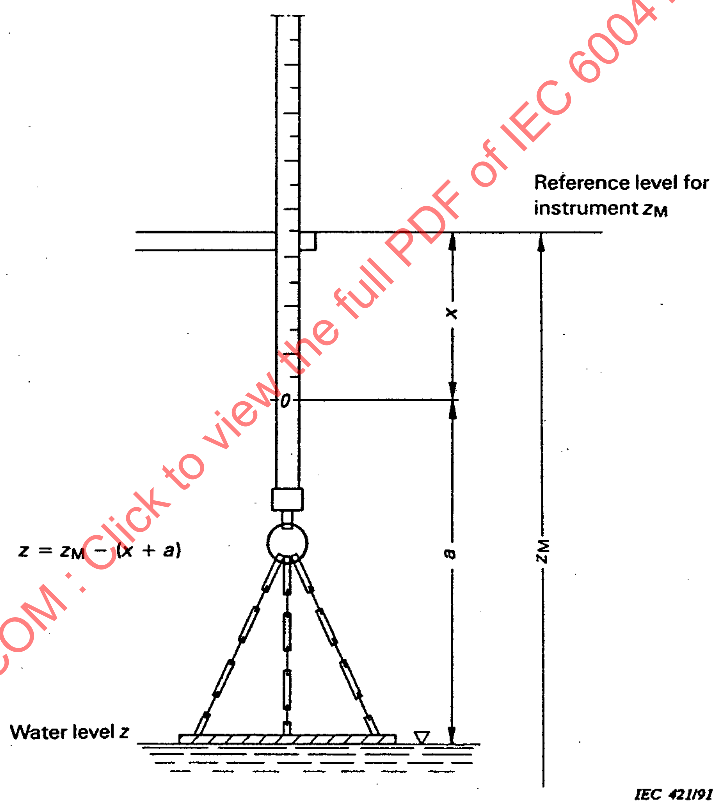


Figure 48 – Plate gauge

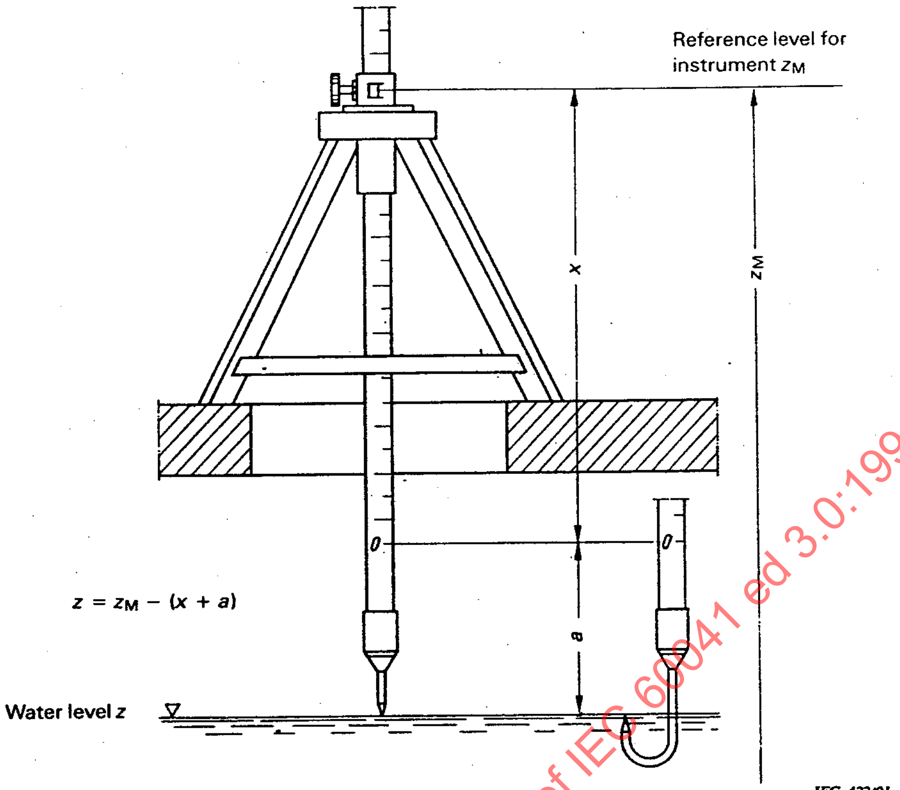


Figure 49 – Point and hook gauges

11.5.4.3 Float gauge

Float gauges, properly calibrated and in good working order, may be used and recommended where the water level is variable. The float diameter should be at least 200 mm. Such gauges should be sensitive within 5 mm when manually displaced from the true reading (resolution of $\pm 0,005$ m).

A float diameter of 200 mm is considered adequate for use with stilling boxes 250 mm square which often is the largest size suitable for installation in stop-log grooves.

11.5.4.4 Staff gauge

Fixed staff gauges, installed flush with the wall of the measuring section may be used where a resolution of $\pm 0,01$ m is sufficient.

11.5.4.5 Immersible pressure transducers

To determine the water level in measuring wells immersible transducers can be used. The transducer indication has to be checked when no water is flowing.

11.5.4.6 Liquid column manometers

If measuring sections are inaccessible, the free water level may be determined by means of two or more liquid column manometers. The same instruments can be used as described in 11.4.6.1 (see also Figure 44).

For the evaluation of the water level from pressure measurement, a simple stand pipe can be used in some cases (see Figure 50).

The pressure taps shall be constructed as described in 11.4.3.

In the case of dirty water or water with a high content of undissolved air special precautions should be taken. It is recommended to apply the gas purge (bubbler) technique as described in ISO 4373 (see also Figure 51).

In the case of an inverted U-tube the second leg of the U-tube is connected to a reference vessel in which water is maintained at a fixed level. If the free water level to be measured is above the manometer, the upper portion for the U-tube must be unwatered by means of compressed air (Figure 44d). If, however, the free water level to be measured is below the manometer, the levels in the two U-tube legs must be raised by suction. The connecting tubes to the manometer must allow for ready purging to remove any air pockets and to maintain the same water temperature throughout the system. They must be sufficiently air-tight to avoid leakage of air into sections below atmospheric pressure. The density of the air in the unbalanced air column usually is negligible compared to the density of the liquid column.

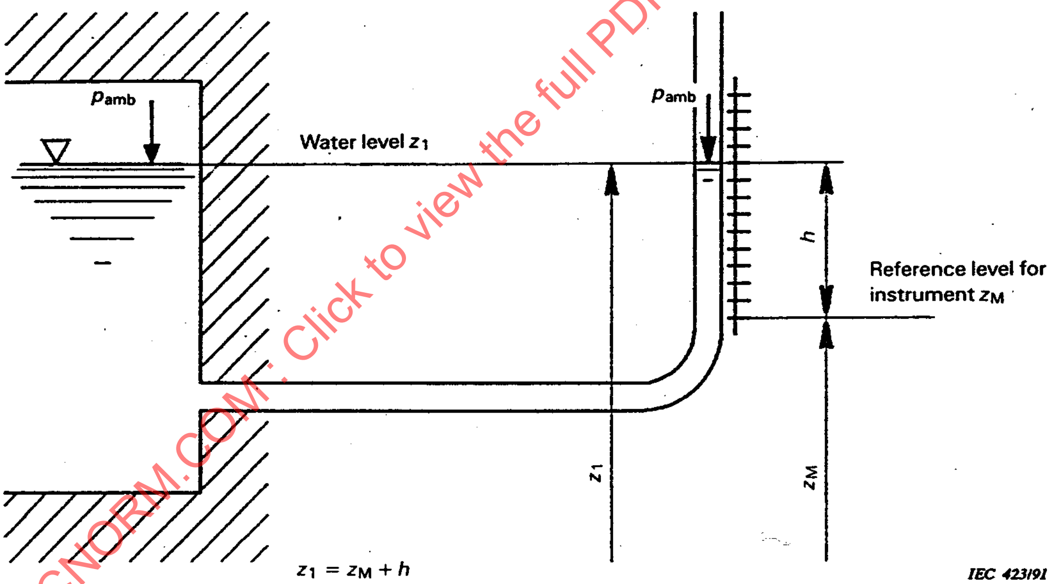
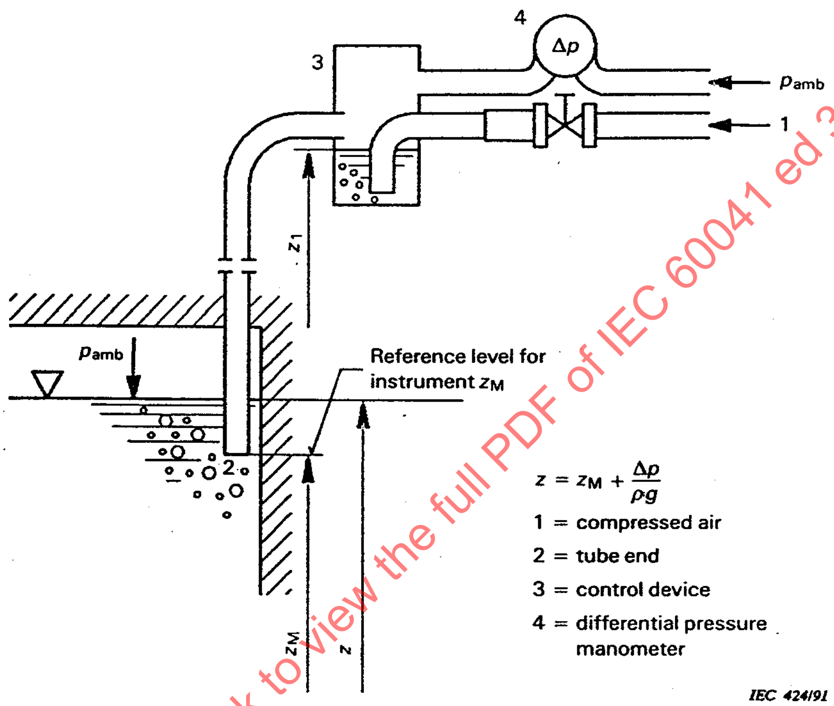


Figure 50 – Stand pipe measurement

11.5.4.7 Measurements by means of compressed air (gas purge technique)

The free water level may be determined by means of the pressure inside a tube filled with compressed air. One end of this tube is connected to a small compressor or pressure chamber through a reducing valve and the other (open) end is located below the water surface to be measured at a known elevation (which can be taken as reference level for instrument z_M, see Figure 51). As the pressure loss in the tube supplying air falsifies the measurements, this loss must be kept to a minimum (< 50 Pa). For this reason, the cross-sectional area of the tube should be large, the tube should be as short as possible and the air volume which flows through the tube and escapes in the form of bubbles under water should be as small as possible. The air tube should be used only in still water, otherwise dynamic effects are liable to cause appreciable errors.



Note. – It may be necessary to take into account the air density in the tube whenever Δp and $z_1 - z$ are large.

Figure 51 – Example for measurement by means of compressed air (gas purge "bubbler" technique)

11.5.4.8 Measuring wells and stilling boxes

If the free water surface is not accessible or not sufficiently calm, measuring wells with an area of about 0,1 m^2 which permit accurate and convenient measurements shall be provided. All connections shall be normal to the wall of the measuring section and should preferably be covered with smooth perforated plates (perforations of 5 mm to 10 mm diameter). Such coverplates must be flush with the wall of the measuring section to eliminate any local disturbances (Figure 52). The connection between the measuring section and well should have a passage area of at least 0,01 m^2. The total area of perforation should be in the order of 25 % of the passage area. It is recommended that at least two measuring wells be provided at each measuring section on opposite sides of the canal.

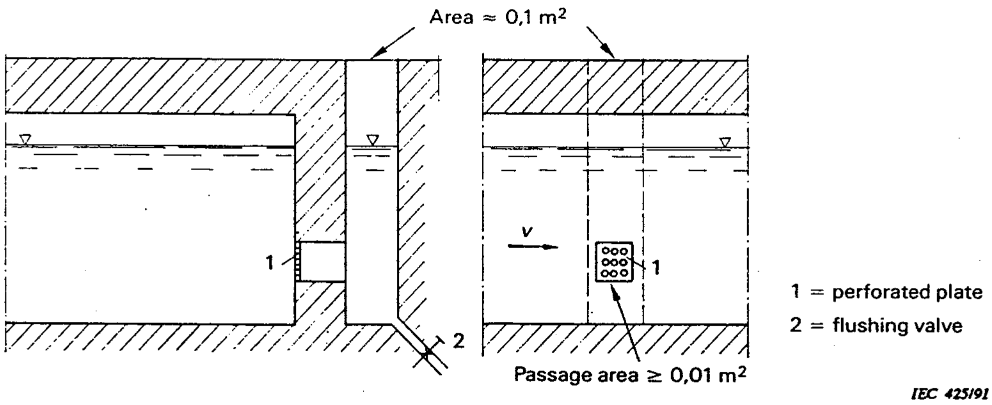


Figure 52 – Measuring well

11.5.4.9 Other methods

Other measuring methods may be used, for example, ultrasonic devices, as long as they meet the required accuracy, see 11.6.

11.6 *Uncertainty of measurements*

11.6.1 *Pressure measurements**

Absolute systematic uncertainties (at 95 % confidence level):

– Liquid column manometers				
mercury/water	±100	to	±500	Pa
water/air	±10	to	±50	Pa
– Dead weight manometers	±(1 to 3)	$\times 10^{-3} p$		Pa
– Spring pressure gauges	±(3 to 10)	$\times 10^{-3} p_{max}$ **		Pa
– Pressure transducers	±(2 to 6)	$\times 10^{-3} p_{max}$ **		Pa

11.6.2 *Free water level measurements****

Absolute systematic uncertainties (at 95 % confidence level):

In the case of calm water conditions and $v \leq 1,5$ m/s:

– Plate gauges, fixed scales	±0,01	to	±0,04	m
– Float gauges	±0,005	to	±0,015	m
– Point or hook gauges	±0,002	to	±0,01	m
– Bubbler with compressed air	±0,005	to	±0,015	m
– Immersible pressure transducers	±(2 to 6) $\times 10^{-3} Z_{max}$ **			m

In the case of very turbulent flow and $v > 1,5$ m/s, for example near the outlet of a turbine draft tube, the uncertainties may be considerably higher.

* These values are for turbines. It should be noted that pressure fluctuations at a pump outlet can be important and more or less asymmetrical, so that when they are not correctly damped (see 11.4.5), the uncertainties may be increased.

** Z_{max} and p_{max} are full scale readings of the instrument.

*** Not for weir measurements.

11.6.3 *Determination of the specific hydraulic energy*

For the relative systematic uncertainty f_E see Appendix A.

12. Power

12.1 *Indirect method of power measurement*

The choice of instruments for measuring electrical power is more or less linked to the measuring method used for the other quantities, especially for discharge measurement.

Integrating electrical instruments (watthourmeters and counters) are more suitable in those cases where integrating discharge measurements are made.

Power integration conducted during the period over which discharge is measured cancels the effect of variations in the discharge and power that may occur within this period. However, beside integration measurement, instantaneous readings should be taken to monitor the amount of the possible variations but a higher uncertainty may be expected in these instantaneous readings.

When the pressure/time method is used for measuring the discharge, the power shall be registered before, and up to, the beginning of the measurement (see 5.1.2).

When it is necessary to use permanently installed transformers, they should be calibrated before installation for the conditions to be encountered during the test period (load on the secondary due to extra measuring instruments, power factor, etc.). Their actual characteristics should also be measured so that any abnormality may be detected at the time of the test.

