

Method for

Measuring the efficiency of hydraulic turbines, storage pumps and pump-turbines (thermodynamic method)

[IEC title: Thermodynamic method for measuring the efficiency
of hydraulic turbines, storage pumps and pump-turbines]

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The organizations marked with an asterisk in the above list, together with the following, were directly represented on the committee entrusted with the preparation of this British Standard:

Institution of Civil Engineers	North of Scotland Hydro-electric Board
Institution of Electrical Engineers	Power Generation Association (BEAMA)

This British Standard, having been prepared under the direction of the Mechanical Engineering Standards Committee, was published under the authority of the Executive Board and comes into effect on 29 February 1980

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National foreword

This British Standard was prepared under the direction of the Mechanical Engineering Standards Committee and is identical with IEC Publication 607 “*Thermodynamic method for measuring the efficiency of hydraulic turbines, storage pumps and pump-turbines*” published in 1978 by the International Electrotechnical Commission (IEC).

Terminology and conventions. The text of the International Standard has been approved as suitable for publication, without deviation, as a British Standard. Some terminology and certain conventions are not identical with those used in British Standards; attention is especially drawn to the following:

The comma has been used in tables as a decimal marker. In British Standards it is current practice to use a full point on the baseline as a decimal marker.

In the titles of Table I, Table II and Table III unit symbols have been printed in italic (sloping) type instead of roman (upright) type as required by convention (as described in BS 0 “*A standard for standards*” Part 4 “*BSI editorial practice*”).

Cross-references. There are no British Standard equivalents for IEC 41 and IEC 198 to which references are made in clause 4 and 6.1.

The technical committee has reviewed their provisions, and has decided that they are acceptable for use in conjunction with this standard.

NOTE *Textual error.* When adopting the text of the International Standard, the errors listed below were noticed. They have been corrected in this British Standard and have been reported to IEC in a proposal to amend the text of the International Standard.

In 2.6 Pressure, in the unit column, P_a has been deleted and replaced by Pa.

In 2.7 Mass per unit area, in the definition column, $\frac{1}{\rho}$ has been deleted and replaced by $\frac{1}{\rho}$.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 23 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Object and scope

1.1 Purpose of the standard

This standard serves as a basis for the measurements to be made on hydraulic turbines, storage pumps and pump-turbines and for the computation of their efficiency applying the thermodynamic method. This method is based on the evaluation of the energy per unit mass of water delivered to a turbine shaft or received by water from a pump shaft. It may be determined by measurements of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water.

This standard may be used for acceptance tests or for any other efficiency test.

1.2 Excluded topics and limitations

Technological aspects of 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. The only requirements of instruments are to satisfy conditions stipulated in this standard (accuracy, heat exchange, etc.).

Due to the lack of uniformity in values measured at the inlet and outlet 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 scope of this method is limited and it can only be used for heads in excess of 100 m. However, under highly favourable conditions, the range could be extended to cover lower heads subject to an analysis of the accuracy of the measurements.

1.3 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 machine through which it is flowing.

In the case of actual machine operation, the energy per unit mass delivered to a turbine shaft or received by water from a pump shaft may be determined by measurement of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water. This exchange of energy will be referred to as “mechanical energy per unit mass” (see Sub-clause 2.2 and Clause 3).

In the case of ideal operation, i.e. frictionless flow (assuming identical pressures at the inlet and at the outlet and an identical temperature at the *inlet* as in actual operation), the same application can be used for calculating the ideal energy per unit mass delivered to a turbine shaft or received from a pump shaft. Such energy is dependent solely upon the properties of the water and the characteristics of the hydroelectric plant. It is referred to as “hydraulic energy per unit mass” (see Sub-Clause 2.1 and Clause 4).

The need to measure mass rate of flow is eliminated by using the two values of energy per unit mass calculated as above.

The above principle presupposes that all losses in hydraulic machines are dissipated in the flow. In actual operation, friction losses in the bearings may be dissipated differently. In this case, a corresponding correction is made to mechanical energy per unit mass (see Sub-Clause 2.4).

