



BSI Standards Publication

Pelton hydraulic turbines — Model acceptance tests

National foreword

This British Standard is the UK implementation of EN IEC 63461:2024. It is identical to IEC 63461:2024, incorporating corrigendum March 2025. It supersedes BS EN IEC 60193:2019.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by IEC corrigendum March 2025 is indicated in the text by AC1 AC1.

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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English Version

Pelton hydraulic turbines - Model acceptance tests
(IEC 63461:2024)

Turbines Pelton - Essais de réception sur modèle
(IEC 63461:2024)

Hydraulische Pelton Turbinen - Modellabnahmeprüfungen
(IEC 63461:2024)

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European foreword

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The following dates are fixed:

- latest date by which the document has to be implemented at national (dop) 2025-05-02 level by publication of an identical national standard or by endorsement
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In the official version, for Bibliography, the following notes have to be added for the standard indicated:

60041:1991	NOTE	Approved as EN 60041:1994
60609-1:2004	NOTE	Approved as EN 60609-1:2005 (not modified)
60609-2:1997	NOTE	Approved as EN 60609-2:1999 (not modified)
60994:1991	NOTE	Approved as EN 60994:1992 (not modified)
4006:1991	NOTE	Approved as EN 24006:1993 (not modified)
4373:2022	NOTE	Approved as EN ISO 4373:2022 (not modified)
5167-1:2022	NOTE	Approved as EN ISO 5167-1:2022 (not modified)
20456:2017	NOTE	Approved as EN ISO 20456:2019 (not modified)
80000-4:2019	NOTE	Approved as EN ISO 80000-4:2019 (not modified)
80000-11:2019	NOTE	Approved as EN ISO 80000-11:2020 (not modified)
21920-2:2021	NOTE	Approved as EN ISO 21920-2:2022 (not modified)
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Endorsement notice to IEC corrigendum March 2025

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Annex ZA
(normative)

**Normative references to international publications
with their corresponding European publications**

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cencenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
ISO 2186	2007	Fluid flow in closed conduits_ - Connections for pressure signal transmissions between primary and secondary elements	-	-
ISO 2533	1975	Standard Atmosphere	-	-
ISO 4185	1980	Measurement of liquid flow in closed conduits - Weighing method	EN 24185	1993
-	-		+ AC	1993
ISO 8316	1987	Measurement of liquid flow in closed conduits - Method by collection of the liquid in a volumetric tank	EN ISO 8316	1995

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**PELTON HYDRAULIC TURBINES –
MODEL ACCEPTANCE TESTS****FOREWORD**

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IEC 63461 has been prepared by IEC technical committee 4: Hydraulic turbines. It is an International Standard.

This first edition of IEC 63461 cancels and replaces the third edition of IEC 60193 published in 2019. This edition constitutes a technical revision.

AC1 This first edition of IEC 63461 partially replaces the third edition of IEC 60193 published in 2019. This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to IEC 60193:2019:

- a) the Pelton-specific requirements are being removed;
- b) the new standard is published as a stand-alone publication. **AC1**

The text of this International Standard is based on the following documents:

Draft	Report on voting
4/460/CDV	4/483/RVC

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

PELTON HYDRAULIC TURBINES – MODEL ACCEPTANCE TESTS

1 Scope

This document applies to laboratory model tests of any type of Pelton hydraulic turbine.

This document applies to models of prototype machines with unit power greater than 5 MW. Full application of the procedures herein described is not generally justified for machines with smaller power. Nevertheless, this document can be used for such machines by agreement between the purchaser and the supplier.

This document excludes all matters of purely commercial interest, except those inextricably bound up with the conduct of the tests.

This document is concerned with neither the structural details of the machines nor the mechanical properties of their components, so long as these do not affect model performance or the relationship between model and prototype performances.

This document covers the arrangements for model acceptance tests to be performed on Pelton turbines to determine if the main hydraulic performance contract guarantees (see 9.2) have been satisfied.

It contains the rules governing test conduct and provides measures to be taken if any phase of the tests is disputed.

The main objectives of this document are:

- to define the terms and quantities used;
- to specify methods of testing and of measuring the quantities involved, in order to ascertain the hydraulic performance of the model;
- to specify the methods of computation of results and of comparison with guarantees;
- to determine if the contract guarantees that fall within the scope of this document have been fulfilled;
- to define the extent, content and structure of the final report.

The guarantees can be given in one of the following ways:

- guarantees for prototype hydraulic performance, computed from model test results considering scale effects;
- guarantees for model hydraulic performance.

Moreover, additional performance data (see Clause 10) can be needed for the design or the operation of the prototype of the hydraulic machine. Contrary to the requirements of Clause 8 related to main hydraulic performance, the information of these additional data given in Clause 10 is considered only as recommendation or guidance to the user (see 10.1).

Model acceptance tests are performed if the expected field conditions for acceptance tests (see IEC 60041:1991) would not allow the verification of guarantees given for the prototype machine.

It is important that the method for performance conversion from model to prototype be clearly defined in the main hydraulic performance contract.

This document can also be applied to model tests for other purposes, i.e. comparative tests and research and development work.

If model acceptance tests have been performed, field tests can be limited to index tests (see IEC 60041:1991).

If a contradiction is found between this document and any other document, this document prevails.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2186:2007, *Fluid flow in closed conduits – Connections for pressure signal transmissions between primary and secondary elements*

ISO 2533:1975, *Standard atmosphere*

ISO 4185:1980, *Measurement of liquid flow in closed conduits – Weighing method*

ISO 8316:1987, *Measurement of liquid flow in closed conduits – Method by collection of the liquid in a volumetric tank*

3 Terms, definitions, symbols and units

3.1 General

For the purposes of this document, the following terms, definitions, symbols and units apply. Specialized terms are explained where they appear.

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.2 Terms and definitions

3.2.1 point

value established by one or more consecutive sets of readings or recordings at unchanged operating condition and settings, sufficient to calculate the performance of the machine at this operating condition and these settings

3.2.2 test

collection of points and results adequate to establish the performance of the machine over a specified range of operating conditions

3.2.3**hydraulic performance**

all performance parameters attributable to the machine owing to hydrodynamic effects

3.2.4**additional data**

subset of hydraulic performance data which can be determined for information on the model (see Clause 10)¹

3.2.5**guarantee**

specified performance data contractually agreed to

3.2.6**measurand**

quantity subjected to measurement

3.2.7**transducer**

measuring device, which provides an output quantity with a given relationship to the input quantity

3.2.8**transducer with digitized output**

measuring device with built-in electronics to give a digitized output

Example Serial port RS 232.

3.2.9**multiplexer****MUX**

device for switching two or more signals in order to share the same analogue-to-digital converter, frequency counter or cabling facilities

3.2.10**analogue-to-digital converter****A/D converter**

device that translates continuous analogue signals into discrete digital signals

3.2.11**counter**

device that measures frequency, time period or number of pulses

3.2.12**voltage-to-frequency converter****V/F converter**

device that translates with a given relationship voltage levels into frequency

3.2.13**aliasing**

when sampling analogue signals with a sampling rate less than twice that of the frequency of the highest frequency signal or noise component ("Nyquist rate"), the sampling process will produce spurious low frequency signals (aliases) that cannot be distinguished from the original signal

¹ However, the prediction of the corresponding prototype data is less accurate than that achievable for the main hydraulic performance data, owing to application of approximate similarity rules.

3.2.14

computer interface

communication port that enables the computer to control and communicate with other compatible devices

3.3 Units

The International System of Units (SI, see ISO 80000-4) has been used throughout this document.

All terms are given in SI base units or derived coherent units². The basic equations are valid using these units. This shall be taken into account if other than coherent SI units are used for certain data (e.g. kilowatt instead of watt for power, kilopascal or bar instead of pascal for pressure, min^{-1} instead of s^{-1} for rotational speed, etc.). Temperatures may be given in degrees Celsius since absolute temperatures (in kelvins) are rarely required.

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

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

The latter term ("head") has the disadvantage that weight is a force which depends on the local value of 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 3.4.7 and head terms in 3.4.8. They differ only by the factor g , which is the local value of acceleration due to gravity.

3.4 Terms, definitions, symbols and units

3.4.1 List by topics

Subclause	Title
3.4.2	Subscripts and symbols
3.4.3	Geometric terms
3.4.4	Physical quantities and properties
3.4.5	Discharge, velocity and speed terms
3.4.6	Pressure terms
3.4.7	Specific energy terms
3.4.8	Height and head terms
3.4.9	Power and torque terms
3.4.10	Efficiency terms
3.4.11	General terms relating to fluctuating quantities
3.4.12	Fluid dynamic and scaling terms
3.4.13	Dimensionless terms
3.4.14	Terms related to additional performance data

² $\text{N} = \text{kg} \cdot \text{m} \cdot \text{s}^{-2}$ $\text{Pa} = \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2}$ $\text{J} = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$ $\text{W} = \text{kg} \cdot \text{m}^2 \cdot \text{s}^{-3}$

3.4.2 Subscripts and symbols

Subclause	Term	Definition	Subscript or symbol
3.4.2.1	High-pressure reference section	The high-pressure section of the machine to which the performance guarantees refer (see Figure 1)	1
3.4.2.2	Low-pressure ^{a)} reference section	The low-pressure section of the machine to which the performance guarantees refer	2
3.4.2.3	High-pressure measuring sections	High-pressure sections of the machine used for measurement Note 1 to entry: Whenever possible, these sections should coincide with section 1; otherwise the measured values shall be adjusted to section 1 (see 8.2.2.1.3)	1', 1''.
3.4.2.4	Low-pressure measuring sections	Low-pressure sections of the machine used for measurement Note 1 to entry: Whenever possible, these sections should coincide with section 2; otherwise, the measured values shall be adjusted to section 2 (see 8.2.2.1.3)	2', 2''.
3.4.2.5	Specified	Subscript denoting values of quantities such as rotational speed, discharge etc. for which other quantities are guaranteed	sp
3.4.2.6	Maximum/minimum	Subscript denoting maximum or minimum values of any term	max min
3.4.2.7	Limits	Contractually defined values: – not to be exceeded – to be reached	<u>///</u> — □ or <u>///</u>
3.4.2.8	Prototype	Subscript denoting values related to the full-size machine	P
3.4.2.9	Model	Subscript denoting values related to the model	M
3.4.2.10	Reference	Subscript denoting values related to a specified reference condition	ref
3.4.2.11	Optimum	Subscript denoting the best efficiency point	opt
3.4.2.12	Ambient	Subscript referring to surrounding atmospheric conditions	amb
3.4.2.13	Plant	Subscript denoting values related to the operating conditions of the prototype in the plant	pl
3.4.2.14	Runaway	Subscript referring to runaway conditions	R
3.4.2.15	Runner bucket	Subscript referring to the runner bucket of a machine.	B
3.4.2.16	Pelton deflector	Subscript referring to the Pelton deflector of a machine.	D
3.4.2.17	Pelton needle	Subscript referring to the Pelton needle of a machine	N
3.4.2.18	Cartesian coordinates	Subscript referring to machine coordinates	x, y, z
3.4.2.19	Theoretical value	Subscript referring to theoretical value	th
3.4.2.20	Hydraulic	Subscript referring to hydraulic value	h

^{a)} The low-pressure section is necessary in the case of Pelton turbine operated with pressurized casing.