In order to simplify the test and to eliminate every source of error, any auxiliaries directly driven by the machine should, whenever possible, be disengaged during the course of the test.

As discharge, specific hydraulic energy and power are functions of the rotational speed (see 6.1.2), during the acceptance test the speed shall be measured with the required accuracy (see Clause 13).

Measurement of electrical power should be made at the terminals of the electrical machine if at all possible. If this cannot be done, the measured power must be corrected for losses occurring between the terminals and the measuring section (see also 12.1.2.1.2).

The power factor shall be unity if possible (i.e. $\cos \varphi = 1$).

In the following sub-clauses the methods for measuring all the components of the mechanical power (see 2.2.8.3) will be illustrated. For the electrical power measurement, only wattmeters or static power meters (or power transducers) are considered, but they may be replaced by watthourmeters or static energy meters (or energy transducers).

Electronic meters for power, current, voltage and phase angle are suitable for use with a data acquisition system.

12.1.1 *Electrical power* P_a

12.1.1.1 Methods of measurement

The following sub-clauses describe the methods of measurement for single-phase and three-phase systems. In the latter case two- and three-wattmeter methods are described.

The three-wattmeter method is slightly better than the two-wattmeter method. In relation to the improvement of the resulting uncertainty of turbine or pump efficiency the difference is however negligible. The two-wattmeter method therefore is used in most cases because it requires less equipment.

At power factors ($\cos \varphi$) less than 0,85 lagging, the ratio P_1/P_2 of the power measured by each instrument using the two-wattmeter method is less than 0,5. In such cases, the three-wattmeter method is preferred. In the case of an electrical machine with a neutral line, the three-wattmeter method has to be used; the two-wattmeter method can be used, if the absence of current in the neutral line can be verified.

12.1.1.1.1 Single-phase system

In Figure 53 a diagram is indicated for a single-phase system:

$$P_{ap} = P_{as} \cdot k_u \cdot k_i (1 + \varepsilon) \quad (1)$$

$$P_{as} = U_s \cdot I_s \cdot \cos \varphi_s \quad (2)$$

where:

P_{ap}	is the primary power whose measurement is required
P_{as}	is the secondary power (measured value)
k_u and k_i	are the rated transformation ratio of voltage and current transformers
ε	is the relative value of the correction for the measuring system established by calibrations
U_s	is the secondary voltage
I_s	is the secondary current
φ_s	is the phase difference between secondary vectors ($\cos \varphi_s = \frac{P_{as}}{U_s I_s}$)

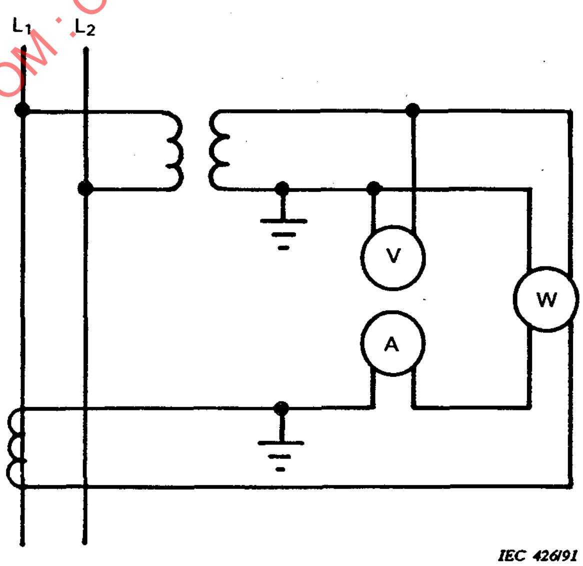


Figure 53 – Single-phase system

The relative value ε of the correction is given by the following formula (see Appendix G):

$$\varepsilon = \varepsilon_w + \varepsilon_u + \varepsilon_i - \delta \cdot \tan \varphi_s \qquad (3)$$

where:

ε_w	is the relative value of the correction for the wattmeter or for the transducer
ε_u	is the relative value of the correction for the voltage transformer ratio including the correction due to the connection cables from transformer terminals to the measuring instruments
ε_i	is the relative value of the correction for the current transformer ratio
$\delta = \delta_i - \delta_u$	is the difference between the phase displacement of the current transformer and voltage transformer, in radians
δ_i	is the phase displacement of the current transformer, in radians
δ_u	is the phase displacement of the voltage transformer, including the correction due to the connection cables from transformer terminals to the measuring instruments, in radians

12.1.1.1.2 Three-phase system: two instruments or one double element instrument (two-wattmeter method)

A1) Balanced conditions – Two voltage transformers

Figure 54 shows the measuring diagram with two single-phase instruments or with a double-element instrument and two voltage transformers. Under balanced conditions, which is substantially the normal case, the power on the primary side is:

$$P_{ap} = P_{as(2w)} \cdot k_u \cdot k_i(1 + \varepsilon) \qquad (4)$$

where:

$P_{as(2w)} = P_{as1} + P_{as2} = \sqrt{3} \cdot U_s I_s \cos \varphi_s$

and:

P_{as1}	$= U_s I_s \cos(\varphi_s + \pi/6)$,	transformers measuring U_{12} and I_1
P_{as2}	$= U_s I_s \cos(\varphi_s - \pi/6)$,	transformers measuring U_{23} and I_3
U_{12s}	$= U_{23s} = U_s =$	secondary line voltage
I_{1s}	$= I_{3s} = I_s =$	secondary current
$\cos \varphi_s$	$= \frac{P_{as(2w)}}{\sqrt{3} \cdot U_s \cdot I_s}$	

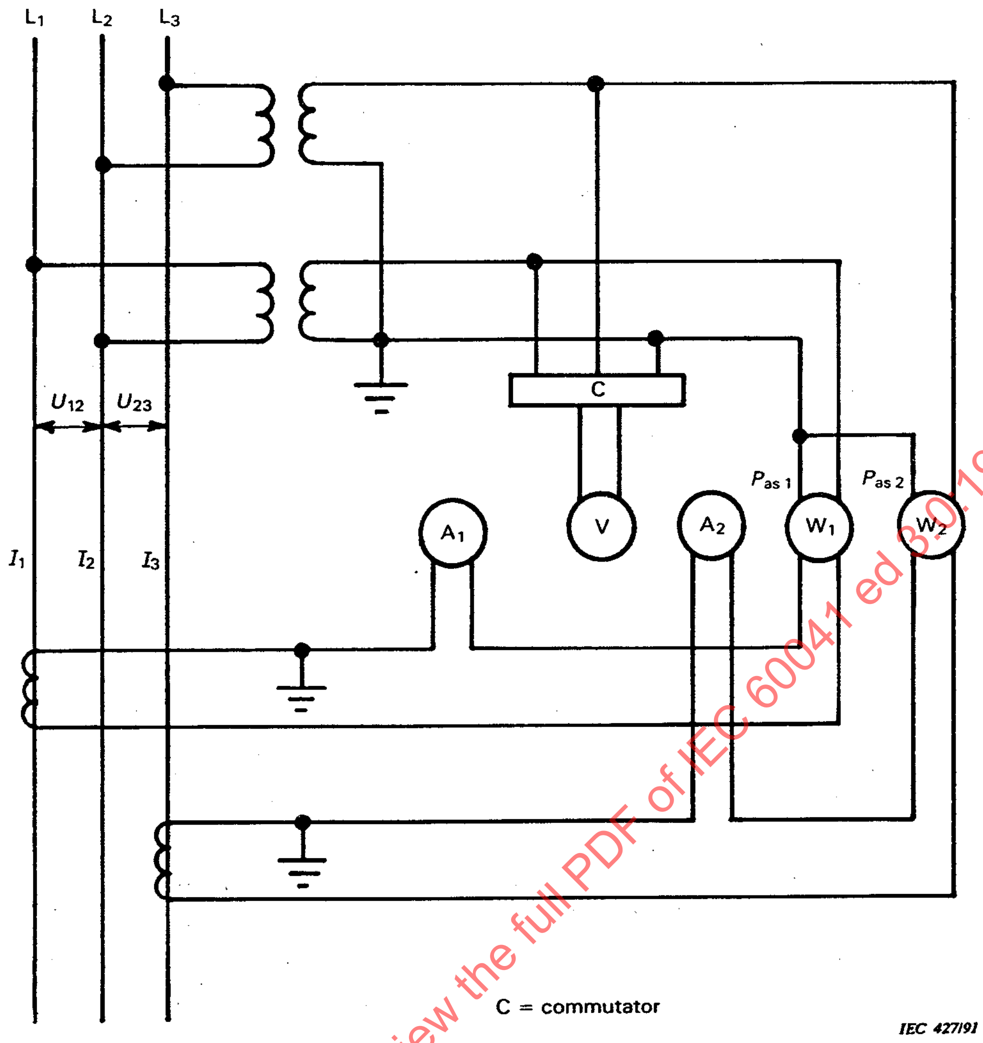


Figure 54 – Three-phase system: two-wattmeter method (two voltage transformers)

With the same considerations made in Appendix G, the relative value of the correction for each measuring system, established by calibrations, is given by:

$$\varepsilon_1 = \varepsilon_{1w} + \varepsilon_{1u} + \varepsilon_{1i} - \delta_1 \cdot \tan \varphi_s$$
$$\varepsilon_2 = \varepsilon_{2w} + \varepsilon_{2u} + \varepsilon_{2i} - \delta_2 \cdot \tan \varphi_s$$

The relative value of the correction of the combined measuring system is given by:

$$\varepsilon = \frac{P_{as1} \cdot \varepsilon_1 + P_{as2} \cdot \varepsilon_2}{P_{as(2w)}}$$

Assuming:

$$k = \frac{P_{as1}}{P_{as2}}$$

therefore:

$$\varepsilon = \frac{k\varepsilon_1 + \varepsilon_2}{1 + k}$$

In balanced conditions it is:

$$k = \frac{\sqrt{3} - \tan \varphi_s}{\sqrt{3} + \tan \varphi_s}$$

and the formula for the relative value of the correction of the combined measuring system is:

$$\varepsilon = \varepsilon_w + \frac{\varepsilon_{1c} + \varepsilon_{2c}}{2} + \frac{\delta_{1c} - \delta_{2c}}{2\sqrt{3}} - \left(\frac{\delta_{1c} + \delta_{2c}}{2} - \frac{\varepsilon_{1c} - \varepsilon_{2c}}{2\sqrt{3}} \right) \tan \varphi_s \qquad (5)$$

where:

$\varepsilon_w = \varepsilon_{1w} + \varepsilon_{2w}$ is the relative value of the combined correction in case of measurement with two wattmeters

$\varepsilon_{1c} = \varepsilon_{1u} + \varepsilon_{1i}$ is the relative value of the combined correction for the voltage and current ratios of system 1 transformers

$\varepsilon_{2c} = \varepsilon_{2u} + \varepsilon_{2i}$ is the relative value of the combined correction for the voltage and current ratios of system 2 transformers

$\delta_{1c} = \delta_{1i} - \delta_{1u}$ is the combined phase displacement of system 1 transformers, in radians

$\delta_{2c} = \delta_{2i} - \delta_{2u}$ is the combined phase displacement of system 2 transformers, in radians

A2) Balanced conditions – Three voltage transformers

Figure 55 shows the measuring diagram with two single-phase instruments or with a double-element instrument and three voltage transformers. Under balanced conditions, which is substantially the normal case, the power on the primary side is:

$P_{ap} = P_{as(2w)} \cdot k_u \cdot k_i (1 + \varepsilon)$ identical to formula (4) of the previous case A1,

where:

$$\varepsilon = \varepsilon_w + \frac{\varepsilon_{1i} + \varepsilon_{2i} + \varepsilon'_{1u} + \varepsilon'_{2u}}{2} + \frac{\delta_{1i} - \delta_{2i} - \delta'_{1u} + \delta'_{2u}}{2\sqrt{3}} - \left(\frac{\delta_{1i} + \delta_{2i} - \delta'_{1u} - \delta'_{2u}}{2} - \frac{\varepsilon_{1i} - \varepsilon_{2i} + \varepsilon'_{1u} - \varepsilon'_{2u}}{2\sqrt{3}} \right) \tan \varphi_s \qquad (6)$$

where:

$$\left. \begin{aligned} \varepsilon'_{1u} &= \frac{\varepsilon_{1u} + \varepsilon_{2u}}{2} \mp \frac{\delta_{1u} - \delta_{2u}}{2\sqrt{3}} \\ \varepsilon'_{2u} &= \frac{\varepsilon_{3u} + \varepsilon_{2u}}{2} \mp \frac{\delta_{3u} - \delta_{2u}}{2\sqrt{3}} \end{aligned} \right\}$$

– if the phase voltage being measured is leading the phase voltage not being measured;
+ if the situation is reversed;

$$\left. \begin{aligned} \delta'_{1u} &= -\frac{\delta_{1u} + \delta_{2u}}{2} \mp \frac{\varepsilon_{1u} - \varepsilon_{2u}}{2\sqrt{3}} \\ \delta'_{2u} &= -\frac{\delta_{3u} + \delta_{2u}}{2} \mp \frac{\varepsilon_{3u} - \varepsilon_{2u}}{2\sqrt{3}} \end{aligned} \right\}$$

– if the phase voltage being measured is lagging the phase voltage not being measured;
+ if the situation is reversed.

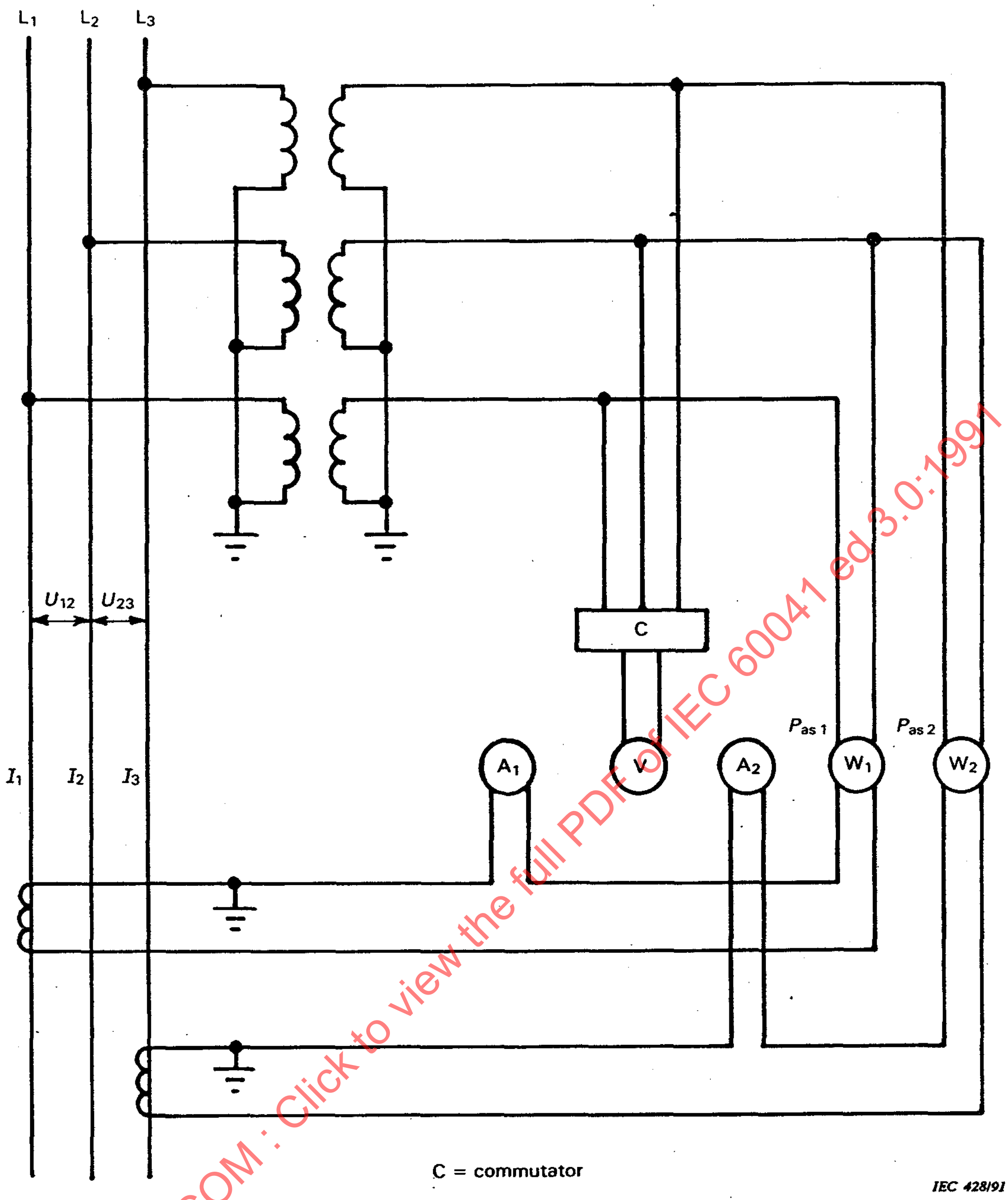


Figure 55 – Three-phase system: two-wattmeter method (three voltage transformers)

B) Unbalanced conditions

The measurement of the electrical power is made in the same manner as under balanced conditions, but the calculation of the correction has to take into account the different values of current, voltage and power factor in the two measuring systems.