2 Terms, definitions, symbols, units

Term		Definition	Symbol	Unit
2.1	Hydraulic energy per unit mass^a	The energy per unit mass delivered to a turbine shaft or received from a pump shaft in the case of ideal machine operation $e_h = \bar{v}(p_{1'} - p_{2'}) + \frac{V_{1'}^2 - V_{2'}^2}{2} + g(z_{1'} - z_{2'})$ The measurement points for determining e_h are marked: 1', 2', etc. (see Figure 1, page 4)	e_h	$\text{J} \cdot \text{kg}^{-1}$
2.2	Mechanical energy per unit mass^a	The energy per unit mass delivered to a turbine shaft or received from a pump shaft in the case of actual operation $e_m = \bar{a}(p_{1-1} - p_{2-1}) + \bar{c}_p(T_{1-1} - T_{2-1}) + \frac{V_{1-1}^2 - V_{2-1}^2}{2} + g(z_{1-1} - z_{2-1}) + \Delta e_m$ The measurement points for determining e_m are marked: 1, 1-1, 1-2, 2-1, etc. (see Figure 1)	e_m	$\text{J} \cdot \text{kg}^{-1}$
2.3	Corrective term for energy due to secondary phenomena	Δe_m is calculated according to the recommendations given in Clause 6	Δe_m	$\text{J} \cdot \text{kg}^{-1}$
2.4	Energy per unit mass corresponding to contractual losses	Energy per unit mass corresponding to contractual losses in the hydraulic machine which are not removed by water between the measuring sections (e.g. losses through bearings, where applicable)	e_x	$\text{J} \cdot \text{kg}^{-1}$
2.5	Machine efficiency	For a turbine: $\eta = \frac{e_m - e_x}{e_h}$ For a pump: $\eta = \frac{e_h}{e_m + e_x}$		
2.6	Pressure	Pressure above atmospheric pressure	p	Pa

^a Use of the term "energy per unit mass" is considered to be preferable to "energy per unit weight" because it offers a more general meaning. Nevertheless, energy per unit weight (i.e. specific head for the installation considered) can be used as a basis. Conversion of numerical values expressing energy per unit mass into head is ensured by dividing the former by $\bar{g}$, the mean value for acceleration due to gravity between the extreme levels of the installation.