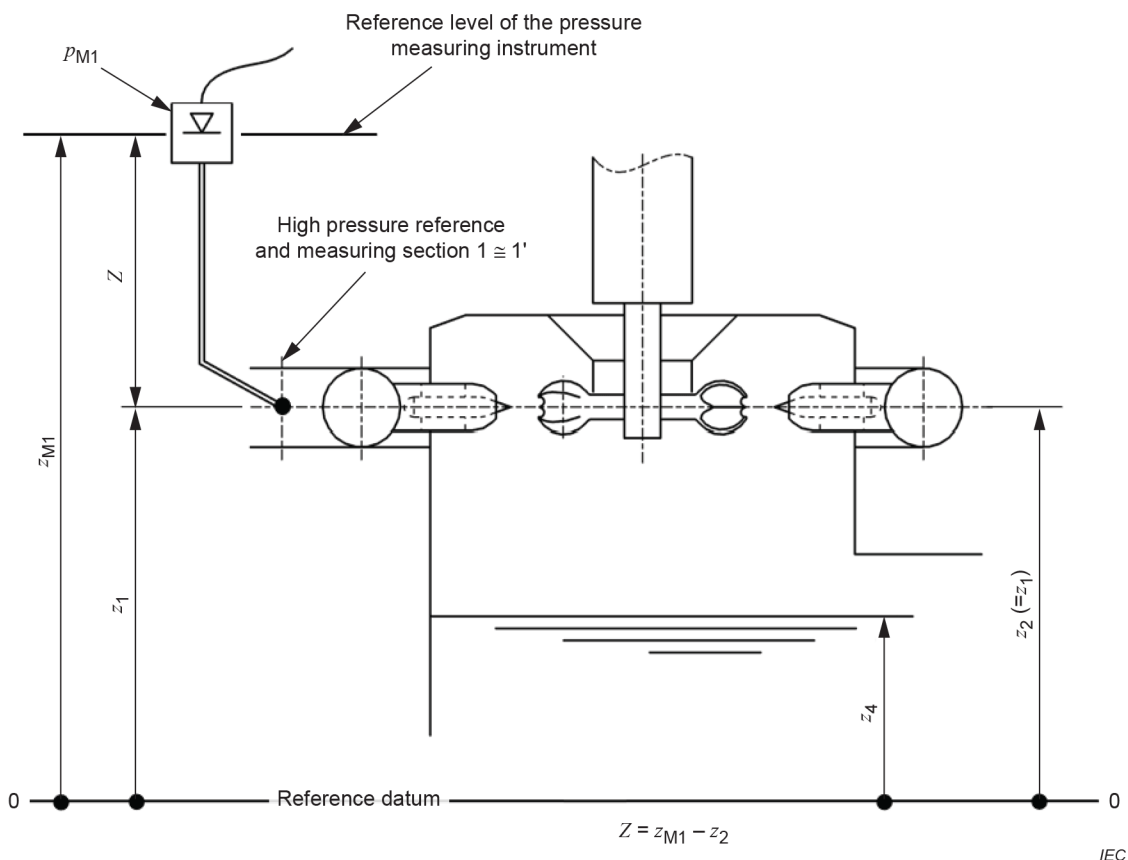


Figure 1 – Schematic representation of a Pelton machine

3.4.3 Geometry

Subclause	Term	Definition	Symbol	Unit
3.4.3.1	Area	Net cross-sectional surface normal to general flow direction	A	m ²
3.4.3.2	Needle stroke	Average needle stroke measured from closed position	s	m
3.4.3.3	Reference diameter	Mean diameter of the circles tangent to the jets axis centred on the runner axis in the mid plane of the runner (see Figure 2)	D	m
3.4.3.4	Bucket width	Inside maximum width of runner bucket of a Pelton turbine (see Figure 2 and Figure 12)	B	m
3.4.3.5	Length scale ratio	The ratio of representative prototype to model lengths; in normal cases this is the reference diameter of the machine Note 1 to entry: In cases where it is difficult to verify this reference, then another significant length may be taken	λ_L	-
3.4.3.6	Level	Elevation of a point in the system above the specified reference datum (usually mean sea level)	z	m
3.4.3.7	Length	Relevant linear size of a component of the machine	L	m
3.4.3.8	Arithmetic roughness	Arithmetic mean deviation of the assessment profile	Ra	µm
3.4.3.9	Number of nozzles	Number of nozzles of the Pelton turbine	z_0	
3.4.3.10	Number of jets in operation	Number of jets of the Pelton turbine in operation	z_j	

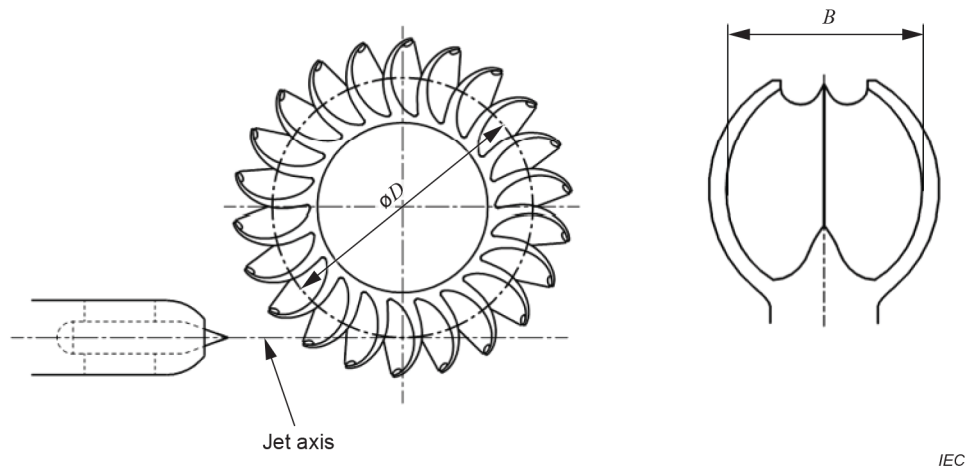


Figure 2 – Reference diameter and bucket width

3.4.4 Physical quantities and properties

Subclause	Term	Definition	Symbol	Unit
3.4.4.1	Acceleration due to gravity	Local value of gravitational acceleration at the place of testing (see 4.2); theoretical values as a function of altitude and latitude are given in Table B.1	g	$\text{m}\cdot\text{s}^{-2}$
3.4.4.2	Temperature	Thermodynamic (kelvin) Degree Celsius $\theta = \Theta - 273,15$	Θ θ	K °C
3.4.4.3	Volume	Quantity of three-dimensional space an object/substance occupies	V	m^3
3.4.4.4	Density	Mass per unit volume a) Density of water ρ is commonly used instead of ρ_{wa} b) Density of distilled water Values for distilled water ρ_{wd} are given in 4.3.1.3 and in Table B.2 c) Density of air Values for air are given in 4.4.1 and in Table B.5 d) Density of mercury Values for mercury are given in 4.5 and in Table B.7	ρ, ρ_{wa} ρ_{wd} ρ_{a} ρ_{Hg}	$\text{kg}\cdot\text{m}^{-3}$
3.4.4.5	Vapour pressure (absolute)	Absolute partial pressure of saturated vapour in a medium where liquid and gaseous phases of a body are in thermodynamic balance Note 1 to entry: The vapour pressure depends only on the temperature. Values for distilled water are given in 4.3.3 and in Table B.4	p_{va}	Pa
3.4.4.6	Dynamic viscosity	A quantity characterizing the mechanical behaviour of a fluid (see ISO 80000-4)	μ	$\text{Pa}\cdot\text{s}$
3.4.4.7	Kinematic viscosity	Ratio of the dynamic viscosity to the density of a fluid Note 1 to entry: Values for distilled water as a function of temperature are given in 4.3.2 and in Table B.3	ν	$\text{m}^2\cdot\text{s}^{-1}$
3.4.4.8	Surface tension	A quantity characterizing the mechanical behaviour of the interface between two fluids (see ISO 80000-4)	σ^*	$\text{J}\cdot\text{m}^{-2}$

3.4.5 Discharge, velocity and speed

Subclause	Term	Definition	Symbol	Unit
3.4.5.1	Discharge	Volume of water per unit time passing through any section in the system	Q	$\text{m}^3 \cdot \text{s}^{-1}$
3.4.5.2	Mass flow rate	Mass of water flowing through any section of the system per unit time Note 1 to entry: Both ρ and Q shall be determined at the same section and at the conditions existing in that section Note 2 to entry: The mass flow rate is constant between two sections if no water is added or removed.	(ρQ)	$\text{kg} \cdot \text{s}^{-1}$
3.4.5.3	Measured discharge	Volume of water per unit time flowing through any measuring section, e.g. 1' or 2' (see 3.4.2.3 and 3.4.2.4)	Q_1 , or Q_2	$\text{m}^3 \cdot \text{s}^{-1}$
3.4.5.4	Discharge at reference section	Volume of water per unit time flowing through the reference section 1 or 2	Q_1 or Q_2	$\text{m}^3 \cdot \text{s}^{-1}$
3.4.5.5	Corrected discharge at reference section	Volume of water per unit time flowing through the reference section referred to the ambient condition (see 3.4.6.2), e.g. $Q_{1c} = (\rho Q)_1 / \rho_{\text{amb}}$ Note 1 to entry: Given the normal conditions of a model test, Q_{1c} may be assumed equal to Q_1 .	Q_{1c} or Q_{2c}	$\text{m}^3 \cdot \text{s}^{-1}$
3.4.5.6	Discharge at steady-state runaway speed	Discharge at n_R (see 3.4.5.12)	Q_R	$\text{m}^3 \cdot \text{s}^{-1}$
3.4.5.7	No-load turbine discharge	Turbine discharge at zero mechanical power at specified speed (usually synchronous) and specified specific hydraulic energy	Q_o	$\text{m}^3 \cdot \text{s}^{-1}$
3.4.5.8	Mean velocity	Discharge Q divided by area A of the cross-section	v	$\text{m} \cdot \text{s}^{-1}$
3.4.5.9	Peripheral velocity	Speed at the reference diameter: $u = \pi D n$	u	$\text{m} \cdot \text{s}^{-1}$
3.4.5.10	Rotational speed	Number of revolutions per unit time	n	s^{-1}
3.4.5.11	Steady-state runaway speed	The steady-state rotational speed at zero mechanical power at specified hydraulic conditions and specified needle opening	n_R	s^{-1}
3.4.5.12	Maximum steady-state runaway speed	The highest value of steady-state runaway speed at specified hydraulic conditions (for the prototype, see detailed definition in IEC 60041:1991, 2.3.4.15)	$n_{R\text{max}}$	s^{-1}

3.4.6 Pressure

Subclause	Term	Definition	Symbol	Unit
3.4.6.1	Absolute pressure	static pressure of a fluid measured with reference to a perfect vacuum	p_{abs}	Pa
3.4.6.2	Ambient pressure	absolute pressure of the ambient air (see 4.4.2) Note 1 to entry: Values for standard atmosphere are given as a function of elevation in Table B.6.	p_{amb}	Pa
3.4.6.3	Gauge pressure	difference between the absolute static pressure of a fluid at the reference level of the pressure measuring instrument and the ambient pressure at the place and time of measurement: $p = p_{\text{abs}} - p_{\text{amb}}$	p	Pa
3.4.6.4	Differential pressure	difference in pressure between two points or sections of measurement	Δp	Pa

3.4.7 Specific energy

Subclause	Term	Definition	Symbol	Unit
3.4.7.1	Specific hydraulic energy of machine	The energy per unit mass of water available between the high and low-pressure reference sections 1 and 2 of the machine, taking into account the influence of compressibility (see 8.2) $E = \frac{p_{abs1} - p_{abs2}}{\bar{\rho}} + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2)$ with $\bar{\rho} = (\rho_1 + \rho_2) / 2$ and assuming $g = g_1 = g_2$ Note 1 to entry: The value 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	$\text{J} \cdot \text{kg}^{-1}$

3.4.8 Height and head

Subclause	Term	Definition	Symbol	Unit
3.4.8.1	Turbine head	Specific energy per local unit weight of water at any section $H = \frac{E}{g}$	H	m
3.4.8.2	Reference level of the machine	Elevation of a point of the machine taken as reference for the setting of the machine (see Figure 3)	z_r	m
3.4.8.3	Reference level of the pressure measuring instrument	Elevation of a pressure measuring device (see Figure 34)	z_M	m