12.1.1.1.3 Three-phase system: three instruments or one three-element instrument (three-wattmeter method)

A) Balanced conditions

Figure 56 shows the measuring diagram with three single-phase instruments or with a three-element instrument. Under balanced conditions, which is substantially the normal case, the power on the primary side is:

$$P_{ap} = P_{as(3w)} \cdot k_u \cdot k_i (1 + \varepsilon)$$

where the secondary power is:

$$P_{as(3w)} = P_{as1} + P_{as2} + P_{as3} = 3\,U_{sph} \cdot I_s \cos\varphi_s$$

where U_{sph} is the secondary phase voltage and I_s the secondary current.

The relative value of the correction for the combined measuring system is given by:

$$\varepsilon = \varepsilon_w + \frac{\varepsilon_{1c} + \varepsilon_{2c} + \varepsilon_{3c}}{3} - \frac{\delta_{1c} + \delta_{2c} + \delta_{3c}}{3} \cdot \tan\varphi_s$$

where:

$\varepsilon_w = \varepsilon_{1w} + \varepsilon_{2w} + \varepsilon_{3w}$ is the relative value of the combined correction in case of measurement with 3 wattmeters

$\left.\begin{array}{l}\varepsilon_{1c} = \varepsilon_{1u} + \varepsilon_{1i}\\ \varepsilon_{2c} = \varepsilon_{2u} + \varepsilon_{2i}\\ \varepsilon_{3c} = \varepsilon_{3u} + \varepsilon_{3i}\end{array}\right\}$ are the relative values of the combined correction for the voltage and current ratio respectively of system 1, 2 and 3 transformers

$\left.\begin{array}{l}\delta_{1c} = \delta_{1i} - \delta_{1u}\\ \delta_{2c} = \delta_{2i} - \delta_{2u}\\ \delta_{3c} = \delta_{3i} - \delta_{3u}\end{array}\right\}$ are the combined phase displacements respectively of system 1, 2 and 3 transformers, in radians

and where the value of φ_s is derived from:

$$\cos\varphi_s = \frac{P_{as(3w)}}{3\,U_{sph} I_s}.$$

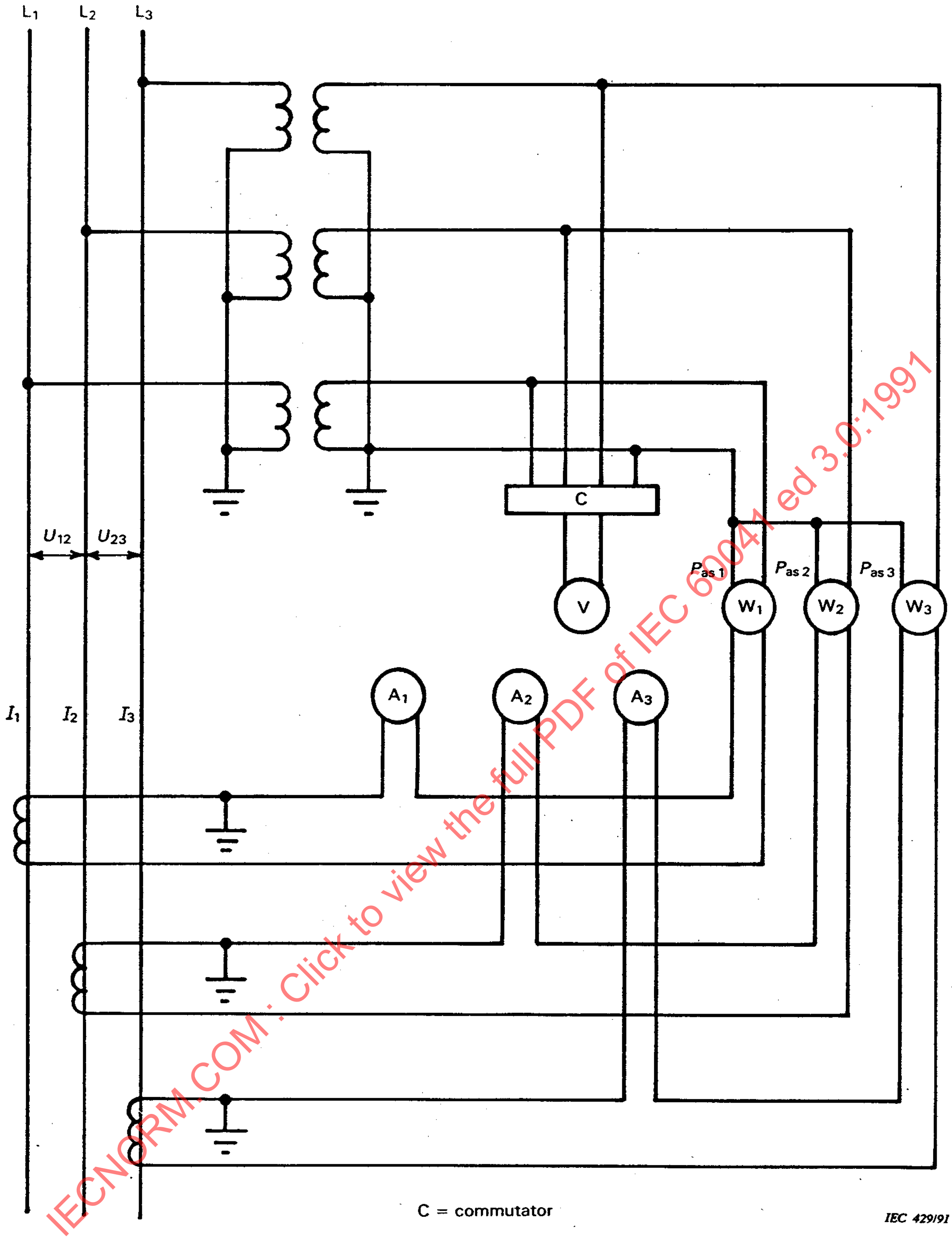


Figure 56 – Three-phase system: three-wattmeter method

B) Unbalanced conditions

The measurement of the electrical power is made in the same manner as under balanced conditions, but the calculation of the correction has to take into account the different values of current, voltage and power factor in the three measuring systems.

12.1.1.1.4 Number of readings

The number of readings shall be sufficient to permit an accurate calculation of the mean power over the duration of the run. The number will depend on the test time and on the stability of readings. As shown in Appendix C the random uncertainty decreases as the number of readings increases. Under difficult conditions integrating meters are preferred.

12.1.1.2 Instrumentation requirements

12.1.1.2.1 Accuracy class of instruments and measuring transformers

Wattmeters shall be of class 0,2 or better, voltmeters and ammeters shall be of class 0,5 or better. Voltage and current transformers shall be of class 0,2 according to IEC 185 and 186.

12.1.1.2.2 Calibration of instruments

According to 4.6.2 all instruments, including measuring transformers, shall be calibrated before and after the test. However, one calibration may be omitted by agreement. Measuring transformers, class 0,2, have such stability that it is normally sufficient to calibrate them either before or after the test. The transformers shall have the same burdens during calibration and test, including additional ones, if any (see 12.1.1.2.5).

12.1.1.2.3 Wattmeter problems associated with site measurements

When measuring on site by means of wattmeters, certain problems will normally arise because the power is not constant due to disturbances from the network and from the hydraulic machine. The disturbances which cause the pointers of the wattmeters to move more or less quickly within certain limits can roughly be divided into three classes:

a) Very slow variations which do no harm because the wattmeter readings can be taken as true readings. The reason may be, for instance, a variation of specific hydraulic energy.

b) Rapid random fluctuations when the pointers of the different wattmeters are moving in the same direction. This phenomenon is typical of active power fluctuations.

c) Rapid random fluctuations when the pointers of the two wattmeters are moving in opposite directions, due to small rapid voltage fluctuations in the network, which are always present to a certain extent depending on network conditions. The instruments should therefore be read simultaneously. To attempt a correct reading over a long period is often very tiring and gross individual errors can easily be introduced. Disturbances from reactive power variations are smallest when the machine is operated with manual control of voltage.

With reference to the preceding text it is clear that the use of wattmeters when measuring on site, involves difficulties which increase the uncertainty of the measurement. It is therefore advisable to use, in addition, a static watt-hourmeter combined with a quartz timer. Digital wattmeters of class 0,2 or better can of course be used. Computerised reading and integration can be applied if the program is properly checked.

12.1.1.2.4 Instrument transformers

Transformers shall be used solely to supply the test instruments if possible. Each transformer shall have separate pairs of leads which are braided up to the place where the instruments are located (twisted pairs). The real burden inclusive of leads shall always be determined for calibration purposes.

12.1.1.2.5 Voltage transformers

The cross-sectional area of the leads shall be such that the total voltage drop is less than 0,1 %. When using modern instruments with very small power consumption it may be advisable to connect additional burdens to the transformer terminals in order to decrease the correction factors of the transformers.

12.1.1.2.6 Current transformers

In many cases it is only possible to install special transformers for machines up to say 40 to 50 MVA. For larger machines an agreement must be reached if built-in transformers are used; the burden shall be adjusted to rated value, if possible. The factory calibration can then be used and no calibration after the test is required.

12.1.1.2.7 Magnetic fields

Magnetic fields can occur in the vicinity of electrical machines, transformers, busbars, etc. which can influence the instruments. Care must be taken to avoid such stray fields.

12.1.2 *Determination of losses*

12.1.2.1 Mechanical and electrical losses in the electrical machine P_b

12.1.2.1.1 Measurement

The losses – including the electrical machine guide bearing losses – shall be determined according to IEC 34-2 and 34-2A. The test method will be chosen with the agreement of the supplier of the hydraulic machine, who shall have the right to be present at the test.

Tests can be made in the manufacturer's workshop or on site. In the first case only component losses can normally be determined and hence the conventional total loss by summation of component losses. Special care must be taken to ensure that the windage losses during the workshop tests are similar to those in the power plant.

Often large machines can only be tested on site, normally by the calorimetric method or retardation (Pelton turbines). In that case both component losses and total losses on load can be determined in a unit equipped with a regulated turbine.

12.1.2.1.2 Adjustment by calculation of losses in the electrical machine when testing the hydraulic machine

It is recommended that the various component losses in the electrical machine be determined.

Iron losses and total load losses (i.e. the sum of load losses and additional losses) are adjusted to the prevailing values of voltage and current during the test, by assuming that they vary in proportion to the square of voltage and current respectively.

On load the iron losses are usually somewhat higher and the total load losses somewhat lower than the corresponding component losses. For high capacity electrical machines losses on load may exceed the sum of the component losses to such an extent that they should be determined by measurement at full load.

When measuring component losses the temperature in the electrical machine is much lower than when it is on load. No temperature corrections are however made for the following reasons. Load losses increase and additional load losses decrease at higher temperatures. Iron losses and windage losses also decrease at higher temperatures. For three-phase synchronous machines the total losses on load are therefore assumed to be independent of temperature. A special agreement shall be made for single-phase generators where the additional load losses are dominant.

Experience shows that the errors introduced by the foregoing assumptions are small, say ±2 % to 3 %, or about the same as for a full-load calorimetric test, category A, according to clause 15 of IEC 34-2A. Other losses in the electrical machine are taken from tests, with the exception of the excitation losses, which are measured directly with instruments if these losses are part of P_b (case of not separated excitation).

12.1.2.2 Thrust bearing losses due to the electrical machine, P_c

12.1.2.2.1 Measurement

The losses in the thrust bearing shall be measured according to IEC 34-2A.

If direct measurement is not possible, the losses shall be estimated by agreement, either by comparison with similar cases or on the basis of existing empirical formulae (see 12.3.1).

In the case of a combined guide/thrust bearing, the two components shall be considered as separated and the relevant losses (measured or calculated) shall be attributed to the electrical machine or to the hydraulic machine according to the contractual specifications.

12.1.2.2.2 Case of a common thrust-bearing

In the case of a common thrust-bearing, the relevant losses shall be attributed to the electrical machine and to the hydraulic machine(s) in proportion to the thrust of each on the bearing.

If:

F_{AE} is the axial component of thrust due to the electrical machine,

F_{AT} is the axial component of thrust due to the turbine: hydraulic thrust acting on the runner(s) (see 12.3.3) and weight of runner(s) and shaft,

F_{AP} is the axial component of thrust due to the pump: hydraulic thrust acting on the impeller(s) (see 12.3.3) and weight of impeller(s) and shaft,

it shall be attributed:

a) in case of a production binary unit:

– to the electrical machine

$$P_{cE} = \frac{F_{AE}}{F_{AE} + F_{AT}} \cdot P_c$$

– to the turbine

$$P_{cT} = \frac{F_{AT}}{F_{AE} + F_{AT}} \cdot P_c$$

b) in case of a pumping binary unit:

– to the electrical machine

$$P_{cE} = \frac{F_{AE}}{F_{AE} + F_{AP}} \cdot P_c$$

– to the pump

$$P_{cP} = \frac{F_{AP}}{F_{AE} + F_{AP}} \cdot P_c$$

c) in the case of a ternary unit operating as a production unit (pump being disconnected):

– to the electrical machine

$$P_{cE} = \frac{F_{AE}}{F_{AE} + F_{AT}} \cdot P_c$$

– to the turbine

$$P_{cT} = \frac{F_{AT}}{F_{AE} + F_{AT}} \cdot P_c$$

d) in the case of a ternary unit operating as a pumping unit:

– to the electrical machine

$$P_{cE} = \frac{F_{AE}}{F_{Atot}} \cdot P_c$$

– to the pump

$$P_{cP} = \frac{F_{AP}}{F_{Atot}} \cdot P_c$$

where:

F_{Atot} is the sum of the axial components of the weight of all rotating parts, of the thrust due to the electrical machine and of the hydraulic thrust acting on the impeller(s) of the pump.