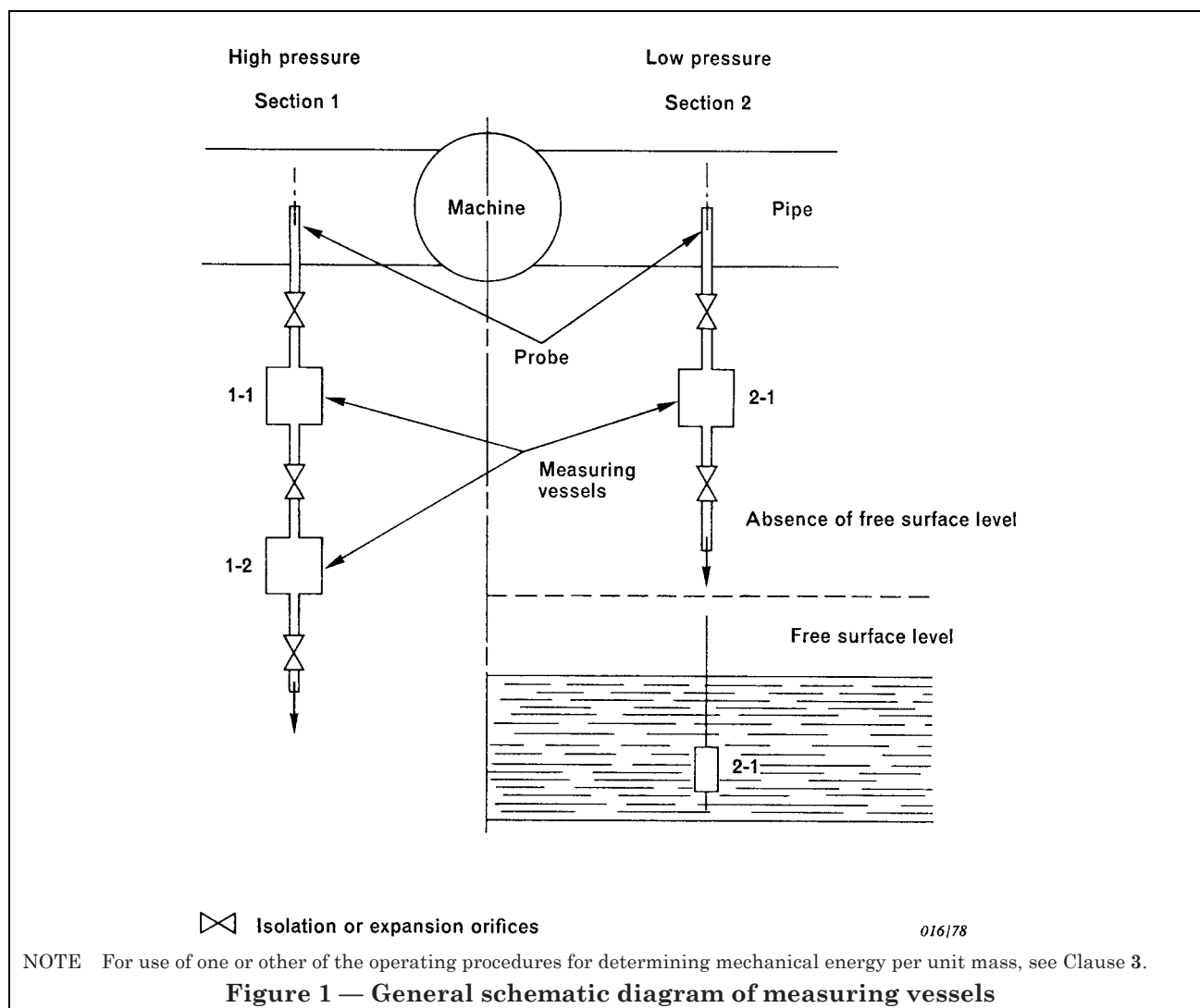
Term		Definition	Symbol	Unit
2.7	Volume per unit mass ^a	(Volume per unit of mass = $\frac{1}{\rho}$)	v	$\text{m}^3 \cdot \text{kg}^{-1}$
2.8	Temperature		T	$^{\circ}\text{C}$
2.9	Isothermal factor ^b	Factor characterizing a thermodynamic property of water	a	$\text{m}^3 \cdot \text{kg}^{-1}$
2.10	Specific heat ^c	Specific heat at constant pressure	c_p	$\text{J} \cdot \text{kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$
2.11	Mean value of α^d	Values of α and c_p corresponding to: the mean value $\bar{p}$ where: $\bar{p} = \frac{p_{1-1} + p_{2-1}}{2}$ and the mean value $\bar{T}$ where: $\bar{T} = \frac{T_{1-1} + T_{2-1}}{2}$	$\bar{a}$	$\text{m}^3 \cdot \text{kg}^{-1}$
2.12	Mean value of c_p^d		$\bar{c}_p$	$\text{J} \cdot \text{kg}^{-1} \cdot ^{\circ}\text{C}^{-1}$
2.13	Mean value of v^d	Value of v corresponding to T_1 and the mean value $\bar{p}$ where: $\bar{p} = \frac{p_{1-1} + p_{2-1}}{2}$	$\bar{v}$	$\text{m}^3 \cdot \text{kg}^{-1}$
2.14	Water velocity		V	$\text{m} \cdot \text{s}^{-1}$
2.15	Measuring point level		z	m
2.16	Shaft power	Shaft power corresponding to mechanical energy per unit mass	P_m	W
2.17	Volume-flow	Volume-flow of water turbinised or pumped past a certain point	Q	$\text{m}^3 \cdot \text{s}^{-1}$
2.18	Density	Mass per unit volume ($= \frac{1}{v}$)	ρ	$\text{kg} \cdot \text{m}^3$
2.19	Acceleration due to gravity	Acceleration due to gravity, at the point considered and at plant level	g	$\text{m} \cdot \text{s}^{-2}$

^a Values for v are given in Table I, page 15.

^b Values for a are given in Table II, page 18.

^c Values for c_p are given in Table III, page 21.

^d Fractional error in e_m and e_h attributable to the adoption of mean values $\bar{a}$, $\bar{v}$ and $\bar{c}_p$ instead of exact integrals (for pressures between 0 and 150 bar and temperatures between 0 and 30 $^{\circ}\text{C}$) does not exceed 0.5×10^{-4} .



3 Procedure for measurement of mechanical energy per unit mass

3.1 General

Due to the difficulties inherent in measuring directly in the flow, quantities defining e_m must be measured in specially designed vessels with tapplings for determination of temperature and pressure (see Sub-clause 5.1.1). When the measuring sections are under pressure, the procedure consists of extracting a sample flow, generally of between 0.1 dm³/s and 0.5 dm³/s, 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 Sub-clause 5.1.1, does not exceed the limit fixed in Sub-clause 6.5. This “sampling” is valid if the recommendations given in Sub-clause 6.1 regarding extraction points are followed.