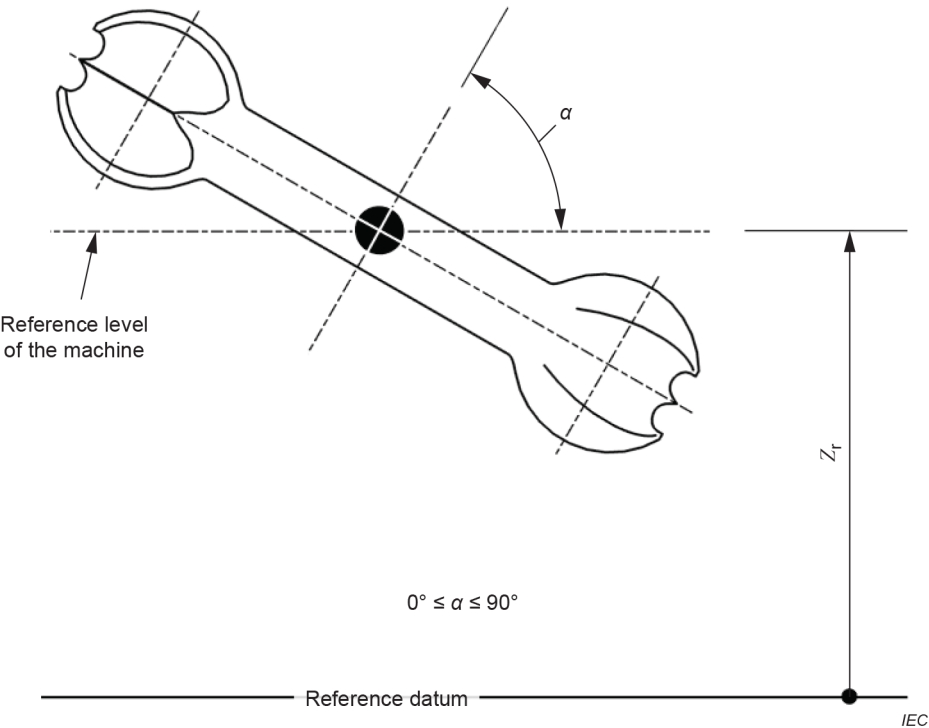
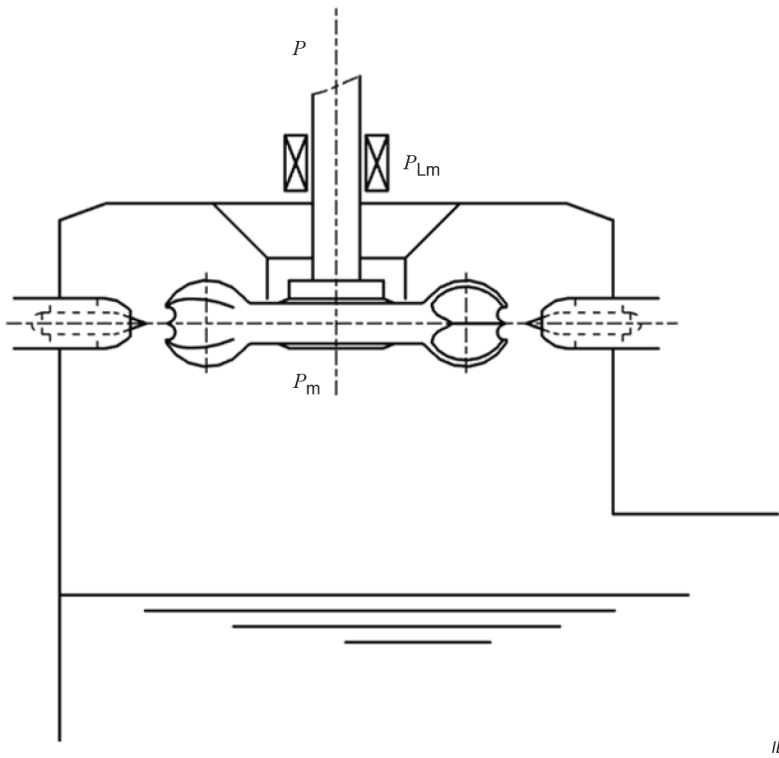


Figure 3 – Reference level of a Pelton machine

3.4.9 Power and torque

Subclause	Term	Definition	Symbol	Unit
3.4.9.1	Hydraulic power	Hydraulic power available for producing power (turbine) or imparted to the water (pump) $P_h = E(\rho Q)_1$	P_h	W
3.4.9.2	Mechanical power of the machine (power)	Mechanical power delivered by the turbine shaft or to the pump shaft, assigning to the hydraulic machine the mechanical losses of the relevant bearings and shaft seals (see Figure 4)	P	W
3.4.9.3	Mechanical power of runner(s)	Mechanical power transmitted through the coupling of the runner(s) and the shaft (see Figure 4)	P_m	W
3.4.9.4	Mechanical power losses	Mechanical power dissipated in guide bearings, thrust bearings and shaft seals of the hydraulic machine (see Figure 4)	P_{Lm}	W
3.4.9.5	Shaft torque	Torque applied to the shaft of the hydraulic machine and corresponding to the mechanical power of the machine (see 3.4.9.2)	T	N·m
3.4.9.6	Runner torque	Torque transmitted through the coupling of the runner and the shaft and corresponding to the mechanical power of runner (see 3.4.9.3)	T_m	N·m
3.4.9.7	Friction torque	Friction torque in guide bearings, thrust bearings and shaft seals of the hydraulic machine (see 3.4.9.4)	T_{Lm}	N·m



Hydraulic power	$P_h = E \rho Q$
Mechanical power of the machine	$P = P_m - P_{Lm}$
Mechanical efficiency	$\eta_m = \frac{P}{P_m}$
Hydraulic efficiency	$\eta_h = \frac{P_m}{P_h}$
Efficiency	$\eta = \frac{P}{P_h}$

- NOTES
- The formulae ignore the compressibility of the water.
 - For detailed analysis of internal losses, refer to Annex I.

Figure 4 – Flux diagram for power

3.4.10 Efficiency

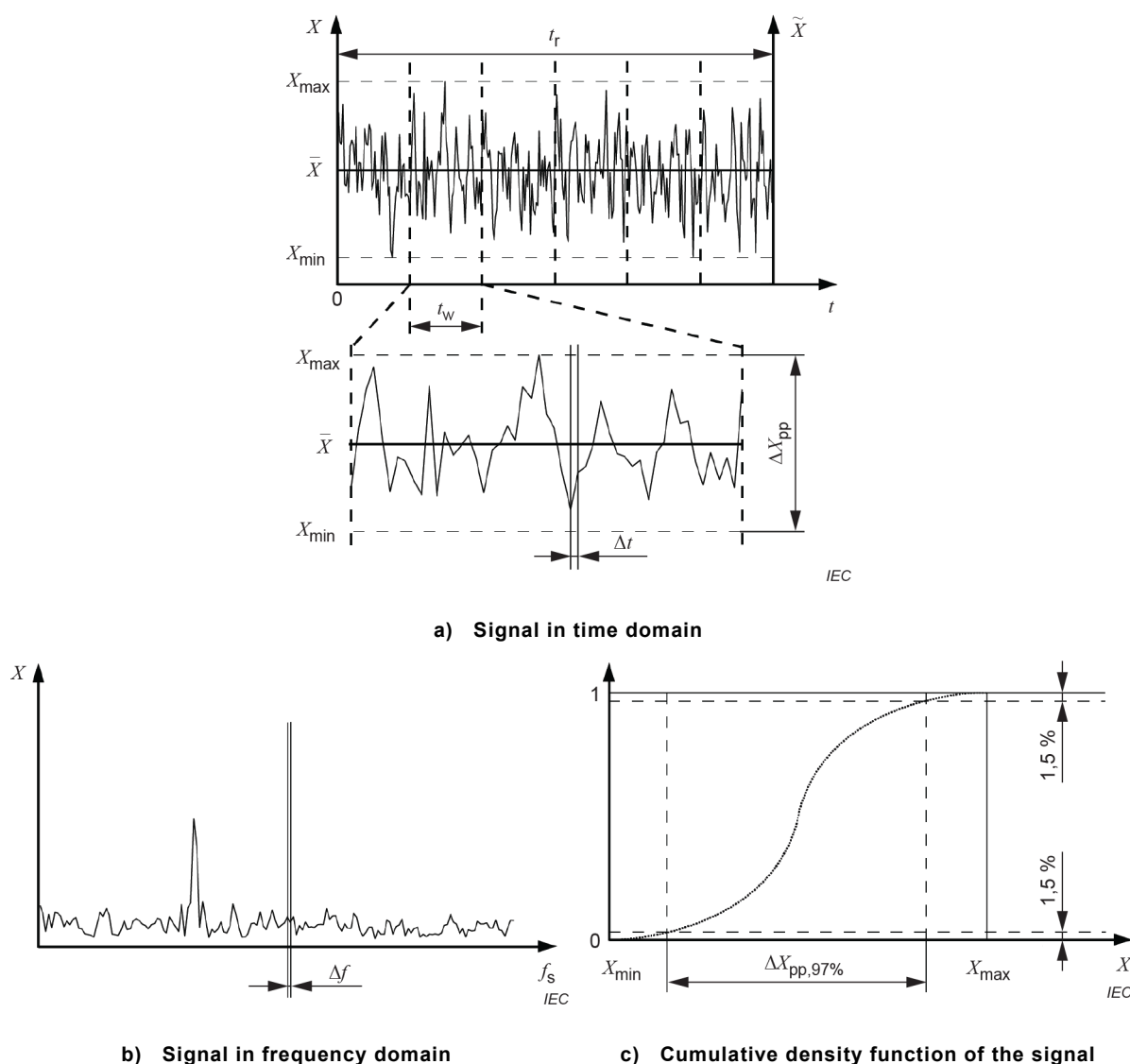
Subclause	Term	Definition	Symbol	Unit
3.4.10.1	Hydraulic efficiency	Ratio of mechanical power of runner to the hydraulic power $\eta_h = \frac{P_m}{P_h}$ See Figure 4	η_h	-
3.4.10.2	Mechanical efficiency	Ratio of mechanical power of the machine to the runner $\eta_m = \frac{P}{P_m}$ See Figure 4	η_m	-
3.4.10.3	Efficiency	Ratio of mechanical power of the machine to the hydraulic power $\eta = \frac{P}{P_h} = \eta_h \times \eta_m$ See Figure 4	η	-
3.4.10.4	Weighted average efficiency	Calculated from the formula $\eta_w = \frac{w_1\eta_1 + w_2\eta_2 + w_3\eta_3 + \dots}{w_1 + w_2 + w_3 + \dots}$ where $\eta_1, \eta_2, \eta_3, \dots$ are the values of efficiency at specified operating conditions and $w_1, w_2, w_3, \dots$ are their agreed weighting factors respectively	η_w	-

3.4.11 Fluctuating quantities

NOTE IEC 60994 provides a reference for terms relating to fluctuating quantities. Terms relevant to this document, some of which are illustrated in Figure 5, are listed below.

Subclause	Term	Definition	Symbol	IEC 60994:1991
3.4.11.1	Discrete quantity	Quantity represented by a sequence of its momentary values	X	
3.4.11.2	Discrete quantity n	Value of the quantity n	X_n	
3.4.11.3	Number of samples	Total number of discrete quantities	N	
3.4.11.4	Number of samples in a time window	Total number of discrete quantities used in the time window duration	N_w	
3.4.11.5	Mean value	Algebraic sum of the discrete quantities divided by the number of samples $\bar{X} = \frac{1}{N} \sum_{n=1}^N X_n$	$\bar{X}$	2.3.3.1
3.4.11.6	Fluctuation of quantity	Oscillatory variation of a quantity X referred to its mean value during a time interval Δt previously selected	$\tilde{X}(t)$	2.3.1.5
3.4.11.7	Maximum value	Maximum value in a chosen time interval	$X_{\max}$	
3.4.11.8	Minimum value	Minimum value in a chosen time interval	$X_{\min}$	
3.4.11.9	Standard deviation Effective value referred to the mean	Root-mean-square value of the deviation of a set of numbers from the mean value $\tilde{X}_{\text{eff}} = \sqrt{\frac{1}{N} \sum_{n=1}^N (X_n - \bar{X})^2}$	$\tilde{X}_{\text{eff}}$	2.3.3.2

Subclause	Term	Definition	Symbol	IEC 60994:1991
3.4.11.10	Root-mean-square value	Square root of the mean value squared $X_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{n=1}^N X_n^2}$	X_{rms}	2.3.3.3
3.4.11.11	Peak-to-peak value	Difference between the maximum and minimum values $\Delta X_{\text{pp}} = X_{\text{max}} - X_{\text{min}}$	ΔX_{pp}	2.3.2.11
3.4.11.12	Peak-to-peak value with a 97 % confidence interval	Difference between the maximum and minimum values of a signal is determined using a probability distribution function for a given probability value (e.g. 97 %) Note 1 to entry: This function is estimated by applying statistical counting. The signal values outside of the corresponding confidence interval are excluded.	$\Delta X_{\text{pp},97\%}$	
3.4.11.13	Amplitude	Maximum value of a sinusoidal quantity $X(t)$ $A = \frac{1}{2} D X_{\text{pp}}$	A	2.3.2.10
3.4.11.14	Time	Physical quantity	t	2.3.2.3
3.4.11.15	Sampling time interval	Time interval between two consecutive samples.	Δt	
3.4.11.16	Frequency	The reciprocal of period s^{-1} (Hz)	f	2.3.2.4
3.4.11.17	Sampling frequency Sampling rate	Inverse of the sampling time interval $f_s = \frac{1}{\Delta t}$	f_s	
3.4.11.18	Time window duration	Selected time window for frequency analyses by Fourier transform methods $t_w = N_w \Delta t$	t_w	
3.4.11.19	Frequency resolution	Frequency interval between two consecutive values in the discrete Fourier transform $\Delta f = 1/t_w = f_s/N$	Δf	
3.4.11.20	Signal recording time Acquisition time	Period of time during which a signal from a transducer is recorded (in seconds).	t_r	2.3.4.14



- A fluctuating signal over a defined signal recording time (t_r). A minimum of 5 window time lengths (t_w) shall be included in each signal record time duration (see 6.2.2.4).
- The signal transformed into the frequency domain using Fourier analysis. The frequency resolution (Δf) required for each analysis is determined by the speed of rotation of the machine (see 6.2.2.4).
- Using probability distribution, each measure point from Figure 5 a) is cumulated and extreme deviations from the mean fluctuation are removed. A 97 % interval of confidence is illustrated in this figure.