Note. – In the case of a horizontal machine, the total thrust losses may be attributed to the hydraulic machine. In the other cases, if the axial component of the total thrust (F_{AT} or F_{AP}) due to the hydraulic machine is negative, the losses attributed to the hydraulic machine will be zero, as long as F_{AT} (or F_{AP}) is not greater than F_{AE}.

12.1.2.3 Losses in all rotating elements external to the hydraulic machine, P_d

12.1.2.3.1 Losses in the gear

The power losses in the gear, if any, or – more generally – in those parts of the transmission located between the electrical machine and the hydraulic machine shall be the object of a separate evaluation by measurement or calculations. The measurement shall be done as closely as possible, under the same conditions as those of the main acceptance test. The losses in a gear may be determined by measuring the heat absorbed by the lubricating oil (or by its cooling water) and by the surrounding air.

12.1.2.3.2 Windage losses of an open flywheel

Windage losses of open flywheels may be calculated approximately by means of the following formula:

$$P_w = 0,35\,(60n)^3 D_a^5 \left(1 + 1,8\,\frac{B}{D_a}\right) \times 10^{-6} = 75,6\,n^3 D_a^5 \left(1 + 1,8\,\frac{B}{D_a}\right) \times 10^{-3}$$

where:

P_w is the windage losses (W)

n is the rotational speed of the flywheel (s^{-1})

D_a is the outside diameter of the flywheel (m)

B is the width of the rim (m)

The uncertainty bandwidth of the formula is ±30 %.

12.1.2.3.3 Losses of the runner/impeller turning in air, P_w

The losses of a runner/impeller turning in air are attributed to friction and windage, excluding the bearing losses. In some cases, for example, the case of a ternary unit with a machine, the runner/impeller of which is turning in air during the acceptance test, or the case of a reversible unit with an impulse starting wheel turning in air during the acceptance test, the losses due to the machine or to the impulse wheel turning in air should be taken into account together with the bearing losses. As it is often impossible or undesirable to uncouple the runner/impeller of the hydraulic machine from the electrical machine, it is recommended to measure the losses of the runner/impeller turning in air, for example, by evaluating the difference between the electrical input measured at the terminals and extrapolated to zero voltage and the losses of the electrical machine – not excited and driven by the turbine – measured by the calorimetric method (see IEC 34-2A).

If such a measure is not possible, the losses of the runner/impeller turning in air may be generally estimated by the following formulae depending on the type of the machine:

1) Kaplan turbines (blades in closed position):

$$P_w = 6,5 \cdot (60\,n)^3 \cdot D^5 \cdot 10^{-7} = 0,14 \cdot n^3 \cdot D^5$$

where:

P_w is the windage losses (W)

n is the rotational speed (s^{-1})

D is the runner outer diameter (m)

The uncertainty bandwidth of the formula is ±50 %.

2) Francis turbines

$$P_w = 4,6 \cdot (60\,n)^3 \cdot B \cdot D^4 \cdot 10^{-4} = 100 n^3 \cdot B \cdot D^4$$

where

P_w is the windage losses (W)

n is the rotational speed (s^{-1})

B is the runner height (m) (see Figure 57)

D is the runner outer diameter (m) (see Figure 57)

The formula is valid for a labyrinth discharge less than $0,8 \cdot 10^{-3}$ of the discharge at the best efficiency point. The uncertainty bandwidth is ±50 %.

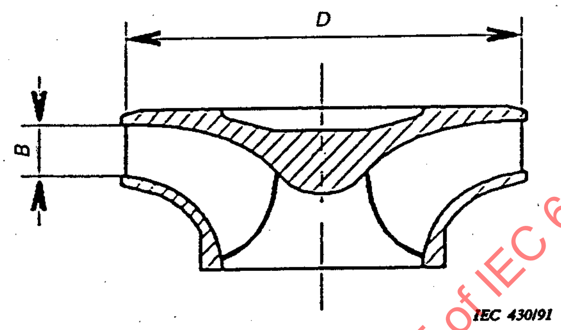


Figure 57 – Main dimensions of runner/impeller of radial machines

3) Pumps and pump-turbines

$$P_w = 2,3 \cdot (60\,n)^3 \cdot B \cdot D^4 \cdot 10^{-4} = 50\,n^3 \cdot B \cdot D^4$$

where:

P_w is the windage losses (W)

n is the rotational speed (s^{-1})

B is the runner/impeller height (m) (see Figure 57)

D is the runner/impeller outer diameter (m) (see Figure 57)

The formula is valid for a labyrinth discharge less than $0,8 \cdot 10^{-3}$ of the discharge at the best efficiency point. The uncertainty bandwidth is ±50 %.

4) Pelton turbines*

a) Horizontal axis (see Figure 58)

$$P_w = 7 \cdot (60\,n)^3 \cdot D^5 \cdot \left(\frac{B_a}{D}\right)^{1/4} \cdot \left(\frac{B_{io}}{D}\right)^{3/4} \cdot \left(\frac{B_{iu}}{D}\right)^{5/4} \cdot \left(\frac{R_{io}}{D}\right)^{7/4} \cdot 10^{-5}$$

$$= 15\,n^3 \cdot D^5 \cdot \left(\frac{B_a}{D}\right)^{1/4} \cdot \left(\frac{B_{io}}{D}\right)^{3/4} \cdot \left(\frac{B_{iu}}{D}\right)^{5/4} \cdot \left(\frac{R_{io}}{D}\right)^{7/4}$$

where

P_w is the windage losses (W)

n is the rotational speed (s^{-1})

D is the maximum outer diameter of the runner (m). Other geometrical data are defined in Figure 58

For the normal distance existing between runner and tailwater level, the influence of the tailwater level is neglected. The uncertainty bandwidth of the formula is ±50 %.

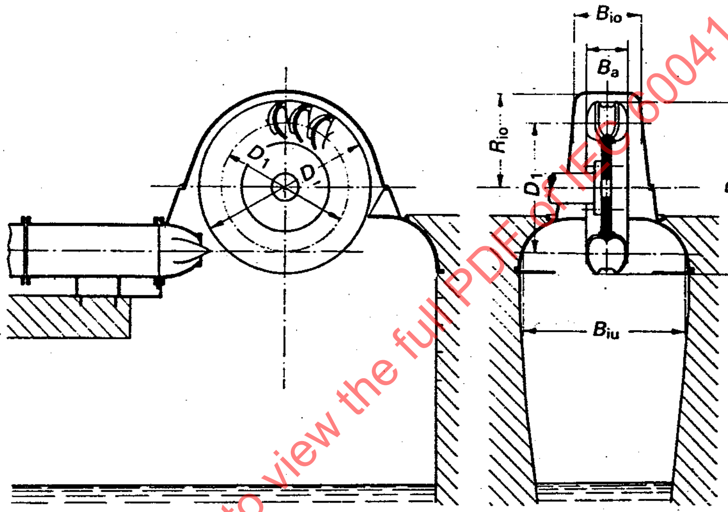


Figure 58 – Dimensions of the housing for Pelton turbines with horizontal runner axis

b) Vertical axis (see Figure 59)

$$P_w = (60\,n)^3 \cdot D^5 \cdot \left(\frac{B_a}{D}\right)^{2/3} \cdot \left(\frac{B_i}{D}\right)^{4/3} \cdot \left(\frac{R_i}{D}\right) \cdot 10^{-4}$$

$$= 22 \cdot n^3 \cdot D^5 \cdot \left(\frac{B_a}{D}\right)^{2/3} \cdot \left(\frac{B_i}{D}\right)^{4/3} \cdot \left(\frac{R_i}{D}\right)$$

For the normal distance existing between runner and tailwater level, the influence of the tailwater level is neglected. The uncertainty bandwidth of the formula is ±50 %.

* Milanese: La valutazione delle perdite di ventilazione delle giranti Pelton (Evaluation of windage losses in Pelton runners), AEI Annual Meeting, 1984.

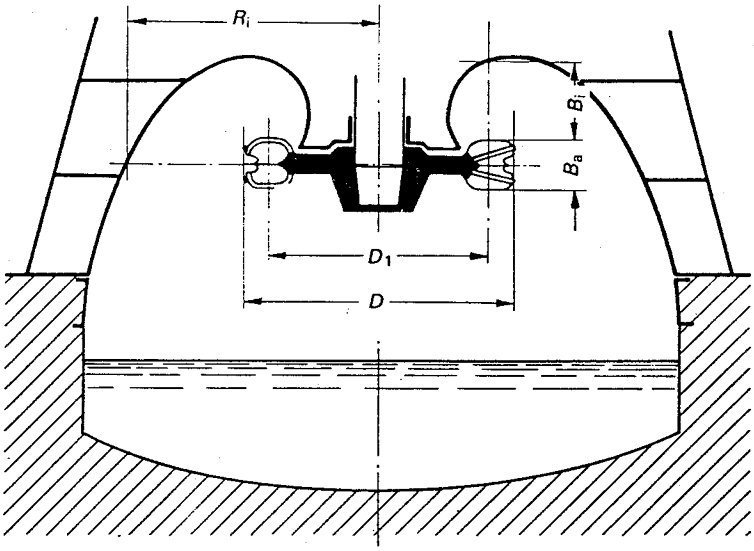


Figure 59 – Dimensions of the housing for Pelton turbines with vertical runner axis

12.1.2.4 Power supplied to any directly driven auxiliary machine, P_e, and to the auxiliary equipment of the hydraulic machine if contractually foreseen as chargeable to it, P_f

If significant, the power absorbed by the various cooling pumps, governor, etc., driven by electric motors shall be determined by measuring the electrical power used by the motors. In more difficult cases, the power absorbed by pumps shall be estimated by measuring their discharge and specific hydraulic energy, taking into account their overall efficiency, as obtained, for instance, by test-stand results. Power absorbed by other accessories may in most cases be estimated, in view of their small magnitude.

12.1.3 *Uncertainty of measurement*

If proper correction is made for the measuring transformers, the resulting systematic uncertainty f_P of the measurement of the mechanical power of the machine is in the order of ±0,5 % to ±1 %, depending on the measuring conditions.

12.2 *Direct method of power measurement*

The direct method of measuring power on the hydraulic machine shaft by means of devices measuring torque and speed is more suited to small units. It may have to be used, however, for hydraulic machines which are not directly coupled to electric machines.

It is necessary to measure the rotational speed of the machine with adequate accuracy (see Clause 13).

12.2.1 *Measurement by means of a brake* (mechanical, hydraulic or electrical*)

These measurements require the accurate determination of the following quantities:

- rotational speed of the shaft;
- length of the brake lever;
- tare weight of the brake lever;
- force on the brake lever.

The brake shall be mounted in such a way as to minimize axial or lateral thrust on the shaft and bearings. The power absorbed by friction in these bearings, because of the existence of such loads, cannot be charged against the hydraulic machine but shall be placed to its credit in calculating power. If the hydraulic machine has a vertical shaft, the brake shall be suspended so as not to impose any bending stress on the shaft.

Care shall be taken to ensure that the brake cooling fluid does not cause a parasitic torque reaction; should it do so, it shall be taken into account in the calculations.

12.2.2 *Measurement by means of a torsion dynamometer*

A torsion dynamometer (or torsion tube) comprises a length of shafting whose strain is measured by some convenient method.

The apparatus must be calibrated before the start and at the end of the test, if possible in situ.

12.2.3 *Uncertainty of measurement*

The resulting systematic uncertainty f_P of the measurement of the mechanical power of the machine is in the order of ±0,8 % to ±1,3 %, depending on the measuring systems and conditions.

12.3 *Bearing losses*

The losses in all the bearings should be measured by the calorimetric method in accordance with IEC 34-2A. However, if it is not possible, these losses may be calculated as a first approximation as explained in the following sub-clauses, if the temperature and the viscosity of oil are known. Other methods exist (e.g. Raimondi method for thrust bearing losses) and can be applied**.

* See also IEC 193.

** Standard handbook of lubrication engineering, McGraw-Hill Book Company, New York, 1968.

Calculation methods for steadily loaded pressure fed hydrodynamic journal bearings, Engineering Science Data N.66023, I.Mech.E., London.

12.3.1 *Calculation of thrust bearing losses*

The thrust bearing is loaded jointly by axial components of the weights of the different machines (hydraulic and electrical) and their shafts, and by the hydraulic thrusts (see 12.1.2.2.2).

For a bearing with segments having:

- an outside diameter d_o
- an inside diameter d_i

so that the radial width of a segment is:

$$b = 0,5(d_o - d_i) \qquad \text{(m)}$$

and its tangential mean length can be assumed:

$$l = \frac{0,80\pi(d_o + d_i)}{2N} \qquad \text{(m)}$$

N being the number of segments, the friction coefficient is given by the formula:

$$f = k\sqrt{\frac{\mu \cdot v_m}{p_m \cdot l}}$$

where:

μ is the dynamic viscosity of the oil (Pa·s)

v_m is the mean speed of the thrust bearing rotating element ($m \cdot s^{-1}$):

$$v_m = \frac{\pi n(d_o + d_i)}{2}$$

p_m is the average specific pressure on the thrust bearing (Pa):

$$p_m = \frac{F_{AE} + F_{AP} + F_{AT}}{N \cdot b \cdot l}$$

k is a constant depending on the shape of the segment. Its value can be considered in first approximation k =3.5 and may vary from 2 to 4.

The corresponding friction losses can be expressed by*

$$P_{tb} = (F_{AE} + F_{AP} + F_{AT}) \cdot f \cdot v_m \qquad \text{(W)}$$

* Standard handbook of lubrication engineering, McGraw-Hill Book Company, New York, 1968.

Calculation methods for steadily loaded pressure fed hydrodynamic journal bearings, Engineering Science Data N.66023, I.Mech.E., London.

12.3.2 *Calculation of guide bearing losses*

The following formulae are applicable for unloaded bearings.

a) Journal bearing:

$$P_{gb} = \frac{1,6 \cdot \mu(60n)^2 \cdot d^3 \cdot l}{\delta} \cdot 10^{-2} = 58 \cdot \frac{\mu \cdot n^2 \cdot d^3 \cdot l}{\delta} \quad \text{(W)}$$

where:

μ is the dynamic viscosity of the oil (Pa·s)

n is the rotational speed (s^{-1})

d is the diameter of the bearing (m)

l is the axial length of the bearing (m)

δ is the total diametrical clearance (m)

b) Segment bearing

$$P_{gb} = k \cdot \frac{N \cdot \mu(60n)^2 \cdot d^2 \cdot l \cdot b}{\delta} \cdot 10^{-3} = k \cdot 3,6 \cdot \frac{N\mu n^2 \cdot d^2 \cdot l \cdot b}{\delta} \quad \text{(W)}$$

where:

k is a constant depending on the shape of the segment and can be considered in first approximation to range between 4 and 7,8

N is the number of the segments

μ is the dynamic viscosity of the oil (Pa·s)

n is the rotational speed (s^{-1})

d is the diameter of the bearing (m)

l is the circumferential length of the segment $= \frac{0,80 \cdot \pi \cdot d}{N}$ (m)

b is the axial length of the segment (m)

δ is the total diametrical clearance (m)

12.3.3 *Hydraulic thrust measurement*

Usually the weight of the rotating parts and the hydraulic thrust are given by the manufacturer.