For the general case where the turbine outlet is at atmospheric pressure, a specially designed measuring device is placed directly in the tail-race.

The $\frac{V^2}{2}$ and $g \cdot z$ terms are of minor importance and their determination calls for no particular remarks. It should be noted that levels z_{1-1} and z_{2-1} are those of the middle points of the measuring vessels. Pressure values are expressed with reference to these levels. Likewise V_{1-1} and V_{2-1} are measured in the vessels.

Other terms defining e_m shall be determined by one of the operating procedures described below which are practical variations of the method. The selection of operating procedure should be based upon machine characteristics and the quality of measuring apparatus available.

At the outlet of turbines operating under back-pressure or at pump inlets, it may be useful, depending upon the selected operating procedure, to reduce water pressure within the measuring vessel to atmospheric pressure.

3.2 “Direct” operating procedure

This is characterized by the direct passage of water from the high-pressure end of the penstock to the measuring vessel with the minimum of expansion. The various terms for e_m , given in Clause 2, are determined as follows:

- $\bar{a}(p_{1-1} - p_{2-1})$ requires a precision manometer (see Sub-clause 5.1.2); the values of $\bar{a}$ are given in Table II, page 18.
- $\bar{c}_p(T_{1-1} - T_{2-1})$ requires measurement of $(T_{1-1} - T_{2-1})$ with requisite accuracy (see Sub-clause 5.1.3); the values of $\bar{c}_p$ are given in Table III, page 21.

The thermometer plays a very important role in this procedure. It shall be exceedingly sensitive and accurate (see Sub-clause 5.1.3) and calibrated beforehand. Whenever this procedure is adopted, “partial expansion” procedure (see Sub-clause 3.3) for one test point or *in situ* calibration of the thermometer will be undertaken for checking purposes (see Sub-clause 3.4).

$(T_{1-1} - T_{2-1})(p_{1-1} - p_{2-1})$ are to be measured simultaneously and at regular intervals.

The range of application of this operating procedure is general.

3.3 “Partial expansion” operating procedure

An expansion valve is located in the sampling circuit between the inlet pipe or penstock and the corresponding measuring vessel. The adjustment of the valve must be very fine and stable such that, by partial expansion, temperature equality is achieved in the measuring vessels at the intake and outlet. Thus, in the expression for e_m , the term $\bar{c}_p(T_{1-1} - T_{2-1})$ becomes zero and the determination of e_m essentially entails the measurement of $(p_{1-1} - p_{2-1})$ with a sensitive and accurate manometer (see Sub-clause 5.1.2). The thermometer must be highly sensitive and reliable (see Sub-clause 5.1.3). Its purpose is to record temperature equality. In practice, it is desirable to establish graphically the correspondence between $(p_{1-1} - p_{2-1})$ and $(T_{1-1} - T_{2-1})$. As often as not, p_{2-1} is practically unvarying and only p_{1-1} need be measured. The pressure value used for calculation is that obtained by graphical interpolation for a null difference of temperature.

Up to the present, this has been the most widely used operating procedure although its use is not altogether general:

- in the case of pumps, pressure at the inlet may be insufficient to ensure that the temperature of the water expanded to atmospheric pressure in the measuring circuit is at least equal to that of the water at the pump outlet;
- in the case of turbines, at the highest known efficiency values, temperature equality cannot be attained if water temperature exceeds about 15 °C.

In all cases where temperature equality is unattainable, graphic extrapolation may be adopted if the range of pressure concerned is small compared with the pressure range accurately measured.

3.4 Expansion procedure for thermometer calibration

Two thermometers, or thermometric gauges, are placed in two vessels separated by an expansion valve through which water flows after having been withdrawn from the conduit. As the efficiency of the whole of the expander unit is zero, the transfer of mechanical energy per unit mass is zero and either:

$$e_m = \bar{a}(p_{1-1} - p_{1-2}) + \bar{c}_p(T_{1-1} - T_{1-2}) + \frac{V_{1-1}^2 - V_{1-2}^2}{2} + g(z_{1-1} - z_{1-2}) = 0$$

or:

$$T_{1-2} - T_{1-1} = \frac{\bar{a}(p_{1-1} - p_{1-2}) + \frac{V_{1-1}^2 - V_{1-2}^2}{2} + g(z_{1-1} - z_{1-2})}{\bar{c}_p}$$