Figure 5 – Illustration of some definitions related to oscillating quantities

3.4.12 Fluid dynamics and scaling^{a)}

Subclause	Term	Definition	Symbol	Unit
3.4.12.1	Reynolds number	Ratio of inertia forces to viscous forces (see 8.4.1) in Pelton turbines $\frac{uB}{\nu}$	Re	-
3.4.12.2	Froude number ^{b)}	Square root of the ratio of inertia forces to gravity forces (see 8.4.1) in Pelton turbines $\left[\frac{E}{gB} \right]^{1/2}$	Fr	-
3.4.12.3	Weber number ^{b)}	Ratio of inertia forces to surface tension forces $We = \left[\frac{\rho B v^2}{\sigma^*} \right]^{1/2}$ (see 8.4.1)	We	-
3.4.12.4	Difference of hydraulic efficiency	Difference between the values of hydraulic efficiency at two hydraulically similar operating points measured at different test conditions (see 8.4.2)	$\Delta\eta_h$	-
a) See ISO 80000-11.				
b) Other definitions of these numbers can be found in relevant scientific works.				

3.4.13 Dimensionless terms and definitions

NOTE 1 Machine performance can be characterized by dimensionless terms based on $E = 1$, $D = 1$ and $\rho = 1$ or on $n = 1$, $D = 1$ and $\rho = 1$.

NOTE 2 The units are: H (m); D (m); E ($\text{J} \cdot \text{kg}^{-1}$); n (s^{-1}); ρ ($\text{kg} \cdot \text{m}^{-3}$); T ($\text{N} \cdot \text{m}$); P (W); Q ($\text{m}^3 \cdot \text{s}^{-1}$).

NOTE 3 The relations of these dimensionless terms to other existing definitions are given in Annex A.

Subclause	Term	Definition	Symbol	Relations
3.4.13.1	Speed factor	$\frac{nD}{E^{0.5}}$	n_{ED}	
3.4.13.2	Discharge factor	$\frac{Q_1}{B^2 E^{0.5}}$	Q_{EB}	
3.4.13.3	Discharge factor per nozzle	$\frac{Q_1}{B^2 E^{0.5} z_j}$	$Q_{EB,zj}$	$= \frac{Q_{EB}}{z_j}$
3.4.13.4	Torque factor	$\frac{T_m}{\rho_1 D^3 E}$	T_{ED}	$= \frac{T_{nD}}{E_{nD}} = \frac{P_{ED}}{2\pi n_{ED}}$
3.4.13.5	Power factor ^{a)}	$\frac{P_m}{\rho_1 D^2 E^{1.5}}$	P_{ED}	$= Q_{EB} \eta_{hT}$ $= 2\pi n_{ED} T_{ED}$
3.4.13.6	Specific flow rate	$\frac{Q_1}{\pi (B/2)^2 (2E)^{0.5} z_j}$	f_B	
3.4.13.7	Energy coefficient	$\frac{E}{n^2 D^2}$	E_{nD}	
a) Reference is made to the mechanical power of the runner, usually measured on the model.				

3.4.14 Additional performance data

NOTE For presentation and analysis of additional performance data such as pressure and torque fluctuations, hydraulic thrust, and hydraulic loads on control components, dimensionless terms are used as defined hereafter and in 10.1 to 10.2. They are identified by the symbol of the measured quantity with subscripts denoting the machine component and the quantities taken as unity; for instance, $T_{D,EB}$ will denote the deflector torque factor, i.e. the torque acting on the deflector based on specific hydraulic energy of the machine and bucket width equal to unity.

The symbols used to define the measurements are listed below:

Subclause	Term	Definition	Symbol	Unit
3.4.14.1	Force	Influence tending to produce motion or stress on a machine component	F	N
3.4.14.2	Moment	Magnitude of a turning effect produced by a force acting at a perpendicular distance to a given point	M	N·m
3.4.14.3	Pressure	Force per unit area	p	Pa
3.4.14.4	Torque	Axial component of the moment	T	N·m

The dimensionless terms relating to additional performance data are listed below:

Subclause	Term	Definition	Symbol	Unit
3.4.14.5	Deflector torque factor	$T_{D,EB} = \frac{T_D}{\rho D B^2 E}$	$T_{D,EB}$	-
3.4.14.6	Deflector torque coefficient	$T_{D,nB} = \frac{T_D}{\rho n^2 D^3 B^2}$	$T_{D,nB}$	-
3.4.14.7	Needle force factor	$F_{N,EB} = \frac{F_N}{\rho B^2 E}$	$F_{N,EB}$	-
3.4.14.8	Needle force coefficient	$F_{N,nB} = \frac{F_N}{\rho n^2 D^2 B^2}$	$F_{N,nB}$	-

4 Physical properties

4.1 General

This subclause defines the main physical properties needed to characterize the hydraulic behaviour of hydraulic machines. The terms and definitions of most of these quantities are listed in 3.4.4 together with their symbols and units.

The formulae, which can be used in data processing to calculate these quantities, are listed in 4.2, 4.3 and 4.4. For convenience, tables of numerical values derived from these formulae are given in Annex B.

4.2 Acceleration due to gravity

Acceleration due to gravity g (see 3.4.4.1) is given as a function of latitude and altitude:

$$g = 9,780\,3 \left(1 + 0,005\,3 \sin^2 \varphi \right) - 3 \times 10^{-6} z \text{ m} \cdot \text{s}^{-2}$$

where

φ is the latitude in radians;

z is the altitude in metres.

Values of g are given in Table B.1 and are represented in Figure 6.

The international standard value of acceleration due to gravity g_n is $9,806\,65\text{ m}\cdot\text{s}^{-2}$.

If measured values of g are available, they shall be used. The local value of g can be measured for example by a pendulum or free fall (in vacuum).

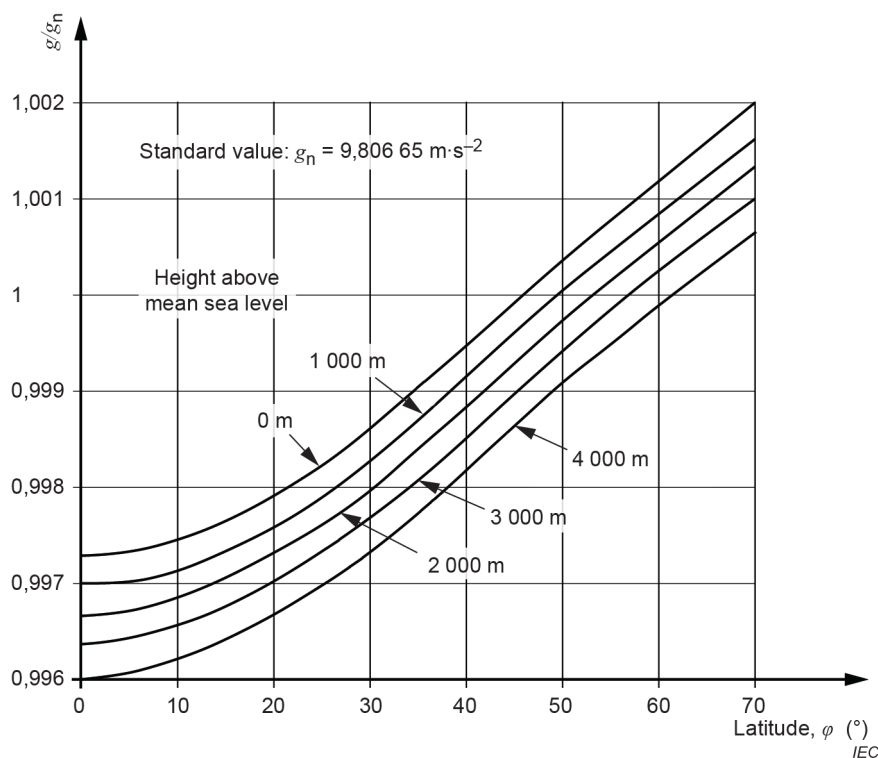


Figure 6 – Acceleration due to gravity g ($\text{m} \cdot \text{s}^{-2}$)

4.3 Physical properties of water

4.3.1 Density of water

4.3.1.1 Application of the density of water

In testing hydraulic machines, the density of water ρ (see 3.4.4.3) shall be known in order to:

- determine the specific hydraulic energy of machine E from pressure measurements (see 3.4.7.1);
- determine the mass flow rate (ρQ) needed for the calculation of the hydraulic power (see 3.4.9.1);

and, if necessary, to:

- calculate the pressure from measurements by using a water column manometer (see 7.2.4.2.1);
- determine the discharge when the weighing method is used for the measurement itself or for the calibration (see 7.1.4.1 and 7.1.4.2).

4.3.1.2 Density of actual water

The water used for model testing in the laboratory contains slight quantities of dissolved substances, depending on the local hydrological conditions. Therefore, its actual density ρ_{wa} is higher than that of distilled water ρ_{wd} (see 4.3.1.3). However, the value of ρ_{wa} in the model test equipment generally differs by less than 0,05 % from the value of distilled water ρ_{wd} .

For calculation of the hydraulic efficiency, this deviation is negligible if the determination of the specific hydraulic energy of the machine E is predominantly obtained by pressure measurement. Therefore, in most cases, it is sufficient and suitable to apply the values for distilled water.

However, if it is necessary to determine the density ρ_{wa} of the water actually used, several methods can be applied:

- an indirect method using a calibrated pressure gauge connected to a static free water level, as described in 7.2.5.2;
- direct methods such as a precision hydrometer (e.g. a pycnometer or so called "density bottle") or a buoyancy method.

It may be assumed that the ratio of the actual and distilled water densities is constant whatever the pressure and temperature. So, if the density of the actual water has been measured at certain conditions of pressure and temperature ($\rho_{wa,c}$), its value for any other condition can be calculated by:

$$\rho_{wa} = \left(\frac{\rho_{wa,c}}{\rho_{wd,c}} \right) \rho_{wd}$$

where ρ_{wd} and $\rho_{wd,c}$ are calculated in accordance with 4.3.1.3.

4.3.1.3 Density of distilled water

The formula for the density ρ_{wd} of distilled water as a function of temperature and pressure is derived by Herbst and Roegenen [1]³ from the empirical state equation of the free enthalpy of distilled water. In determining the coefficients below, all the test results of Kell and Whalley [2] and of Kell, McLaurin and Whalley [3] were used.

$$\rho_{wd} = 10^2 \left[\sum_{i=0}^3 \sum_{j=0}^3 R_{ij} \times \alpha^j \times \beta^{(i-1)} \right]^{-1}$$

where

$$\beta = \frac{1}{p^*} (p_{abs} + 200 \times 10^5)$$

$$\alpha = \frac{1}{\theta^*} (\theta - \theta_1)$$

with

$$p^* = 10^5 \text{ Pa};$$

$$\theta^* = 1 \text{ } ^\circ\text{C};$$

³ Numbers in square brackets refer to the Bibliography.

from 0 °C to 20 °C: $\theta_1 = 0$ °C;

from 20 °C to 50 °C: $\theta_1 = 20$ °C

The formula is valid in the used pressure range from $p_{\text{abs}} = 0$ Pa to 150×10^5 Pa

Table 1 furnishes the coefficients R_{ij} ($\text{m}^3 \cdot \text{kg}^{-1}$).