The hydraulic thrust may be determined by measuring the axial deflection of a shaft supporting element.

The characteristic curve of thrust versus deflection may be determined by calculation. It may be checked by applying a known load to the thrust bearing and measuring the shaft deflection relative to a fixed point, usually located on some part of the machine foundation. The uncertainty of such a measurement is about ±20 % of the known load. With vertical shaft machines, a convenient method of calibration is to measure the axial shaft displacement when the known weight of all the rotating parts is placed on the thrust bearing.

In the case of a hydraulically balanced thrust bearing, the hydraulic thrust can be measured directly through the pressure in the balancing chambers.

The measurement of the hydraulic thrust is an aid in estimating the losses chargeable separately to the electrical and hydraulic machines (see 12.1.2.2.2).

13. Rotational speed

13.1 *General*

The performance of a hydraulic machine is a function of the rotational speed (see 6.1.2). Therefore the rotational speed must be measured with the required accuracy.

13.2 *Speed measurements in the case of direct measurement of power*

When the power is determined by the direct method (see 12.2), the rotational speed must be measured, for example, by means of a calibrated tachometer or electronic counter. The measurement of speed must be made without any slip relative to the hydraulic machine shaft.

13.3 *Speed measurements in the case of indirect measurement of power*

When the power is determined by the indirect method (see 12.1) and the rotational speed is measured with the same methods as for direct measurement of power (see 13.2), the same care should be used in measurement.

It is permitted to measure the speed of a synchronous machine by means of the switchboard frequency meter under the following conditions:

- the system load must be steady;
- the resolution of the frequency meter must be 0,1% of the grid frequency;
- the frequency meter must be checked against a suitable precision instrument.

When the hydraulic machine is coupled to an asynchronous electrical machine, the rotational speed can be measured by the above mentioned devices or can be calculated from the measured grid frequency and from the measured slip of the electrical machine by the following formula:

$$n = \frac{2}{i} \cdot \left(f - \frac{m}{\Delta t}\right) \qquad (s^{-1})$$

where:

i is the number of poles of the electrical machine

f is the measured grid frequency (Hz)

m is the number of images counted with a stroboscope synchronized with the grid during the time interval Δt(s)

13.4 *Uncertainty of measurements*

The estimated systematic uncertainty at 95% confidence level is:

- for tachometer: ±0,2 % to ±0,4 %;
- for electronic counter and other precision devices: less than ±0,2 %.

14. Thermodynamic method for measuring efficiency

14.1 *General*

14.1.1 *Principle*

The thermodynamic method results from the application of the principle of conservation of energy (first law of thermodynamics) to a transfer of energy between water and the runner/impeller through which it is flowing.

The specific mechanical energy at the runner/impeller defined as in 2.3.6.3 may be determined by measurement of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water.

To establish the efficiency, the need to measure the discharge is eliminated by using the specific mechanical energy together with the specific hydraulic energy, as defined in 2.3.6.2.

14.1.2 *Excluded topics and limitations*

Due to the lack of uniformity in values measured at the reference sections of the machines, the limitations of measuring equipment and the relatively high magnitude of the corrective terms originating from the imperfect measuring conditions, the range of application of this method is limited and can only be used for specific hydraulic energies in excess of 1000 $J \cdot kg^{-1}$ (heads in excess of 100 m). However, under highly favourable conditions, the range could be extended to cover lower specific hydraulic energies (heads) subject to an analysis of the accuracy of the measurements.

14.1.3 *Instrumentation*

The technological aspects of the instrumentation have been dealt with in a general way, taking into account the fact that the apparatus presently available varies widely and may possibly become obsolete in the future. Because of this diversity none of them is described in detail.

The only requirements of instruments are that they satisfy the conditions stipulated in this standard (accuracy, heat exchange, etc.).

14.2 *Efficiency and specific mechanical energy*

The efficiencies of machines are defined in 2.3.9.1, 2.3.9.2 and 2.3.9.3. In 2.3.9.1 the hydraulic efficiency is written:

for turbines:

$$\eta_h = P_m / P_h = \frac{E_m}{E \pm \frac{\Delta P_h}{P_m} E_m}$$

for pumps:

$$\eta_h = P_h / P_m = \frac{E \pm \frac{\Delta P_h}{P_m} E_m}{E_m}$$

The thermodynamic method allows direct measurement of the specific mechanical energy E_m.

The specific mechanical energy E_m deals with the specific energy exchanged between the water and the runner/impeller. By definition E_m is related to P_m (see 2.3.8.4 and Figure 9) by:

$$P_m = (\rho Q)_1 E_m$$

If no auxiliary discharge is added or subtracted between the reference sections, E_m is calculated by:

$$E_m = E_{1-2} = \bar{a}(p_{abs1} - p_{abs2}) + \bar{c}_p(\Theta_1 - \Theta_2) + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2)^*$$

- In practice the quantities are measured at the places 11 and 21 in measuring vessels (see 14.3.1).
- The mean values of a and c_p correspond then to:

$$\frac{p_{abs11} + p_{abs21}}{2} \quad \text{and} \quad \frac{\Theta_{11} + \Theta_{21}}{2}$$

- Certain corrective terms (imperfect measurement conditions, secondary phenomena, etc.) defined in 14.6 must be taken into consideration. They are indicated by δE_m.

  The practical expression of E_m is therefore:

$$E_m = E_{11-21} = \bar{a}(p_{abs11} - p_{abs21}) + \bar{c}_p(\Theta_{11} - \Theta_{21}) + \frac{v_{11}^2 - v_{21}^2}{2} + g(z_{11} - z_{21}) + \delta E_m \qquad (1)$$

If an auxiliary discharge is added or subtracted between the high and low pressure measuring sections (e.g. when all or part of the loss P_{Lm}, see 2.3.8.5, is removed by an auxiliary discharge), a balance of power, added or subtracted, allows the computation of the value of E_m in agreement with the general equation. Examples are given in Appendix H.

As the efficiency of the machine (see 2.3.9.3) is $\eta = \eta_h \cdot \eta_m$, it shall be calculated taking into account all the mechanical losses chargeable to the hydraulic machine.

14.3 *Procedure for measurement of specific mechanical energy*

14.3.1 *General*

Due to the difficulties inherent in measuring directly in the main flow, the quantities defining E_m may be measured in specially designed vessels with tappings for the determination of temperature and pressure (see Figure 60 and 14.4.1.1). When the measuring sections are under pressure, the procedure consists of extracting a sample discharge, generally of between 0,1 and 0,5 × $10^{-3} m^3 \cdot s^{-1}$, by a "total head" probe. The water thus extracted is led to the measuring vessel through an insulated pipe to ensure that the heat exchange with the exterior, estimated in accordance with the procedure detailed in 14.4.1.1, does not exceed the limit of corrections fixed in 14.6.3. This sampling is valid if the recommendations given in 14.5.1, regarding extraction points, are followed.

* The theory of the thermodynamic method for measuring efficiency is based on the thermodynamic laws using the thermodynamic temperature Θ in kelvin (K). In the case of temperature differences the temperature can be directly expressed in degrees Celsius (°C) as $\vartheta_1 - \vartheta_2 = \Theta_1 - \Theta_2$ (see 2.3.3.2).

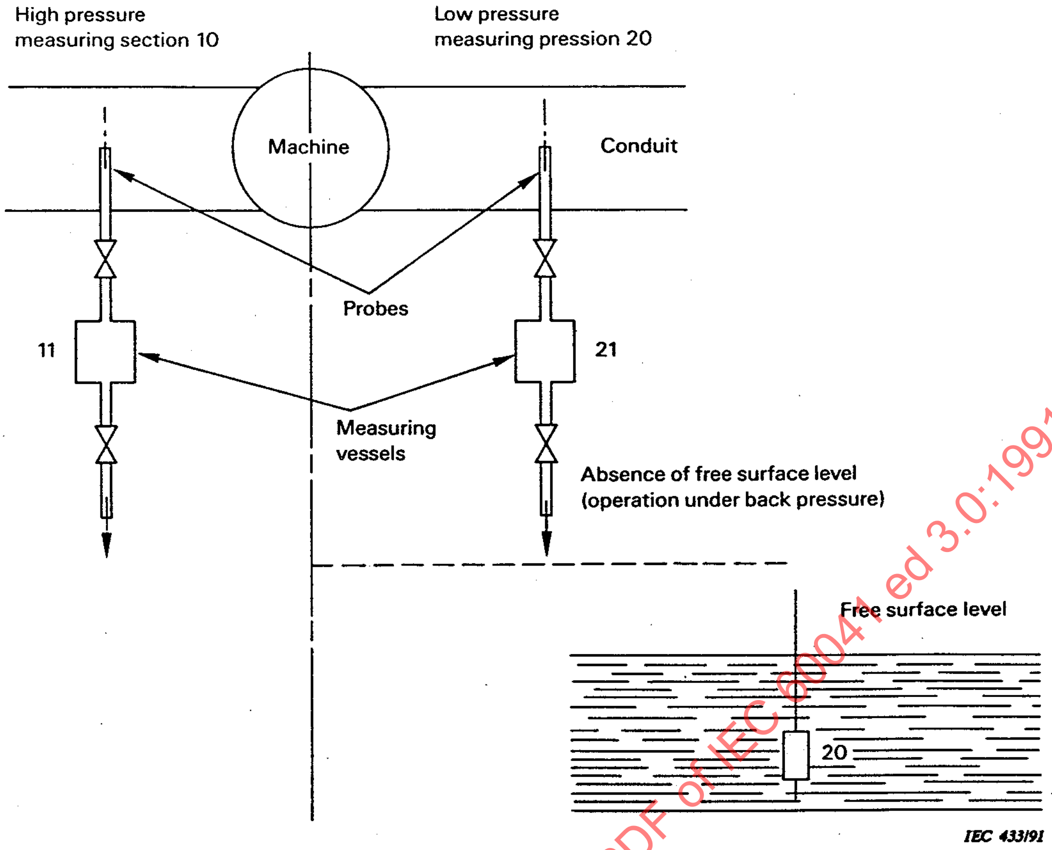


Figure 60 – General schematic diagram of measuring vessels

For the case where the low pressure side section is at atmospheric pressure, the temperature sensor is placed directly in the tailrace.

For the case where the low pressure side section is at a pressure higher than atmospheric pressure (operation under back-pressure), it may be useful, depending upon the selected operating procedure, to reduce water pressure within the measuring vessel.

The pressure and temperature terms in equation (1) may be determined by one of the two operating procedures described below which are practical variations of the method. The selection of operating procedure should be based upon the machine characteristics and quality of measuring apparatus available.

The velocities v_{11} and v_{21} are measured in the vessels.

The levels z_{11} and z_{21} are those of the middle points of the measuring vessels. Pressure values are expressed with reference to these levels. In practice, provided the difference in level between the mid-point of the measuring vessels and the reference point of the manometers does not exceed 3 m, it may be permissible to refer the levels and pressures to the reference point of the manometers.

For the corrective terms determining δE_m see 14.6.

When more than one measuring point is being used at any measuring section, the values of efficiency will be determined from individual connections between individual tappings. If the difference between any two individual values of efficiency is less than 1,5%, the value of the machine efficiency is taken as the mean of the individually measured values. Otherwise proceed as described in 14.5.4.

14.3.2 *Direct operating procedure*

This is characterized by the direct passage of water from the penstock at the high pressure side of the machine to the measuring vessel with a minimum of expansion. The pressure and temperature terms for E_m in equation (1) may be determined as follows:

$\bar{a}(p_{abs11} - p_{abs21})$	requires pressure gauges or transducers of high accuracy. Values of a are given in Table EV of Appendix E.
$\bar{c}_p(\Theta_{11} - \Theta_{21})$	requires thermometers of high accuracy (see 14.4.1.3). Values of c_p are given in Table EVI of Appendix E.

The thermometers shall be calibrated beforehand (see 14.3.4). Whenever this procedure is adopted, the partial expansion operating procedure (see 14.3.3) for one test point or in situ calibration of the thermometer will be untertaken for checking purposes.

$(p_{abs11} - p_{abs21})$ and $(\Theta_{11} - \Theta_{21})$ are to be measured simultaneously and at regular intervals.

The range of application of this operating procedure is general.

14.3.3 *Partial expansion operating procedure*

An expansion valve is located in the sampling circuit between the pipe or penstock at the high pressure side and the corresponding measuring vessel. The adjustment of this valve shall be very fine and stable so that, by partial expansion, temperature equality is achieved in the measuring vessels at the high pressure and low pressure side or at the temperature sensor that is placed directly in the tailrace.

Thus, in equation (1), the term $\bar{c}_p(\Theta_{11} - \Theta_{21})$ becomes zero and the determination of E_m essentially entails the measurement $(p_{abs11} - p_{abs21})$ with pressure gauges or transducers of high accuracy.

The thermometers shall be extremely sensitive and reliable (see 14.4.1.3). Their purpose is to record temperature equality.

In practice, it is desirable to establish graphically or by mathematical methods (e.g. by linear regression with a pocket computer) the relationship between $(p_{abs11} - p_{abs21})$ and $(\Theta_{11} - \Theta_{21})$.

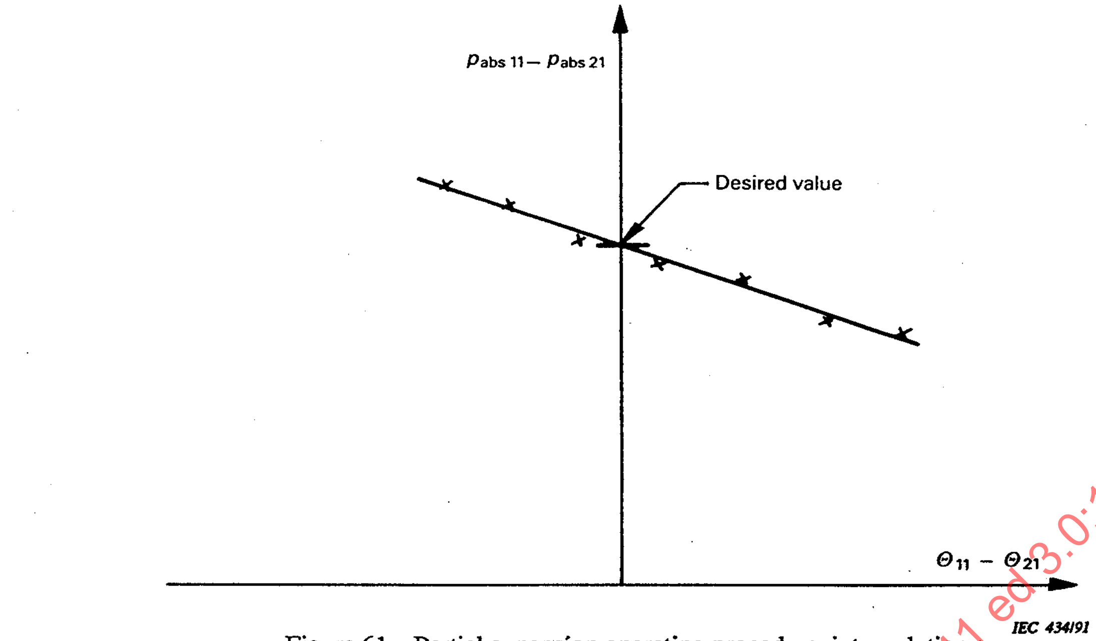


Figure 61 – Partial expansion operating procedure, interpolation

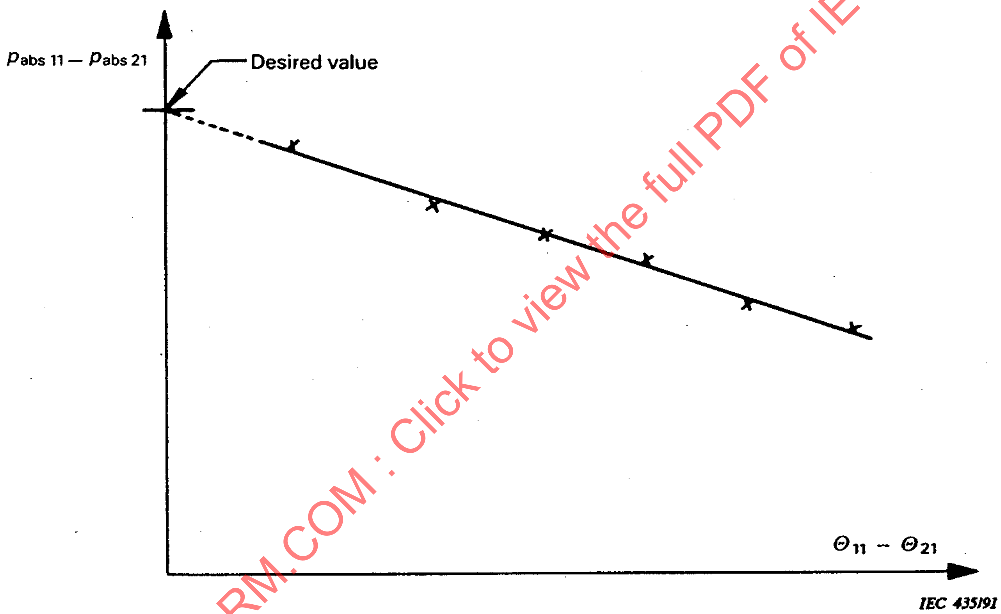


Figure 62 – Partial expansion operating procedure, extrapolation

In many cases p_{abs21} is practically constant (e.g. atmospheric pressure) and only p_{abs11} needs to be measured. The pressure value used for calculation is that obtained by graphical or mathematical interpolation for zero difference of temperature (see Figure 61).