Table 1 – Coefficients of the Herbst and Roegener formula

$R(i,j)$ in the temperature range 0,0 °C to 20,0 °C				
i	$j = 0$	$j = 1$	$j = 2$	$j = 3$
0	$0,446\,674\,155\,7 \times 10^{-4}$	$-0,559\,450\,069\,7 \times 10^{-4}$	$0,340\,259\,195\,5 \times 10^{-5}$	$-0,413\,634\,518\,7 \times 10^{-7}$
1	$0,101\,069\,380\,2$	$-0,151\,370\,926\,3 \times 10^{-4}$	$0,106\,379\,874\,4 \times 10^{-5}$	$-0,814\,607\,899\,5 \times 10^{-8}$
2	$-0,539\,839\,211\,9 \times 10^{-5}$	$0,467\,275\,668\,5 \times 10^{-7}$	$-0,119\,476\,536\,1 \times 10^{-8}$	$0,136\,632\,205\,3 \times 10^{-10}$
3	$0,778\,011\,812\,1 \times 10^{-9}$	$-0,161\,939\,132\,2 \times 10^{-10}$	$0,588\,354\,748\,5 \times 10^{-12}$	$-0,875\,401\,428\,7 \times 10^{-14}$
$R(i,j)$ in the temperature range 20,0 °C to 50,0 °C				
i	$j = 0$	$j = 1$	$j = 2$	$j = 3$
0	$-0,441\,035\,565\,0 \times 10^{-4}$	$0,305\,225\,289\,8 \times 10^{-4}$	$0,920\,784\,842\,7 \times 10^{-6}$	$-0,259\,043\,119\,8 \times 10^{-7}$
1	$0,101\,126\,989\,2$	$0,176\,395\,623\,4 \times 10^{-4}$	$0,575\,034\,004\,4 \times 10^{-6}$	$-0,192\,376\,997\,8 \times 10^{-8}$
2	$-0,483\,244\,116\,3 \times 10^{-5}$	$0,153\,328\,170\,4 \times 10^{-7}$	$-0,374\,972\,129\,4 \times 10^{-9}$	$0,132\,280\,418\,0 \times 10^{-11}$
3	$0,619\,443\,332\,7 \times 10^{-9}$	$-0,316\,454\,043\,1 \times 10^{-11}$	$0,631\,138\,912\,3 \times 10^{-13}$	$0,246\,924\,934\,2 \times 10^{-15}$

Instead of the formulae of Herbst and Roegener [1], the formulae of Borel and Lan [4] or of Haar, Gallagher and Kell [5] can also be used for calculation by computer.

All these authors have taken the experimental values of [2] and [3] as their basis. The values of these references are within the same range of accuracy ($\pm 0,01$ %) in the range of temperature and pressure as mentioned above.

For numerical application, the simpler empirical equation of Weber [6], somewhat transformed, may be used. The values calculated for temperatures up to 35 °C and pressures up to 150×10^5 Pa are within the same range of accuracy as mentioned above:

If V is the specific volume in $\text{m}^3 \cdot \text{kg}^{-1}$:

$$V = \frac{1}{\rho} = V_0 \left[(1 - Ap) + 8 \times 10^{-6} (\theta - B + Cp)^2 - 6 \times 10^{-8} (\theta - B + Cp)^3 \right]$$

with

$$V_0 = 1 \times 10^{-3} \text{ m}^3 \cdot \text{kg}^{-1}$$

$$p = p_{\text{abs}} \text{ (Pa)}$$

$$\theta = \text{temperature (°C)}$$

$$A = 4,669\,9 \times 10^{-10}$$

$$B = 4,0$$

$$C = 2,131\,891\,3 \times 10^{-7}$$

Values for distilled water on the basis of the formula of Herbst and Roegener [1] are given in Table B.2 and are represented in Figure 7.

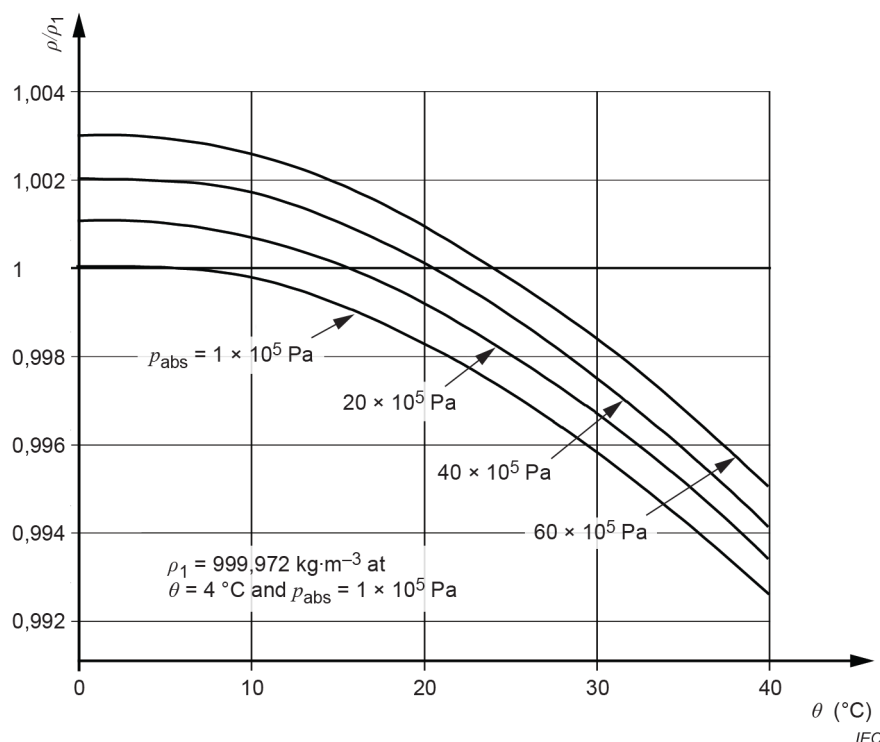


Figure 7 – Density of distilled water ρ_{wd} ($\text{kg} \cdot \text{m}^{-3}$)

4.3.2 Kinematic viscosity

The kinematic viscosity ν (see 3.4.4.6) of water depends on its temperature θ and absolute pressure p_{abs} and is derived from the basic physical property dynamic viscosity μ using $\nu = \mu / \rho$.

A formula for μ is given in [10].

However, for practical reasons in hydraulic machinery, an approximate value of ν can be computed using the following formula:

$$\nu = e^{\left(-16,921 + \frac{396,13}{107,41 + \theta} \right)}$$

Using this equation, the average deviation from the standard values given in [11] is $\pm 0,05 \%$, the maximum deviation is $\pm 0,09 \%$.

The influence of pressure is negligible. The deviation for $p = 10 \times 10^5 \text{ Pa}$ against a reference pressure of $p = 10^5 \text{ Pa}$ is about $-0,05 \%$.

Values for ν are given in Table B.3.

4.3.3 Vapour pressure

The vapour pressure p_{va} (see 3.4.4.5) of water between the water temperatures of $\theta = 0 \text{ }^{\circ}\text{C}$ and $\theta = 40 \text{ }^{\circ}\text{C}$ can be calculated using the following empirical formula:

$$p_{\text{va}} = 10^{\left(2,786 + 0,031 \cdot 2\theta - 0,000 \cdot 104\theta^2 \right)}$$

The resulting error is less than ± 7 Pa. Numerical values of p_{va} are given in Table B.4, see [5].

Attention shall be paid to dissolved chemical substances in water which can influence the vapour pressure.

4.4 Physical conditions of atmosphere

4.4.1 Density of dry air

The density of air ρ_a (see 3.4.4.4) as a function of p_{abs} (see 3.4.6.1) and temperature of air θ can be calculated using the following formula, in accordance with ISO 2533:

$$\rho_a = \frac{3,483\,7 \times 10^{-3} p_{abs}}{273,15 + \theta}$$

Values of ρ_a are given in Table B.5.

The influence of humidity on the density of air is negligible for the determination of E .

4.4.2 Ambient pressure

Normally, the ambient pressure p_{amb} (see 3.4.6.2) is the barometric pressure measured in the laboratory by a barometer. For conversion of test results to the conditions of prototype at site the ambient pressure shall be calculated using the standard atmosphere defined in ISO 2533.

Using sea level as the baseline reference, the ambient pressure may be calculated by the following approximate formula derived from ISO 2533:

$$p_{amb} = 101\,325 \left(1 - 2,256 \times 10^{-5} z \right)^{5,256}$$

where

z is the elevation (m).

The resulting error is less than ± 15 Pa. Values for p_{amb} from ISO 2533 are given in Table B.6.

4.5 Density of mercury

The density of mercury ρ_{Hg} (see 3.4.4.4) used in liquid manometers is calculated for pure mercury by the following equation:

$$\rho_{Hg} = (13,595 - 2,46\theta) \left[1 + 3,85 \times 10^{-11} (p - p_0) \right]$$

where

$p_0 = 101\,325$ Pa (standard ambient pressure at sea level)

Values of ρ_{Hg} are given in Table B.7, see [12].

Mercury used in practical applications can be contaminated by dissolved metal or by other materials. To ensure valid measurements the mercury shall be pure and clean.

5 Requirements of tests

5.1 Requirement of test installation and model

5.1.1 Choice of laboratory

Any laboratory satisfying the criteria set out in this document concerning general layout, capacity and quality of instrumentation should be deemed suitable. An independent laboratory is sometimes preferable, particularly when comparative tests are required with models from different manufacturers.

5.1.2 Test installation

5.1.2.1 General characteristics of the test circuit

Any entrained gas bubbles in the model shall not affect the functioning of instrumentation, particularly the flow measuring device and the pressure measurement lines.

The circuit shall be designed in such a manner that no leakage or addition of water can occur between the flow measuring instrument and the model. These criteria should be easily verifiable.

5.1.2.2 Capacity of the test installation

The capacity of the test installation (i.e. power, pressure, specific hydraulic energy and discharge) shall be such that the minimum values for model size and the required test conditions as listed in 8.5.2 can be met.

The operation shall be stable and steady without surging or fluctuating effects (see 8.5.3).

5.1.2.3 Condition of the water

The test water shall be clean, clear and free of any solid material in suspension and any chemical impurities which can have an influence on the water properties such as viscosity and vapour pressure. Free gas and air bubbles should be removed as far as possible before testing.

The water temperature should be within the range of 8 °C and 35 °C and not vary more than 5 °C per day. Large differences between the water temperature and the ambient temperature of instruments should be avoided, as they could influence the accuracy of the measurements.

5.1.2.4 Flow conditions given by the installation

At the model inlet, the test installation shall ensure favourable hydraulic conditions free from vortices, undue turbulence and unsteadiness.

At the model outlet, the flow pattern should not be influenced by the layout of the test facility.

5.1.2.5 Measuring instruments

The measuring equipment used to determine the main parameters shall satisfy the specified conditions of this document.

The traceability of each instrument to a recognized national or international standard shall be ensured. All instruments, especially discharge and torque, should be calibrated *in situ*. Some calibrations can be performed prior to installation on the test rig e.g. calibration of the dynamic instruments.

The measuring instruments should be such that a parallel reading, independent of the data acquisition system, is possible in order to permit an easy verification.

The instrument temperature shall be verified to be within the allowable specification of the manufacturer.

5.1.3 Model requirements

5.1.3.1 Model size

The required minimum values for model size are given in 8.5.2.

Normally, models shall be as large as practical but never less than the values stated. The same model should be used for all tests related to main hydraulic performance (see 9.2). Comparative model tests shall be performed with models of the same size.

5.1.3.2 Layout and mechanical design of the model

The layout and mechanical design of the model shall comply with the specified items of testing. The following points are rigorously considered:

- deformations due to loading under the chosen test specific hydraulic energy shall be minimized by appropriate design and choice of material;
- moveable elements used to vary machine geometry (nozzles) shall be capable of repeating and maintaining a set position;
- bearing system, shaft and stationary parts shall have sufficient rigidity to avoid contact in normal operation;
- hydraulically smooth surfaces of the water passages are recommended;
- in addition to general requirements for surface conditions, great care should be given to the proper matching of joints in order to avoid any local flow separation;
- materials should be chosen to avoid oxidation and electrochemical corrosion. The water passage surfaces should remain in good condition for the test duration;
- provision shall be made for easy cleaning or repairing of water passages;
- a transparent cone or windows should be provided for observation of the flow in the housing;
- where additional data have to be measured (velocity distribution) the model shall permit easy installation and checks of the corresponding measuring equipment;
- when it is required to proceed to an optimization or modification of the individual component (e.g. nozzles, casing inserts, etc.), the model shall permit easy installation of various configurations;
- if any non-homology exists, any analytical procedures adopted to account for these differences shall be mutually agreed.