This operating procedure is widely used, but its range of application is not altogether general:

- in the case of pumps, pressure at the low pressure side may be insufficient to ensure that the temperature of water expanded to atmospheric pressure in the measuring circuit is at least equal to that of the water at the high pressure side;
- in the case of turbines, temperature equality cannot be attained at high efficiency if the water temperature exceeds about 15 °C.

In these particular cases where water temperature equality is unattainable, graphical or mathematical extrapolation may be adopted if the range of pressure concerned is small compared with the pressure range accurately measured (see Figure 62).

The linearity of the thermometers must be previously verified.

14.3.4 *Thermometer calibration*

For the application of the direct operating procedure described in 14.3.2, the temperature-difference thermometer must be calibrated.

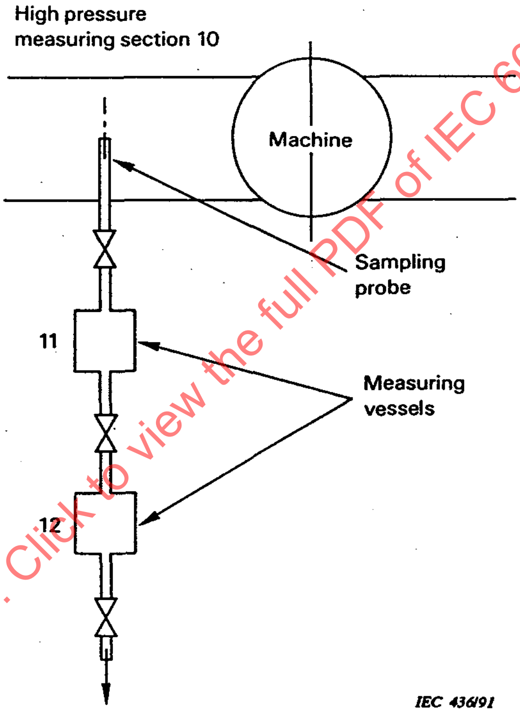


Figure 63 – Schematic diagram of measuring vessels for calibration of two thermometers

For calibration, two thermometers, or temperature sensors, for instance, are placed in two vessels, the locations 11 and 12 (Figure 63) being separated by an expansion valve through which water flows after having been withdrawn from the conduit. As the efficiency of the whole expander is zero, the transfer of specific mechanical energy is zero and:

$$E_m = \bar{a}(p_{abs11} - p_{abs12}) + \bar{c}_p(\Theta_{11} - \Theta_{12}) + \frac{v_{11}^2 - v_{12}^2}{2} + g(z_{11} - z_{12}) = 0$$

ou

$$-(\Theta_{11} - \Theta_{12}) = \frac{\bar{a}(p_{abs11} - p_{abs12}) + (v_{11}^2 - v_{12}^2)/2 + g(z_{11} - z_{12})}{\bar{c}_p}$$

Thus, the difference in temperature between the two vessels is calculated and the temperature-difference thermometer can be calibrated.

For this procedure it is essential that the expansion should be progressive and stable and the vessels well insulated from the surroundings.

The reading of the differential thermometer for a zero temperature difference must be calibrated over a total range, which includes the water temperature in the penstock, of 5 K. For this the two thermometer probes are placed together in water baths of at least three different temperatures within this range.

Note. – The properties of the water ρ, a and c_p (see Tables EII, EV and EVI in Appendix E) are valid only for pure water. Suspended matter, dissolved salt and undissolved gas can affect these values. Contents less than 0,10 g of suspended matter and 5 cm^3 of undissolved gas per kg of water at atmospheric pressure have a negligible effect. In extreme situations there also exists a certain influence on the calibration of the thermometer.

14.4 *Apparatus*

14.4.1 *Main measurements*

14.4.1.1 Sampling water circuits

Water samples from the conduit shall be taken by means of a probe fixed perpendicularly to the conduit and penetrating into the conduit. This probe shall have a perfectly smooth orifice at its end, of diameter equal to the internal diameter of the probe and pointing in an upstream direction. The distance of this orifice from the internal wall of the conduit shall be at least 0,05 m.

The probe shall be designed to avoid vibration and/or rupture and marked in such a manner that the orifice can be correctly oriented and identified.

The external diameter of the probe, in the vicinity of the sampling hole, may be in the range of 15 mm to 40 mm, the internal diameter being at least 8 mm. The external diameter may be increased gradually towards the wall in order to ensure sufficient mechanical strength, provided it does not influence the flow essentially (see Figure 64).

The measuring vessels shall be designed so that the flow velocity of the water inside is very low and good mixing occurs before the flow passes around the thermometer pockets. Particular construction arrangements are necessary to avoid, as far as possible, heat transfer at the walls of these pockets or by the connecting wires; for example, the wires shall be in contact with the wall under the insulation of the vessel.

The expansion orifices shall ensure a high degree of flow stability and, when adjustable, shall ensure steady progressive variation in discharge.

Exploration of flow in the open-channelled section requires the use of a suitable device to ensure that operating conditions are in accordance with the recommendations given in 14.5.1.2.1.

All active elements of the hydraulic circuits (pipes, expanders, vessels) shall be carefully insulated so that the sampling flow is of constant total energy. Any imperfections in the thermal insulation shall be taken into account by the following procedure:

a) It is assumed, as a first approximation, that the rate of heat exchange with the exterior is constant. The measured value of specific mechanical energy varies linearly with the inverse value of the sampling discharge.

b) The quantity E_m shall be measured for at least three sampling discharges.

c) A graph of E_m as a function of the inverse of the discharge permits, by extrapolation, determination of the correction required to E_m to allow for heat transfer (see Figure 65).

The above check shall be made for all points of the efficiency curve. However, if the correction is in the order of 0,2 % on efficiency, the number of measuring points for which these auxiliary measurements shall be made may be reduced by mutual agreement.

It is recommended that the probe be checked in the following manner, in as much as rupture is always possible, but difficult to see: in the absence of a sampling discharge, the pressure measured in the vessel shall be compared with the sum of the pressure measured at the pipe wall, plus the term $\rho v^2/2$. Any significant difference in this comparison shall be considered as being abnormal.

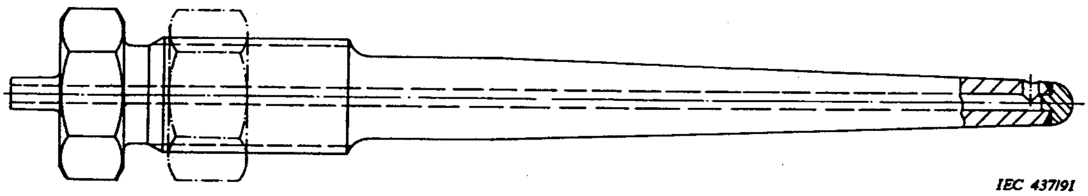


Figure 64 – Example of a sampling probe

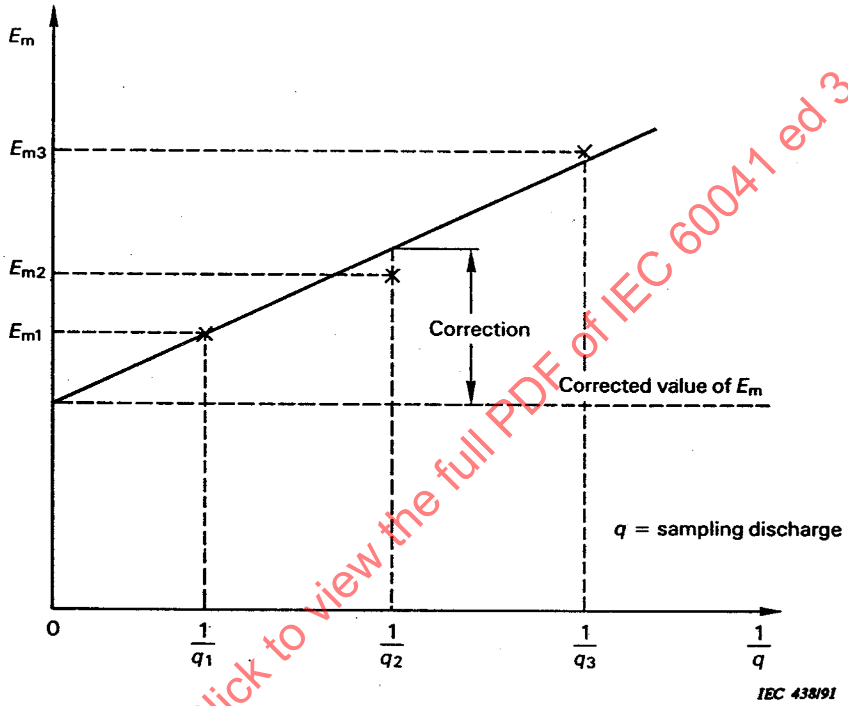


Figure 65 – Example of graphic determination of the correction in E_m to allow for heat transfer

14.4.1.2 Pressure measurement

It is recommended that the same manometer, pressure gauge or transducer be used for measuring E_m and E.

14.4.1.3 Temperature measurement

The accuracy and sensitivity of the temperature measuring instrumentation must be sufficient to provide an indication of the temperature difference between measuring points to at least 0,001 K.

The reading of the differential thermometer for a zero temperature difference must be determined before the test (see 14.3.4). This reading has to be checked during the test. Only small changes corresponding to a difference of temperature of 0,002 K are allowed and must be taken into account if necessary.

14.4.2 *Auxiliary measurements*

A measuring tank or flowmeter is necessary for checking the sampling discharge with an accuracy of about ±5 %.

The temperature of the water drawn off shall be continuously monitored by thermometers of at least ±0,05 K accuracy and 0,01 K sensitivity. The use of a recorder is recommended.

An apparatus shall be provided for measuring air flow and humidity to determine heat exchange with the surrounding atmosphere when aeration of the machine is needed (see 14.6.2.2).

14.5 *Test conditions to be fulfilled*

14.5.1 *Measuring sections and sampling conditions*

The measuring sections chosen to calculate E_m do not necessarily coincide with the high and low pressure reference sections. They are chosen according to the following considerations:

- heat exchange between water and the surroundings shall be within limits (especially as indicated in 14.5.3 and 14.6.2.1);
- no significant abnormalities of energy distribution occur within the sections.

In accordance with 2.3.1.3 and 2.3.1.4 the measured values must be adjusted to the reference sections.

In any case heat exchange must be taken into account (see 14.6.2.1).

14.5.1.1 High pressure measuring section

14.5.1.1.1 Turbines

The tappings at the high pressure side measuring section will be set near the machine. Location of the section in the immediate wake of a butterfly valve is prohibited.

Experience has shown that a single tapping point is generally sufficient for conduits whose diameter is less than 2,5 m. Two points are recommended for diameters between 2,5 m and 5 m. Three or four tapping points are recommended for a diameter larger than 5 m or for all cases where the total length of the conduit is less than 150 m.

A minimum distance of four pipe diameters upstream of the nozzle of a Pelton turbine shall be maintained (keeping clear of such features as bends, support vanes, etc.). In the case where there are several jets, the part of the pipe immediately upstream of the first bifurcation is a permissible location. If this part of the pipe is inaccessible and provided that such features as mentioned above are avoided, a tapping on the pipe leading to one nozzle may also be suitable.

14.5.1.1.2 Pumps

At least two diametrically opposed tapping points shall be provided. Three or four tapping points are recommended for a diameter larger than 5 m. In all cases, different depths of penetration for the probe at each of these points are recommended.

The section shall be located at a reasonable distance from the machine, for example five times the impeller diameter.

14.5.1.2 Low pressure measuring section

14.5.1.2.1 Open measuring section

The measuring section with free surface at the low pressure side of a turbine must be located at such a distance from the runner that adequate mixing is ensured but no farther than necessary because of heat exchange. Distances from the runner of four to ten maximum runner diameters for impulse turbines have been found to be satisfactory.

A section with free surface at the low pressure side of a pump can be used as the measuring section if the temperature is sufficiently constant in all points of this section. The measuring section shall be no farther than necessary from the impeller because of heat exchange.

Exploration of temperature variation across the measuring section shall be made in at least six points. If there is a difference of at least 1,5% between the efficiency values at any two locations, proceed as described in 14.5.4.

14.5.1.2.2 Closed measuring section

The measuring section on the low pressure side shall be located away from the runner at a distance of at least five times the maximum runner diameter for turbines, at least three times the maximum impeller diameter for pumps.

a) Measuring section accessible

Three or four tapping points are recommended in the measuring section. If this section is circular, the tapping points will be positioned at 120° or at 90° to each other. If this section is rectangular, the tapping points will be positioned in the middle of each side, if possible.

In addition, in the case of a turbine different depths of penetration for the probe at each of these points are recommended. If there is a difference of at least 1,5% between the efficiency values at any two locations, proceed as described in 14.5.4.

b) Measuring section inaccessible

In this case, the only possibility for exploring the temperatures is by means of a tapping device located inside the conduit which may be totally or partially full. This device consists of at least two tubes which collect the partial discharges issuing from several orifices positioned at equal intervals along each tube. The device should give either a single discharge or, better, an individual discharge for each tube, to obtain information on the energy distribution.

The conditions for the use of this device giving a representative sample are as follows:

a) Diameter of orifices small compared to that of the tubes (orders of size: 7 mm for the orifices, at least 30 mm for the tubes).

b) Interconnecting piping of relatively large diameter and with smooth walls so as to satisfy condition *d)* below.

c) Interconnecting piping designed to avoid heat exchange by lagging with an insulating material or jacketing by water taken from the main flow, particularly when passing through concrete walls.

d) The sample discharge controlled by a suitable regulating device at the outlet of the piping to a value close to:

$$q = v \cdot i \cdot A$$

where:

v is the average flow velocity in the measuring section

i is the number of orifices in the tubes

A is the cross section of an orifice

This discharge should be of about 0,005 $m^3 \cdot s^{-1}$ in order to reduce the heat exchange to a negligible value.

If there is a difference of at least 1,5% between the efficiency values at any two locations (corresponding to two different tubes) proceed as described in 14.5.4.

14.5.2 *Repetition of measurements*

For each run, each of the quantities defining the hydraulic efficiency of the machine shall be subject to repeated measurements made at equal intervals during the test, the number of readings being strongly dependent on the stability of the measurement (about 5 to 10 readings).

14.5.3 *Particular flow arrangements*

Any inflow of auxiliary discharge between the high pressure and low pressure sections is not recommended, when the mixing of this water and the main discharge may not be complete.

In each case where auxiliary discharges are added or subtracted between the high pressure and low pressure measuring sections (e.g., leakage from the seal not led into the main discharge), particular measuring arrangements shall be taken for balance of power (see Appendix H) in order to allow the computation of E_m as explained at 14.2.

If the low pressure side of the turbine or pump is very close to the ventilation duct of the electric machine, exploratory temperature measurements shall be taken at 12 points. The wall will have to be insulated if there are deviations of the order of 0,5% in efficiency, indicative of a well-defined positive temperature gradient between the centre of the section and the wall common to both flows.

14.5.4 *Unfavourable operating conditions*

Measurements by the thermodynamic method are not recommended under unfavourable measuring conditions such as irregular temperature or velocity distribution in the measuring sections, unstable temperature etc., which may occur at some operating conditions. For these operating conditions it is strongly recommended (see 15.1.3) to use index tests as described in 15.2. The relative discharge measurement should be calibrated by the thermodynamic method at favourable operating conditions.

14.6 *Corrective terms*

In some cases (see 14.2) corrective terms must be introduced in equation (1).

14.6.1 *Variations of temperature*

It is advisable to take measurements during periods when the conduit (high pressure side of turbine, low pressure side of pump if existing) is not exposed to strong sunlight. It is also recommended that secondary inflows should be avoided. Moreover, if the conduit supplies several units, the power of units not under the test shall be maintained constant.

As indicated in 14.4.2, a check on the change in temperature of water shall be carried out. A slow and continuous variation of temperature, less than 0,005 K per minute during one run, is admissible. Nevertheless, a suitable correction shall be applied to E_m from the temperature variation $\Delta\Theta/\Delta t$ measured in $K \cdot s^{-1}$ and calculated as follows:

– for turbines: $$\delta E_m = \bar{c}_p \frac{\Delta\Theta}{\Delta t}(t_a - t - t_b)$$

– for pumps: $$\delta E_m = \bar{c}_p \frac{\Delta\Theta}{\Delta t}(t_a + t - t_b)$$

where:

t is the time, in seconds, taken by the water to pass through the machine between the two measuring sections

t_a is the time, in seconds, taken by the water to pass from the high pressure tapping point to the corresponding measuring vessel

t_b is the time, in seconds, taken by the water to pass from the low pressure tapping point to the corresponding measuring vessel

14.6.2 *Extraneous heat exchange*

Only heat exchange between the main flow through the hydraulic machine and surroundings will be dealt with here. Heat exchange concerning the sampling circuit is treated in 14.4.1.1. The possibility of heat exchange with the ventilation circuits was mentioned in 14.5.3.

14.6.2.1 Heat exchange through the walls

As heat exchange through concrete and rock walls is negligible, only heat exchange through metal walls will be considered. The following correction for heat exchange with dry air shall be applied:

$$\delta E_m = \pm \frac{1}{(\rho Q)_1} \cdot A \cdot P_{a-w} \cdot (\Theta_a - \Theta_w)$$

("+" for turbines, "–" for pumps)

where:

P_{a-w} is the power exchanged coefficient, in $Wm^{-2}K^{-1}$
From experience, P_{a-w} is considered equal to 10 $Wm^{-2}K^{-1}$

A is the area of exchange surface, in m^2

Θ_a is the ambient air temperature, in K

Θ_w is the temperature of water in the turbine or the pump, in K

The possible effect of condensation from ambient air upon the machine surfaces must also be considered. If there is considerable condensation, the resultant increase in heat exchange (not more than 400 %) shall either be calculated from the air humidity or efficiently depressed by sufficient thermal insulation of the metal surfaces by screening jackets.

Calculation of the influence of condensation can be made with sufficient accuracy by increasing the correction δE_m for the dry heat exchange in the proportion ψ:

$$\psi = \frac{1}{1 - kx/\Delta i}$$

where:

Δi is the specific enthalpy difference, in $J \cdot kg^{-1}$

x is the difference of relative water content of the air, in $kg \cdot kg^{-1}$

k $= 2,5 \times 10^6 \; J \cdot kg^{-1}$

The values Δi and x are to be derived from the condition of the humid air surrounding the turbine and that of saturated air at metal surface temperature and shall be taken from a normal Mollier diagram for humid air.

14.6.2.2 Direct exchange with the ambient air

Where water and air currents are closely mixed (aeration), a correction of the mechanical energy E_m shall be applied as follows:

$$\delta E_m = \pm \frac{\rho_a \cdot Q_a}{(\rho Q)_1} \cdot [c_{pa} \cdot (\Theta_a - \Theta_{20}) + K_w \cdot (\alpha_a - \alpha_{20})]$$

(where "+" for turbine, "–" for pump)

where:

Q_a is the volumetric discharge of air ($m^3 s^{-1}$)

c_{pa} is the specific heat of air at constant pressure ($J\,kg^{-1}\,K^{-1}$)

Θ_a is the temperature of injected air (K)

Θ_{20} is the temperature of water in the measuring section 20 (K)

K_w is the water evaporation latent heat at normal atmospheric pressure ($J\,kg^{-1}$)

α_a is the ratio between steam and air masses at the injection point

α_{20} is the ratio between steam and air masses in section 20

Assuming:

$\rho_a = 1,3\;kg\,m^{-3}$ $\qquad c_{pa} = 1\,000\;J\,kg^{-1}\,K^{-1}$

$\rho_1 = 1\,000\;kg\,m^{-3}$ $\qquad K_w = 2,5 \times 10^6\;J\,kg^{-1}$

the above mentioned formula becomes:

$$\delta E_m = \pm \frac{Q_a}{Q_1} \cdot \frac{1}{p_{a0}} \cdot \frac{1}{\Theta_a} [350\, p_a \cdot (\Theta_a - \Theta_{20}) + 545 \cdot 10^3 (\varepsilon \cdot p_{s,\Theta_a} - p_{s,\Theta_{20}})]$$

where:

p_a is the presssure of humid air at its contact with water (Pa)

p_{a0} is the normal atmospheric pressure (10^5 Pa)

ε is the relative humidity of air (as a decimal value and not as a percentage)

p_{s,Θ_a} is the saturated steam pressure at temperature Θ_a (Pa)

14.6.2.3 Heat exchange with still water areas

In the case of exchange with still water areas (e.g. several turbines discharging into a common tailrace) a physical separator shall be placed in these areas in order to avoid mixing of the flow with the still water areas which may be at a different temperature from that of the flowing water.

14.6.3 *Limit of corrections*

Measurement shall not be considered valid whenever the corrections obtained from the measuring procedures or calculations given above exceed one of the following limits in relation to E_m:

- heat exchange between water in the sampling circuit and surroundings (see 14.4.1.1) at high pressure and low pressure measuring sections .... 1 %

  in the special case of extraction using pipes traversing concrete walls (see 14.5.1.2.2 *b*)) .... 1,5 %
- variation of temperature at inlet and extraneous exchange:

  arithmetical sum of the corrections δE_m detailed in 14.6.1 and 14.6.2 .... 2 %

14.7 *Uncertainty of measurement*

The total uncertainty in efficiency f_η is obtained from the root-sum-square of random and systematic uncertainties in the numerator and denominator of the efficiency expressions given in 2.3.9.1.

Disregarding the term:

$$\left(\frac{\Delta P_h}{P_m} \cdot E_m\right),$$

it is:

$$f_\eta = \pm\sqrt{(f_{E_m})^2 + (f_E)^2}$$

The systematic uncertainties f_E and f_{E_m} are examined in Appendix A which also includes an example of calculation. For the determination of E_m the systematic uncertainty in the temperature difference measurement $\Delta\Theta$ exists for all methods (direct and partial expansion operating procedures): the value to be expected in normal conditions is ±0,001 K.

It is reasonable to assume that the relative systematic uncertainty in correction due to each secondary phenomenon is in the order of 20%.

The systematic uncertainty due to the absence of exploration of energy distribution can amount to:

	turbine	pump
– high pressure side	± 0,2 %	±0,6 %
– low pressure side	± 0,6 %	±0,4 %

of the specific mechanical energy.

15. Index tests

15.1 *General*

15.1.1 *Object*

The methods of discharge measurement described in Clause 10 are fundamental methods as they give among others the absolute values of discharge and efficiency, which determine whether or not the machine meets the guarantees (see 3.2). On the contrary the index tests give only relative values of the above-mentioned quantities and are considered as secondary methods. They are normally used during the commissioning and operation of the machine (see IEC 545 and 805) and can be considered as a part of the field acceptance test only when the relative discharge measuring method is calibrated by a method accepted in this standard or when it is used to determine the correct relationship between runner/impeller blade angle and guide vane opening in the case of a double-regulated machine (see 5.1.4). In some cases an index test can be used, if both parties agree, to check the power guarantee.

Except for the cases described above, the results of index tests are for information and should never be used for assessment of penalty or bonus payments or any other contractual consequences concerning guarantees.

15.1.2 *Definitions*

An index value is an arbitrarily scaled value. Relative values are derived from index values by expressing them as a proportion of the value at an agreed condition.

The index efficiency is calculated using the measured values of specific hydraulic energy (see 15.3.1) and power, and the discharge, measured as an index value by an uncalibrated device. Relative efficiency is expressed as a proportion of any index efficiency at a reference index efficiency, for example the maximum value.

15.1.3 *Applications*

An index test may be used as a part of the field acceptance test for any of the following purposes:

- to determine the correct relationship between runner/impeller blade angle and guide vane opening for most efficient operation of double-regulated machines. This procedure may essentially reduce the number of points for which the actual efficiency must be determined and thus the time needed for the acceptance test (see 5.1.4 and 5.1.5).
- to provide additional test data during a field efficiency test. This is particularly important if the primary method shows excessive uncertainties or falls out in a certain operating range. The index discharge device in this case shall be calibrated by discharge field measurements performed in the favourable operating range (see 14.5.4).

In addition to the field acceptance test, an index test may be useful also for other purposes, such as:

- to determine the performance characteristics as expressed by the relative values of power, discharge and efficiency;
- to check the power guarantee if both parties agree;
- to extend information on performance outside the guaranteed range if the index discharge device has been calibrated;
- to assess the change in efficiency and/or power due to the onset of cavitation resulting from a change of suction specific potential energy and/or specific hydraulic energy of machine;

- to assess the change in efficiency and/or power of the machine resulting from wear, repair or modification. When using an index test for this purpose it must be noted that modifications may affect flow patterns in the measuring sections;
- to obtain data for permanent discharge measuring instruments by assuming an absolute value of turbine efficiency at some operating point or by calibration with field efficiency test results;
- to optimize the operation of a power station with several units;
- to compare the index curves on the prototype with the curves expected on the basis of model tests.

Index tests are of reduced value if the available operating range of the machine is not such that a reasonable portion of the performance curve can be covered.

15.2 *Relative discharge measurement*

An index test does not require any absolute measurement of discharge. For the measurement of relative discharge one of the following methods may be used.

15.2.1 *Relative discharge measurement by differential pressure methods*

15.2.1.1 Measurement of the pressure difference between suitably located taps on the turbine spiral case

This is the Winter-Kennedy method and discharge is usually well represented by $Q = kh^n$ where h is the reading of a differential manometer connected between the taps and n theoretically equal to 0,5 (see 15.5).

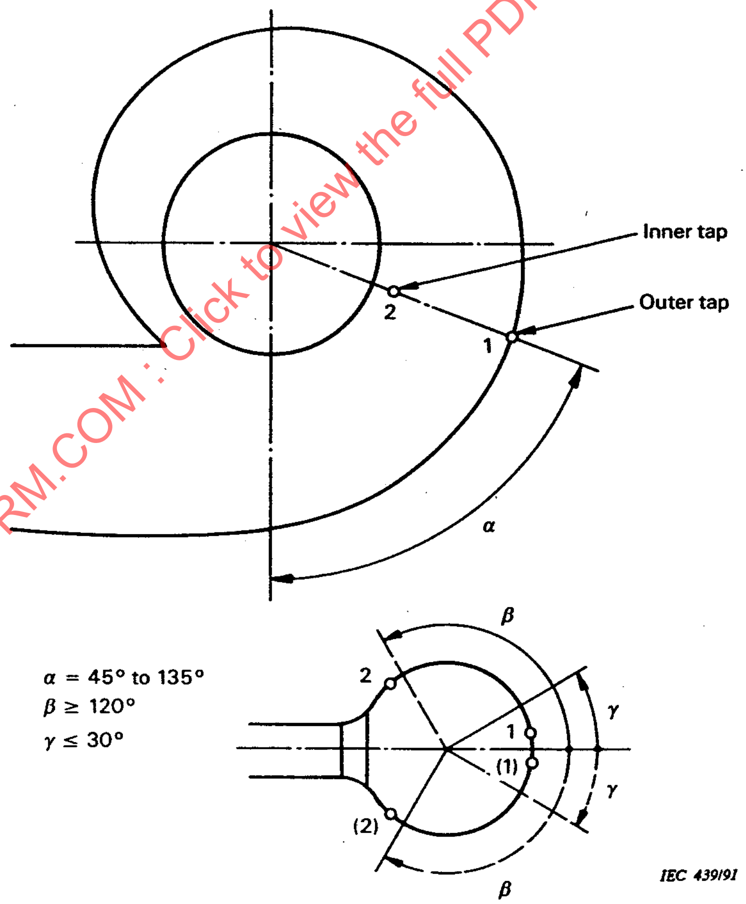


Figure 66 – Location of taps for Winter-Kennedy method of discharge measurement through a turbine equipped with a steel spiral case

The Winter-Kennedy method is applicable to turbines only. In installations with a steel spiral case it requires taps located as a general rule in the same radial section of the spiral case (see Figure 66). The outer tap "1" is located at the outer side of the spiral. The inner tap "2" shall be located outside of the stay vanes on a flow line passing midway between the two adjacent stay vanes. It is recommended that a second pair of taps be located in another radial section.

With a horizontal spiral case the taps shall be arranged in the upper half because of the better possibility of purging. The gauge taps should not be in proximity to weld joints or abrupt changes in the spiral section.

In the application of the Winter-Kennedy method to turbines with a concrete semi-spiral case the taps have to be located in a similar way in a radial section of the concrete case as shown in Figure 67. Also here it is good practice to locate two pairs of taps.