5.1.3.3 Extent of model

The position of reference sections and the extent of the water passages from inlet to outlet to be included in the model (at least the part between the high-pressure and low-pressure reference sections) shall be clearly defined in the contract (see Figure 1 and as examples Figure 8 and Figure 9).

The homology limit on the low-pressure section shall be defined by mutual agreement.

Attention shall be paid to the distance between runner center line and tail water level as well as to the geometry of the tail race channel, especially in case of tail water level influence measurements (see 10.3).

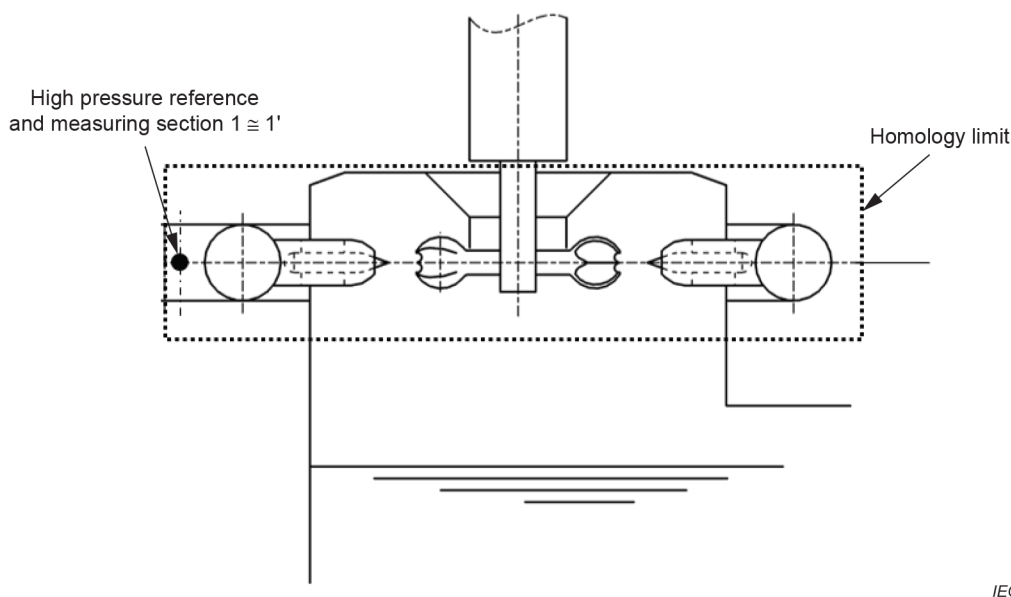


Figure 8 – Example for homology limits for wetted parts of a vertical Pelton turbine

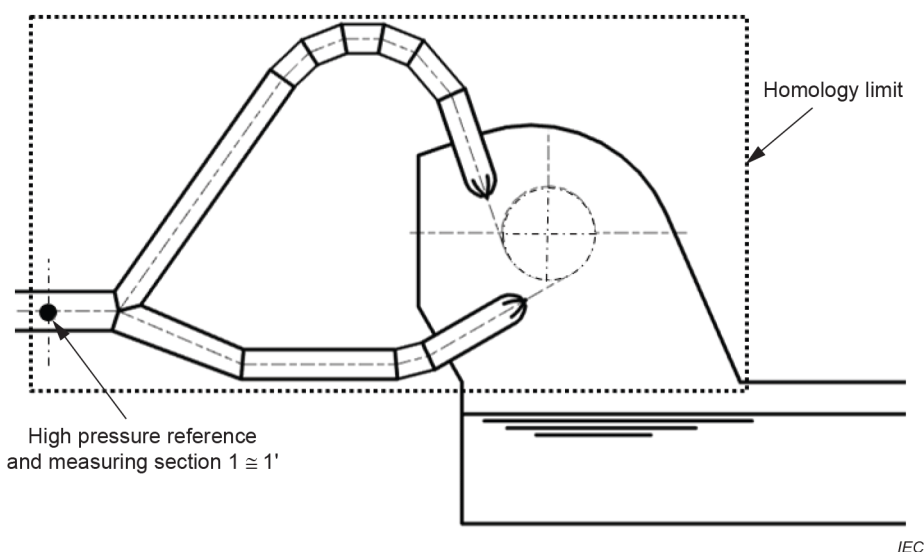


Figure 9 – Example for homology limit for wetted parts of a horizontal Pelton turbine

All the water passages influencing the performance of the prototype, i.e. inflow and outflow conditions, should as far as possible be included in the model.

Upstream or downstream gate slots are not required, unless they are located between the measuring or reference sections of the machine.

5.1.3.4 Geometric similarity of model and prototype

A basic requirement for determining prototype performance from model tests is to have geometrical similarity (homology) between model and prototype. Therefore, it is necessary to compare on both machines the geometrical dimensions and the surface finish of all components in contact with the flow.

The geometric similarity between model and prototype shall be checked in accordance with 6.2

Unless otherwise specified, the model shall be geometrically similar (homologous) to the prototype in all wetted parts within the limits defined in 5.1.3.3. This also includes details that can have a measurable influence on the performance. However, in particular cases where some minor deviations from the similarity cannot be avoided, an agreement shall be reached to determine if the results are to be corrected.

Some specific configurations can have a measurable influence on the turbine behaviour, such as heat exchangers in the tail race. An agreement shall be reached whether specific measurements or actions shall be made.

On the prototype, any non-homology or deviations that can occur during manufacturing or installation should be evaluated and corrective measures shall be mutually agreed to reduce the influence on hydraulic performance.

All abrupt changes should be corrected. It is recommended to use at least a ratio of 1:10 to correct the transition area.

On the prototype, in addition to general requirements for surface conditions, great care should be given to the proper matching of joints for all components in contact with the flow in order to avoid any local flow disturbances.

The direction of rotation has no measurable impact on performances and can differ between model and prototype.

In the case of acceptance tests on both model and prototype, the same measuring sections should be used if possible. If not possible, an agreement shall be reached to determine if the results are to be corrected.

For comparative model tests, all models should rotate in the same direction.

5.2 Dimensional check of model and prototype

5.2.1 General

As stated in 5.1.3.4, the geometrical similarity between model and prototype shall be checked.

To provide information on major and relevant geometric details that influence the hydraulic performance, the checking procedure and admissible tolerances are described below.

These tolerances shall be considered as maximum permissible values to ensure the geometric similarity and measurable influence on performance. In any case, these tolerances are reflecting the technical accuracy achievable in manufacturing.

Due to the improvement in manufacturing processes, it is quite common to have, by mutual agreement, more stringent homology requirements than those provided in 5.2.9.

The geometrical homology (openings, angles and waviness) becomes more consistent if the profile is entirely CNC machined as it is a common practice in the industry for runner manufacturing.

This applies even in the case where the model is manufactured according to an existing machine and hence the prototype is the starting point of the process.

5.2.2 Explanation of terms used for model and prototype

General terms used for model and prototype:

a) individual value

The value resulting from:

- the measurement of the dimension of the same element of the same component taken at different locations (e.g. reference diameter of a runner);
- or
- the measurement of the dimension of the same element of different recurrent components taken at the same location (e.g. bucket width).

b) average value

The value is the arithmetical mean value calculated from several individual values.

c) theoretical value

The design value indicated on a drawing. Corresponding model and prototype component lengths L_M and L_P are linked by the length scale ratio λ_L (see 3.4.3.5).

5.2.3 Purpose of dimensional checks

Dimensional checking:

- a) ascertains the main dimensions of model and prototype;
- b) checks the uniformity of model and prototype in their recurrent components, i.e. compares the relative deviation between the individual values and the corresponding average value. The permissible maximum deviations are given in the "uniformity tolerance" columns of Table 2;
- c) checks the geometrical similarity between prototype and model, i.e. compares the relative deviation between the average prototype value and the corresponding average model value scaled up by λ_L . The permissible maximum deviations are given in the "similarity tolerance" columns in Table 2. This includes verification of the relative position between all the components compared with each other (see 5.2.4);
- d) compares the measured geometrical shape or 3-D profile with the theoretical geometry, e.g. single bucket before assembly.

5.2.4 General rules

At the contract stage, the methods used for the dimensional check shall be mutually agreed. If this has been omitted, an agreement shall be made before the acceptance model test at the latest.

In practice, the reduced scale physical model is compared with the design values to fulfil similarity requirements. However, the actual similarity shall be fulfilled between the reduced scale model and the physical prototype. During the dimensional check of the prototype, the reduced scale model data shall be used as reference.

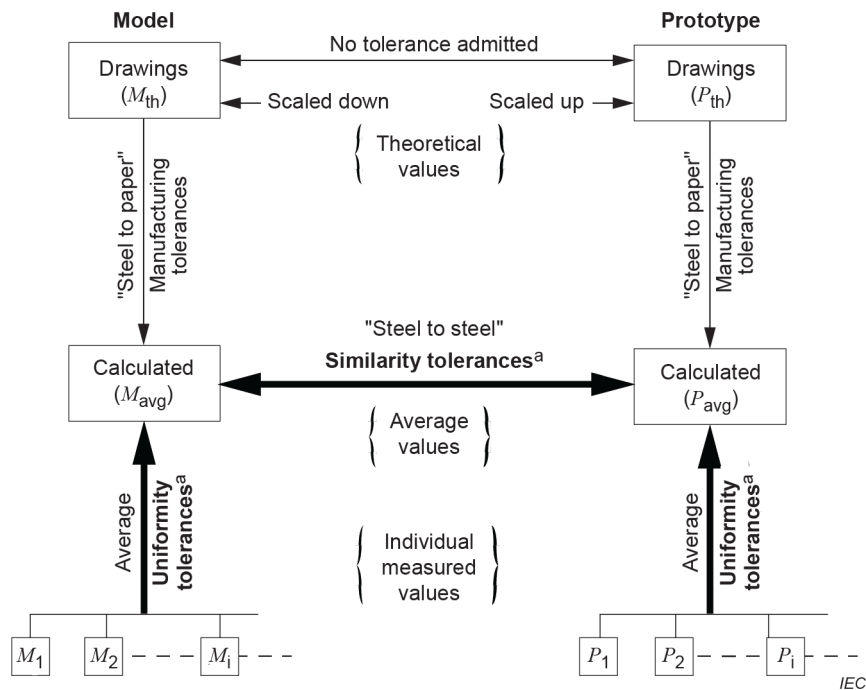
As the prototype is usually not physically available at the time of model testing, a comparison with design values is sufficient.

If the measured deviation between the physical model and the theoretical design exceeds half of the allowed maximum tolerance (see 5.2.9), the prototype shall be manufactured in a way that the total deviation stays within this tolerance. Furthermore, the prototype manufacturing tolerance shall be revised accordingly. Addition of tolerances to the theoretical design is not permissible. Alternatively, the manufacturer is allowed to revise the prototype manufacturing dimensions to be in accordance with the average value measured during the acceptance model test.

5.2.5 Procedure

5.2.5.1 Geometrical tolerances to consider

Figure 10 illustrates schematically the application of the geometrical tolerances given by this document, on individual and average values of model and prototype.



^a Numerical values of similarity tolerances and uniformity tolerances are given in 5.2.9.

Figure 10 – Procedure for dimensional checks, comparison of results "steel to steel" and application of tolerances for model and prototype

5.2.5.2 Uniformity of model and prototype components

By comparing the measurement of individual values with the corresponding average value, it is possible to determine if the uniformity requirements of model and prototype components have been met.

If the uniformity requirement is not fulfilled, agreement shall be reached on what components are to be corrected or remanufactured.

In the case where the difference between the average value and the theoretical value is outside the uniformity tolerance, it shall be agreed whether the theoretical value or the geometry of the component shall be corrected.

Where spot-checks are performed, i.e. when not all recurrent components or dimensions are checked, it can be agreed that the individual values are compared directly with the theoretical value.

5.2.5.3 Geometric similarity between prototype and model

By comparing the corresponding average values of model and prototype and considering the similarity tolerances as given by this document (see 5.2.9) or as per contract requirements, it can be determined whether the geometric similarity requirement has been met. If agreed, the corresponding theoretical values can be substituted for the average values.

If the deviations are greater than the similarity tolerances, further steps shall be agreed which could include a new test with the corrected model.

The theoretical prototype dimensions shall have significant digits that comply with the dimensional tolerance.

For some dimensions (e.g. overall dimensions) which are difficult to measure on the model or prototype, it can be agreed that, instead of average values of model or prototype, theoretical values can be used for comparison, provided that the sum of manufacturing and installation tolerances is less than the similarity tolerance.

5.2.6 Methods

5.2.6.1 General

To measure the shape and check the homology of the runner, individual profiles of the model and prototype buckets, as well as assembled runners shall be measured using coordinate measuring machines (CMM), optical measuring systems, templates, etc.

To check absolute positioning of the blades on assembled runners/impellers, templates or equivalent methods should be used.

For witness tests on model runners/impellers, if CMM is used and the dimensional check according to 5.2.9 are within tolerances, it is only necessary to check two adjacent buckets. The measured profile should then be graphically compared with the theoretical design.

CAD geometry and coordinates of hydraulic design check points are the intellectual property of the manufacturer. The manufacturer is not required to give the CAD geometry or the coordinates to the purchaser.

To protect the confidentiality and the intellectual property of the hydraulic design, the manufacturer shall report only the differences between the measured and the theoretical profile.

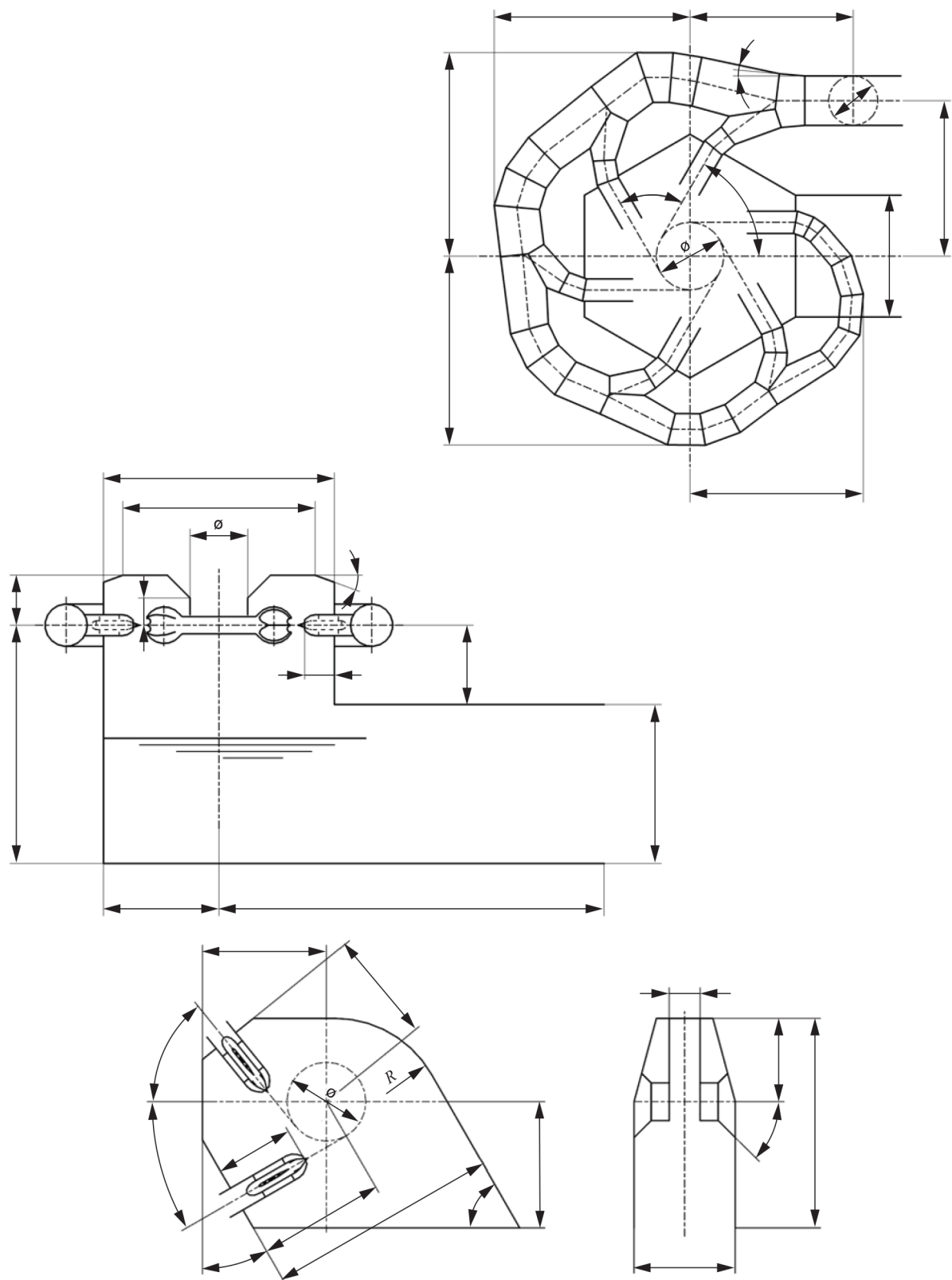
If further checks are required on either the model or prototype, the number, the coordinates of the check points and their storage format shall be defined by mutual agreement.

Considering the manufacturing and measuring methods of the runner/impeller, the manufacturer shall propose the most appropriate method and location of checking in agreement with the purchaser to demonstrate the geometric similarity between prototype and model.

Figure 11 to Figure 12 give examples showing schematically the location and extent of the geometric checking. However, the checking procedure is neither limited to the given examples nor does it mean that all of these dimensions should be checked.

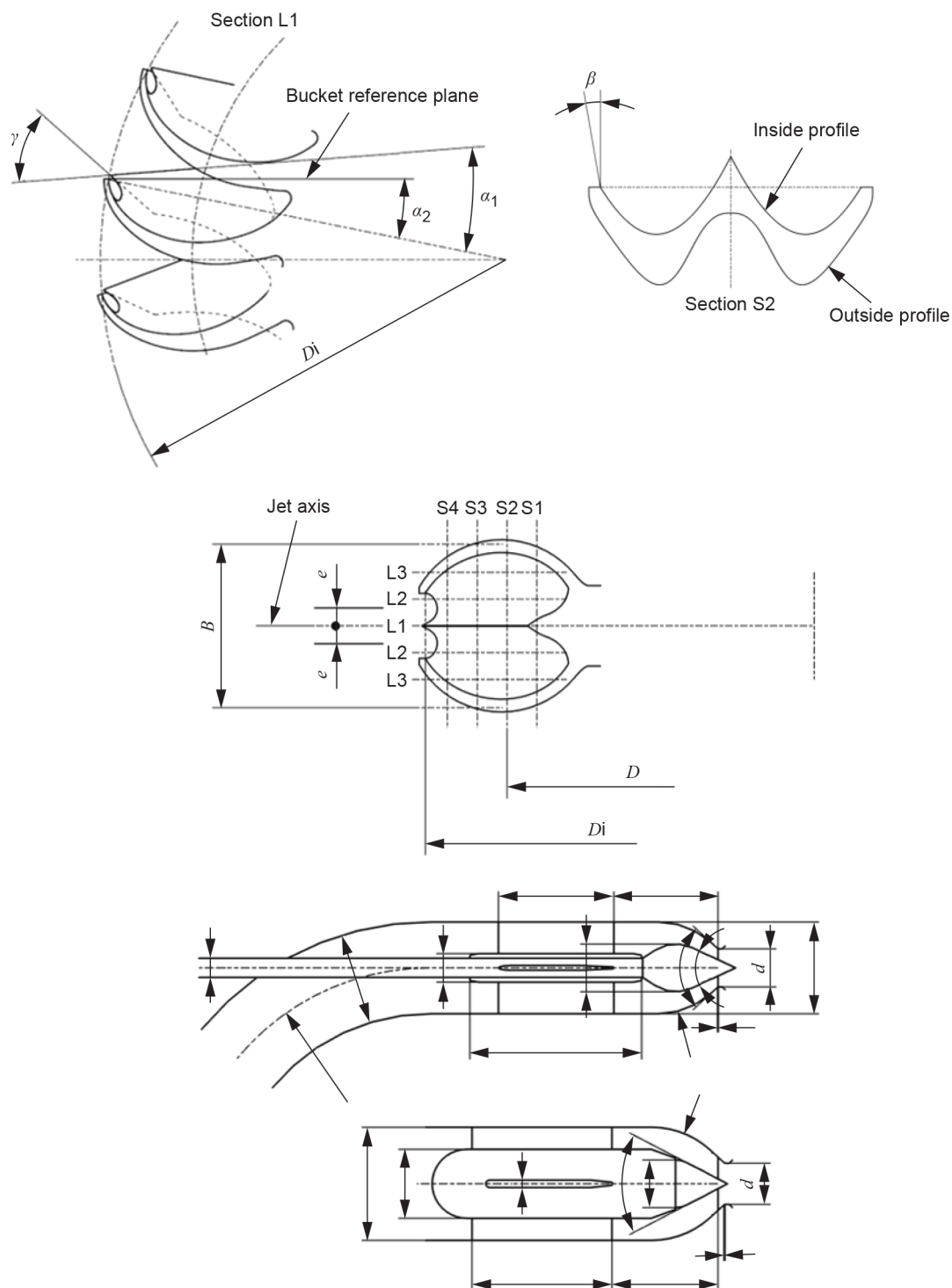
If the outlet edge of the Pelton bucket is contained in a plane, it defines the bucket reference plane (see Figure 12). Else, the definition of the bucket reference plane has to be agreed upon.

When a length cannot be measured directly, e.g. if a point of intersection is covered by a fillet, the measurement shall be made according to an agreed upon procedure.



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Figure 11 – Pelton turbine: example of dimensions to be checked on the distributor and the housing of vertical and horizontal shaft machines



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Figure 12 – Pelton turbine: example of dimensions to be checked on the buckets and nozzles

5.2.6.2 Geometrical measurements using templates

The geometrical homology between model and prototype can be checked using templates. The templates should be homologous in size, offset and positioning between the prototype and the model. However, it shall be considered that it can be difficult to position the templates depending on the component.

5.2.6.3 Geometrical measurements using coordinate measuring machines (CMM)

Coordinate measuring machines are based on different methods and technologies. They can be classified by the type of the probe support system (e.g. bridge type, articulated arm), the probe type (e.g. mechanical, optical/scanner) or the type of control (e.g. manual, numerical). Regardless of type, all CMM machines supply a large number of 3-D coordinate points that are recorded in a data file and then processed with dedicated software.

The measured data can be processed in several ways; for example, if mechanical probes with spheres are used, the measured centre point of the probe is corrected with the sphere radius. For these tasks, dedicated software is available with the CMM.

Prior to the dimensional check, a preliminary check of the certificated CMM shall be performed with a calibrated standard.

To check the homology by CMM, the relevant CAD part of the theoretical design shall be used. Therefore, the purchaser shall be able to check that the same CAD geometry is used during the model and the prototype homology check. To protect the Intellectual Property (IP) of the manufacturer, the following methods can be used:

a) CMM template mode:

- In general, four longitudinal and four transverse sections per bucket are required . Absolute coordinates of a total of approximately 100 points are given to the purchaser.

b) CMM mapping mode:

- Arbitrary number of points is measured on the model;
- ASCII (text) file with coordinates is stored and digitally signed with officially verified algorithm (like NIST FIPS 180-4 or SHA-3) or kept in a sealed envelope;
- The manufacturer shall supply the purchaser with results presenting the deviations from the theoretical hydraulic design;
- During the check of the prototype, the ASCII file with the coordinates is used to demonstrate that the CAD geometry used is the same as during the model check (except that the values shall be scaled from model to prototype).

These methods provide only some examples of how to protect the confidentiality of the theoretical design of the manufacturer. The list of examples is not complete and any procedure mutually agreed upon can be used.

5.2.7 Accuracy of measurements

As a detailed description of methods and measuring accuracies goes beyond the purpose of this document, the following recommendations are given:

- A detailed description of the used instrument together with a description of the assorted accuracy and repeatability shall be given;
- The total error consists of the error caused by the coordinate system positioning, plus the systematic error of the measuring instrument and the random error;
- A best fit of data computed by CMM can only show if the surface of a single component itself is according to the drawing, but does not guarantee that the component be positioned correctly in the 3-D space or relative to other components.

5.2.8 Dimensions of model and prototype to be checked

5.2.8.1 General

The dimensions of all significant components defining the water passages shall be checked to an extent agreeable to the parties concerned.

The relevant dimensions and tolerances for Pelton turbines are defined in 5.2.9. When a location is defined by more than one dimension, the tolerance applies to only the most relevant dimension. Whenever possible, the dimensions of the wetted water passage shall be used.