The outer tap 1 (or 1′) shall be located sufficiently far from the corners. The inner tap 2 (or 2′) shall be located outside of the stay vanes on a flow line passing midway between two adjacent stay vanes. A third tap 3 may be arranged on a stay vane, preferably at the elevation of the centerline of the guide vanes, or on the roof between two stay vanes.

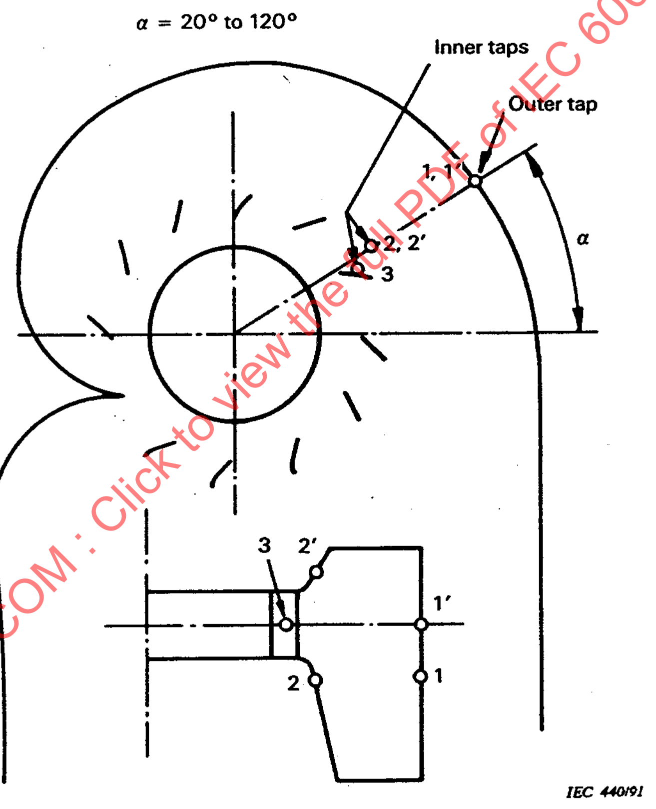


Figure 67 – Location of taps for Winter-Kennedy method of discharge measurement through a turbine equipped with concrete semi-spiral case

15.2.1.2 Measurement of the pressure difference existing between suitably located taps in a converging part of the penstock

A suitable convergence must exist to give a pressure difference large enough to be measured accurately. Discharge may be assumed proportional to the square root of the differential pressure (see 15.5).

Two pressure taps are required located at two cross-sections of different areas. The most stable pressure difference will be obtained if both taps are located on the converging part of the pipe. However, the differential pressure thus obtained is not the maximum possible and for this reason it may be preferable to locate one tap a short distance upstream of the convergent part and the second not less than half a diameter downstream of the convergent part.

15.2.1.3 Measurement of the pressure difference between suitably located taps in tubular turbines

In application of the differential pressure method of measuring relative discharge through a bulb unit the taps may be located as shown in Figure 68. The tap for higher pressure may be arranged at the stagnation point of the bulb (point 1) or of the access shaft (point 1′) and the tap for lower pressure should be located on the wall directly upstream from the guide vanes, however with sufficient distance from their profile nose at maximum guide vane opening (point 2 or 2′). Discharge may be assumed proportional to the square root of the differential pressure (see 15.5).

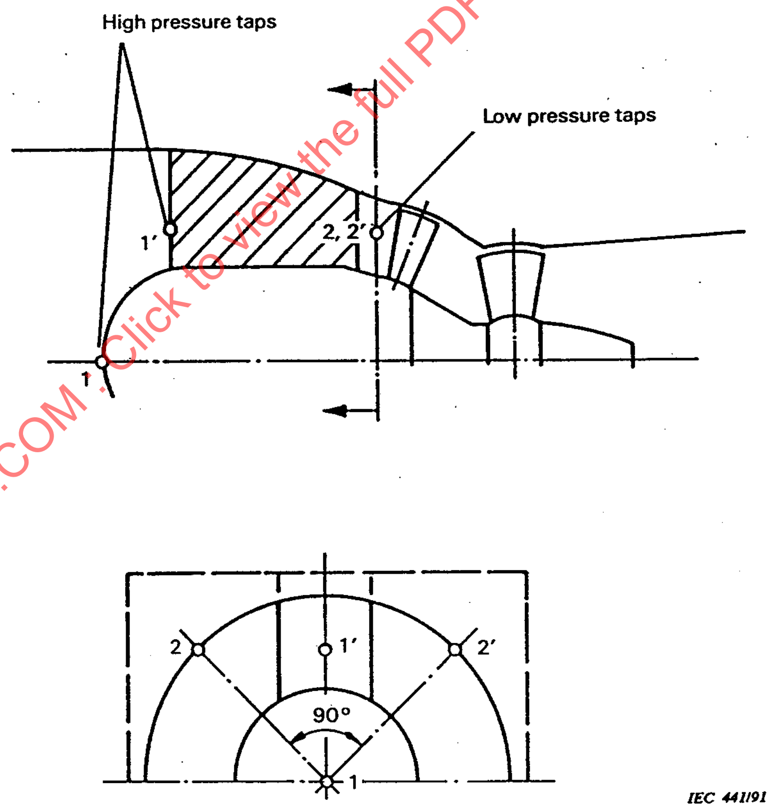


Figure 68 – Location of taps for differential pressure method of discharge measurement through a bulb turbine

For all other types of tubular turbines (e.g., pit turbine) analogous application may be made.

15.2.1.4 Measurement of the pressure difference between suitably located taps in the pump suction tube

Discharge may be assumed proportional to the square root of the differential pressure.

15.2.1.5 Specifications for pressure taps and gauge piping

The pressure taps used shall comply with the dimensional requirements of 11.4.3. Since the differential pressures to be measured may be small, special attention should be given to removing surface irregularities.

An upward sloping pipe is normally required for test purposes (see 11.4.4) since it is most easily purged. With prolonged use, an upward sloping pipe may gradually accumulate air and thus require purging, and for this reason where the pressure taps are to be used for a permanently operating discharge recorder it may be preferable to locate the pressure taps below the axis of the spiral case (see Figure 66) and use pipework with a continuous downward slope to the discharge recorder or differential pressure gauge. In this case a device is recommended to collect the possible debris.

15.2.2 Relative discharge measurement by acoustic method

This method (see Appendix J) is suitable for index testing, due to the good repeatability of measurements and good linear characteristic. For index test applications of the acoustic method, one single-path system or a double-plane single-path system, as shown in Figures 69 and 70, may be sufficient.

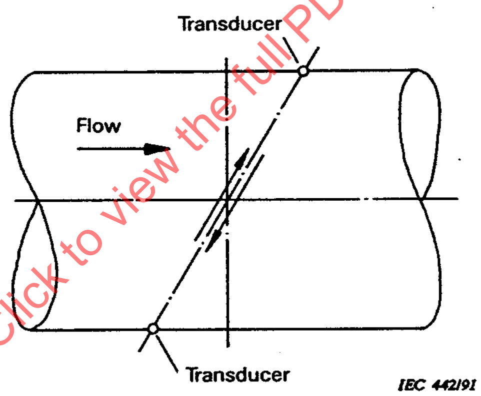


Figure 69 – Acoustic method of discharge measurement: example for single path system (successive signal transmission)

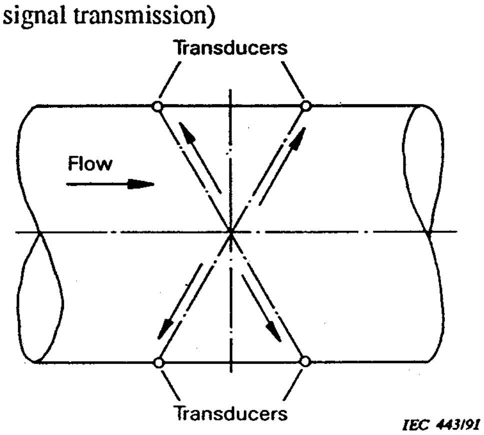


Figure 70 – Acoustic method of discharge measurement: example for double plane single path system (synchronous or successive signal transmission)

15.2.3 *Other methods*

15.2.3.1 Measurement of the needle stroke on Pelton turbines

It may be used to give an index discharge provided that the discharge/stroke characteristic shape has been checked by tests on a homologous model of the turbine and great care is taken to ensure that, during the test, the needle, nozzle and support vanes are clean and in good order.

15.2.3.2 Measurement by means of one single current-meter suitably located

This index method is commonly used particularly for low head turbines.

15.2.3.3 Other methods of obtaining index discharge

Other methods may be used (for instance differential pressure in a bend, in a divergence etc.), provided they give a representative value.

15.3 *Measurement of other quantities*

15.3.1 *Specific hydraulic energy*

The specific hydraulic energy of the hydraulic machine is determined in accordance with Clause 11. When only a relative discharge by index test is measured, specific kinetic energies can only be estimated. This may be done by assuming a value of turbine efficiency, usually the peak value, and thus estimate the discharge.

15.3.2 *Power*

The power of the hydraulic machine or of the complete unit is determined in accordance with Clause 12. In some cases it is sufficient to use the switch board instruments.

15.3.3 *Rotational speed*

The rotational speed of the hydraulic machine is determined in accordance with Clause 13. In some cases it is sufficient to use the switch board instruments.

15.3.4 *Machine openings*

The relevant openings shall be recorded for each run.

Attention shall be given to the accurate calibration of the openings against an external scale. The calibration should include a check that differences between individual openings are not significant.

15.4 *Computation of results*

15.4.1 The test data shall provide for each run the index discharge Q_i, the specific hydraulic energy E, the power of the machine P, the rotational speed n and the machine openings.

15.4.2 Relative turbine efficiency is given by $\eta_{rel} = (P/E \cdot Q_i)/(P/E \cdot Q_i)_{ref}$

relative pump efficiency is given by $\eta_{rel} = (E \cdot Q_i/P)/(E \cdot Q_i/P)_{ref}$

relative discharge is given by $Q_{rel} = Q_i/Q_{i\,ref}$

$Q_{i\,ref}$ is often estimated assuming a probable absolute value for the maximum relative efficiency, for instance the maximum guaranteed or expected value at the same specific hydraulic energy measured during the test.

15.5 *Uncertainty of measurement*

If the index test is a part of the field acceptance test and absolute values are derived from relative discharge measurements, the index discharge device being calibrated by means of an absolute method (see 15.1.3), the total uncertainty of the calibration method becomes the systematic uncertainty of the discharge measurement.

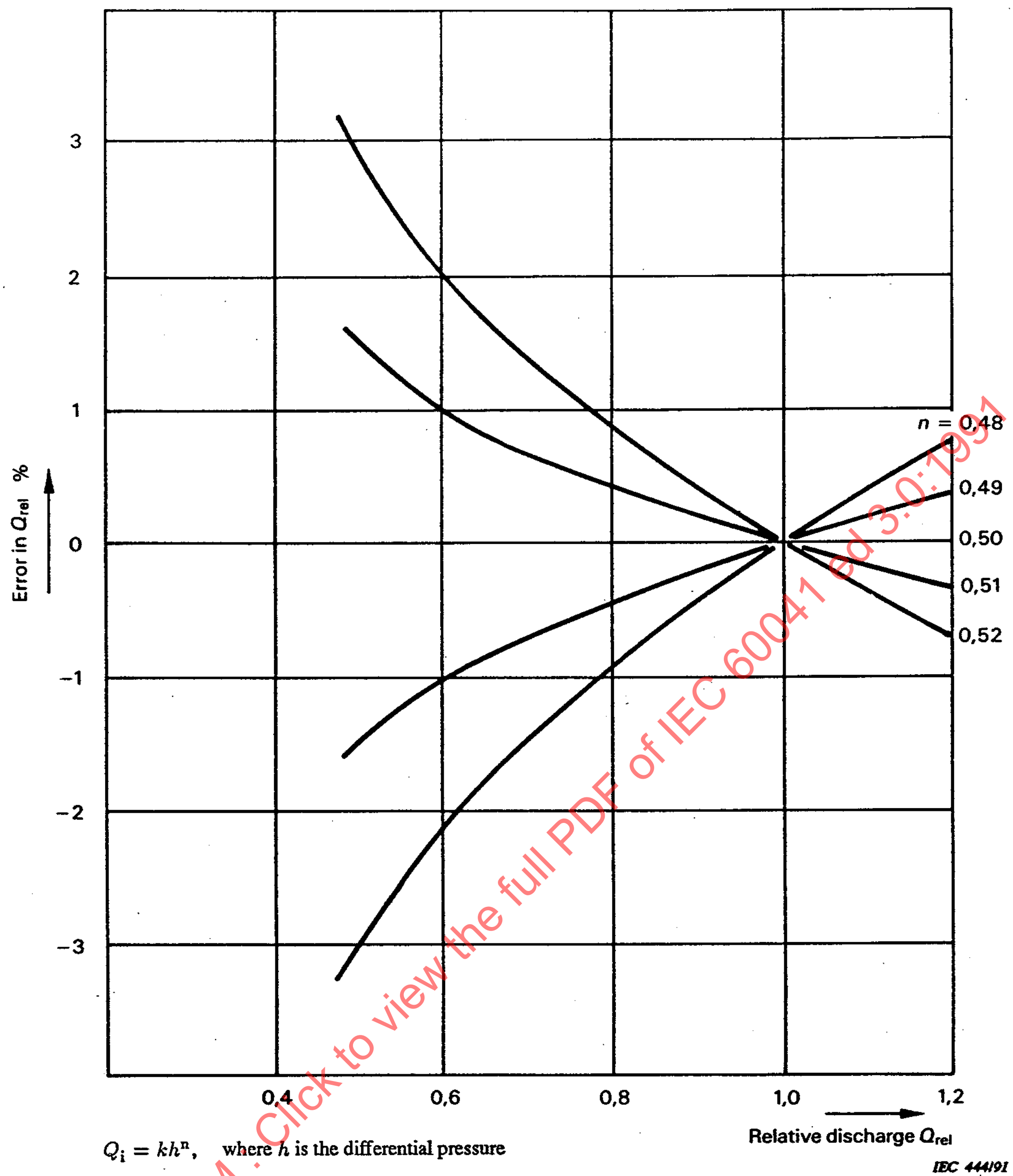
In other cases the systematic errors, if they are a constant percentage (although unknown in magnitude), do not affect the results.

The main systematic error which can affect the index test in the case of measurement of index discharge by differential pressure methods (see 15.2.1) arises from possible deviation of the exponent n theoretically equal to 0,5 in the equation relating index discharge to differential pressure. Various factors may produce different exponents. The widest deviations in exponent occasionally encountered are 0,48 to 0,52 usually under such unfavourable circumstances as low spiral velocities or semi-spiral construction. The effects of these deviations in exponent n on relative discharge are shown in Figure 71.

Random errors affect the results and a sufficient number of points should be made in accordance with the procedures set out in Appendix D.

The main systematic error which can affect the index test in the case of measurement of index discharge by the acoustic method arises from non-linearity attributable to cross-flow effects, or changing velocity distribution.

When using local velocity measurement with a single current-meter, the main error arises from the possible changes in velocity distribution, so that the ratio of the mean flow velocity to the measured local velocity may not remain constant when the discharge varies.



$Q_i = kh^n$, where h is the differential pressure

$Q_{rel} = Q_i / Q_{i\,ref}$

The error is arising from assuming $n = 0,5$ when true value is 0,48 to 0,52.

Figure 71 – Differential pressure methods – Effect of the deviation in the exponent n on the computation of relative discharge