A check of geometric similarity comprises both:

- a) a check on the homology of the individual components before assembly. For practical reasons the dimensions shall refer to the component itself;
- b) a check on the homology of the whole machine, i.e. with the components assembled. The relevant overall dimensions usually refer to the runner axis. Special attention shall be paid to water passages formed by the transition between adjacent components, stationary or rotating, for which no general value of tolerance can be required in this document.

In 5.2.8, the permissible maximum deviations refer either to the corresponding scaled model average value or to the following reference dimensions:

- D reference diameter (see Figure 2);
- P_i bucket pitch;
- d nozzle orifice diameter (see Figure 12);
- B maximum inside width of runner bucket (see Figure 12).

The terms used in the following subclauses to indicate the various components of hydraulic machines are defined in IEC TR 61364.

5.2.8.2 Main wetted components

5.2.8.2.1 General

The main components to check:

- the principal dimensions of the runner, manifold, housing and nozzles (see Figure 11);
- the number of buckets;
- the form of buckets, nozzles and needles (see Figure 12);
- the alignment of the jets to the runner;
- the surface roughness and waviness of the buckets, nozzles and needles (usually only relevant for the prototype) (see 5.2.10.2 and 5.2.10.3).

5.2.8.2.2 Pelton turbine runner

The profile of at least one bucket shall be checked at a minimum of four transverse and four longitudinal sections or randomly on the whole surface. See Figure 12. Special attention shall be paid close to the cutout and outlet edge.

The bucket position and inclination in the runner shall be checked. See Figure 12.

The discharge angle β of each bucket shall be checked at four points on each side. See Figure 12.

The form of the cutout, the angle γ of the back of the cutout, the splitter edge and the bucket inclination α shall be checked on minimum three buckets. See Figure 12.

The bucket inside width and profile shall be checked.

The bucket outside profile shall also be checked. To ensure that the interference between the jet and the bucket on the prototype is always less than that on the model, the tolerances of the outside profile shall be applied to the bucket discharge area which can influence this interference. See 5.2.9.

5.2.9 Permissible maximum deviations in geometrical similarity between prototype and model

The following points apply:

- the reference value is taken to be scaled model average ($\lambda_L L_M$), unless otherwise indicated;
- where the bucket surface is sufficiently defined, the independent determination of angles can be omitted;
- if a complete bucket profile is provided, the bucket thickness T is not required.

Table 2 – Permissible maximum deviations

	Reference value	Permissible maximum deviation		
		Uniformity tolerance		Similarity tolerance
		Model	Prototype	Prototype/Model
		Individual value to average value	Individual value to average value	Prototype average value to scaled model average value ($(L_P - \lambda_L L_M)/(\text{reference value})$)
Metallic or concrete water passages (manifold, housing, tailrace channel)	Average value	$\pm 2 \%$	$\pm 2 \%$	$\pm 1 \%$
Needle and nozzle diameter	d	$\pm 0,3 \%$	$\pm 0,3 \%$	$\pm 0,3 \%$
Needle and nozzle profile	d	$\pm 1 \%$	$\pm 1 \%$	$\pm 1 \%$
Lengths of injector (torpedo, rib)	Average value	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
Rib thickness	Average value	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$
Nozzle angle	1	$\pm 0,5^\circ$	$\pm 1^\circ$	$\pm 1^\circ$
Needle angle	1	$\pm 0,5^\circ$	$\pm 1^\circ$	$\pm 1^\circ$
Bucket inside width B	Average value	$\pm 0,3 \%$	$+0,8$ $-0,5 \%$	$+0,8$ $-0,5 \%$
Bucket outside profile	B	$\pm 0,5 \%$	$+1$ $-0,8 \%$	$+1$ $-0,8 \%$
Bucket inside profile	B	$\pm 0,5 \%$	$\pm 0,5 \%$	$\pm 0,5 \%$
Bucket inclination α	1	$\pm 1^\circ$	$\pm 1^\circ$	$\pm 1^\circ$
Bucket discharge angle β	1	$\pm 1^\circ$	$\pm 1^\circ$	$\pm 1^\circ$
Cut-out profile (inside / outside)	B	$\pm 0,5 \%$	$\pm 0,5 \%$	$\pm 0,5 \%$
Jet circle diameter D	Average value	$\pm 0,2 \%$	$\pm 0,2 \%$	$\pm 0,2 \%$
Offset of jet to runner e	B	$\pm 0,5 \%$	$\pm 0,5 \%$	$\pm 0,25 \%$
Alignment of jet to runner δ	1	$\pm 0,5^\circ$	$\pm 0,5^\circ$	$\pm 0,5^\circ$
Bucket pitch at outer diameter P_i	B	$\pm 1 \%$	$\pm 1 \%$	$\pm 1 \%$
Bucket thickness at outlet	B	$+1$ $-0,5 \%$	$+1$ $-0,5 \%$	$+1$ $-0,5 \%$
Bucket tip diameter	D	$\pm 0,2 \%$	$\pm 0,2 \%$	$\pm 0,2 \%$

5.2.10 Surface waviness and roughness

5.2.10.1 Geometrical characteristics

5.2.10.1.1 Waviness

Waviness is the deviation of a surface profile from a smooth design curve. Waviness is expressed as the ratio of maximum deviation to distance over which the deviation from the smooth curve occurs. This is the ratio X/U of Figure 13. A flexible stick that readily conforms to the bucket shape is an example of a tool that can be used to evaluate waviness. In order to distinguish waviness from surface roughness, U should be not less than 50 mm. The point of maximum deviation X should be in the middle third of U .

Bumps on the surface are more difficult to assess than hollows. However, bumps are typically easier to correct.

5.2.10.1.2 Surface roughness

Surface roughness is the characteristic quality of the surface due to small departures from its general form such as those produced by the cutting action of tool edges, abrasive grains, feed of the machine, coating and painting or originally produced by the fabrication (welding) process.

It is characterized by the roughness criterion R_a (arithmetic mean deviation of the assessment profile) as defined in ISO 4287:1997.

5.2.10.2 Waviness requirements

To fulfil geometrical homology requirements, prototype waviness shall be measured and the maximum permissible values are listed below.

The whole surface of the main wetted components as described in 5.2.8.2 shall be checked to establish that profiles are smooth continuous curves with a waviness value of less than $\pm 0,01$.

For surfaces having a profile variation with contact points distance between 10 mm and 50 mm, acceptable waviness shall be less than $\pm 0,02$. It is important to highlight that the waviness criteria as defined is used to evaluate a continuous surface after machining and grinding. This excludes any waviness that is part of the design profile.

In the case of CNC machined components, the accuracy of the manufacturing process with a waviness value of less than $\pm 0,004$ and $\pm 0,002$ for surfaces subject to cavitation should be achievable. A fully controlled machining process (for example, by limiting the scallop height to 0,2 mm between two adjacent passes) should assure a smooth continuous profile within the recommended waviness values after grinding.

For waviness measurement, typical minimum distance between contact points between two peaks should not be less than 10 mm. If the contact point distance is less than 10 mm, then the waviness measurement should be replaced by roughness measurement.

Waviness criteria should never be used to assess holes, defects, porosity, lack of material, any abrupt changes in surface profile or matching of joints.

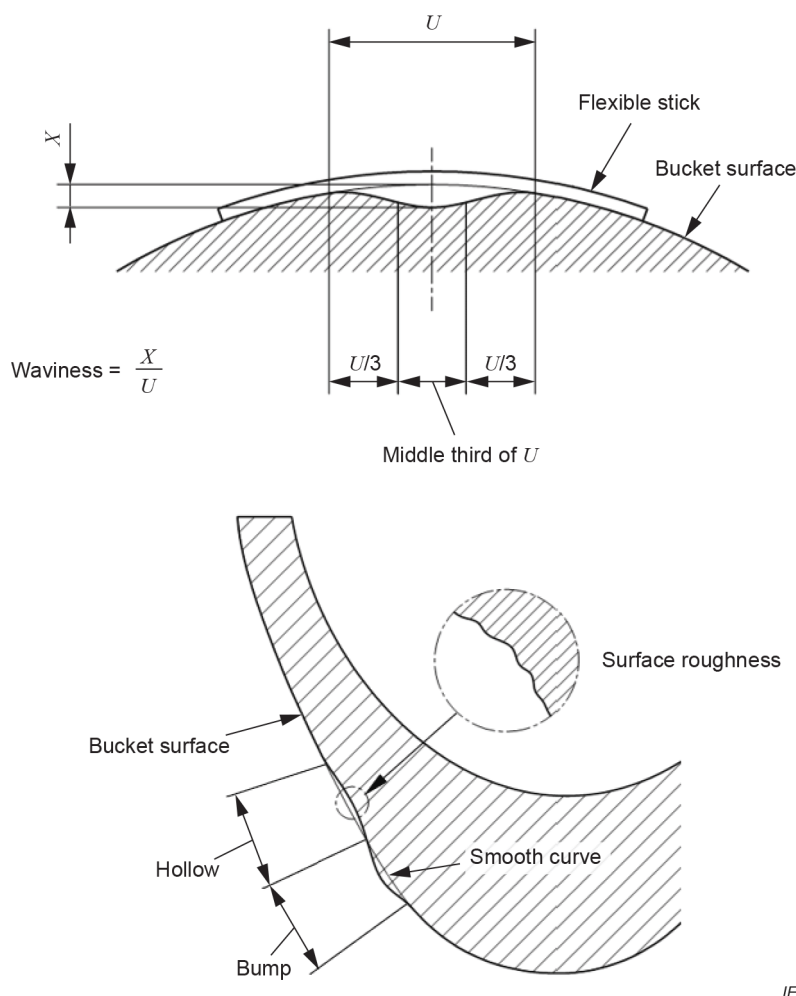


Figure 13 – Definition of waviness and surface roughness

5.2.10.3 Roughness requirements

Rough surfaces in the water passages of both model and prototype machines reduce the efficiency below the value that is potentially achievable.

If the effect of surface roughness on performance is not considered, both the model and prototype should be such that hydraulically smooth flow is achieved. However, this is difficult to achieve on the prototype. Therefore, maximum recommended values of prototype surface roughness are provided below.

The recommendations for surface roughness values are given in Table 3 for various types of machines, corresponding approximately to machines with lower to medium head and to machines with high head.

The values of prototype surface roughness are valid for the finished condition of the surface. This means that if the hydraulic wetted components have painted or coated surfaces, this condition shall be checked.

Moreover, the finish required may be chosen at some locations to improve cavitation resistance or for fatigue reasons; then the choice of finish is not related to model-to-prototype dimensional similarity.

The values given in Table 3 are maximum recommended values for the total surface of the component involved, finished surfaces and eventual painting included. The maximum surface

roughness as recommended in Table 3 does not necessarily yield hydraulically smooth flow conditions.

Table 3 – Maximum recommended prototype surface roughness R_a

Component	R_a μm			
	E	$> 5\,000\text{ J}\cdot\text{kg}^{-1}$	E	$> 5\,000\text{ J}\cdot\text{kg}^{-1}$
Wetted surfaces of buckets, nozzle needle and orifice:		$\leq 3,2$		$\leq 1,6$
Nozzle wetted surfaces:		$\leq 6,3$		$\leq 3,2$
Dry bucket surfaces		$\leq 12,5$		$\leq 12,5$
Manifold:		$\leq 25,0$		$\leq 12,5$

5.3 Test procedures

5.3.1 Organization of tests

5.3.1.1 General

When planning model tests, Subclauses 5.3.1.2 to 5.3.1.7 covering general aspects of preparation, organization and realization shall be clarified and agreed on by the parties involved.

5.3.1.2 Specification for model tests

A specification for model tests is the basis for planning and preparing a model acceptance test and for drafting the detailed technical programme of tests (see 5.3.3.2). This model test specification is often part of the general technical or commercial specification for a whole project issued by the purchaser or its representative.

Among other items, the specification for model tests shall define:

- object, scope and extent of model tests;
- reference to guaranteed and specified plant data;
- reference to test standards;
- model scale and/or size;
- place(s) where the model(s) is (are) tested;
- documentation of results (test reports);
- time schedule indicating, at a minimum, start and end dates of work for model testing;
- model property ownership and/or storage.

5.3.1.3 Time schedule

A time schedule should be agreed on, which indicates as a minimum, the different stages, deadlines or duration for the following items:

- submission of model drawings (especially those showing model construction and principal dimensions of model high and low-pressure side at the transition to the test rig);
- submission of the test procedure containing a description of testing equipment (including methods of calibration, calculation and representation of results and expected uncertainties of measurement);