

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Hydraulic turbines, storage pumps and pump-turbines –
Model acceptance tests

(standards.iteh.ai)

Turbines hydrauliques, pompes d'accumulation et pompes-turbines –
Essais de réception sur modèle

<https://standards.iteh.ai/catalog/standards/sist/e473e535-bcfb-45dc-8b0b-3e60bc13d4c4/iec-60193-2019>



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2019 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de l'IEC ou du Comité national de l'IEC du pays du demandeur. Si vous avez des questions sur le copyright de l'IEC ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de l'IEC de votre pays de résidence.

IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22,000 terminological entries in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary

67,000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

A propos de l'IEC

La Commission Electrotechnique Internationale (IEC) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications IEC

Le contenu technique des publications IEC est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Recherche de publications IEC -

webstore.iec.ch/advsearchform

La recherche avancée permet de trouver des publications IEC en utilisant différents critères (numéro de référence, texte, comité d'études,...). Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

IEC Just Published - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications IEC. Just Published détaille les nouvelles publications parues. Disponible en ligne et une fois par mois par email.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: sales@iec.ch.

Electropedia - www.electropedia.org

Le premier dictionnaire d'électrotechnologie en ligne au monde, avec plus de 22 000 articles terminologiques en anglais et en français, ainsi que les termes équivalents dans 16 langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (IEV) en ligne.

Glossaire IEC - std.iec.ch/glossary

67 000 entrées terminologiques électrotechniques, en anglais et en français, extraites des articles Termes et Définitions des publications IEC parues depuis 2002. Plus certaines entrées antérieures extraites des publications des CE 37, 77, 86 et CISPR de l'IEC.

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Hydraulic turbines, storage pumps and pump-turbines –
Model acceptance tests (standards.iteh.ai)

Turbines hydrauliques, pompes d'accumulation et pompes-turbines –
Essais de réception sur modèle

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.140

ISBN 978-2-8322-6659-5

**Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.**

CONTENTS

FOREWORD.....	13
1 Scope.....	15
2 Normative references	17
3 Terms, definitions, symbols and units	18
3.1 General.....	18
3.2 General terminology.....	18
3.3 Units.....	20
3.4 Definition of terms, symbols and units.....	20
3.4.1 List of terms and definitions by topic.....	20
3.4.2 Subscripts and symbols	21
3.4.3 Geometric terms	23
3.4.4 Physical quantities and properties	25
3.4.5 Discharge, velocity and speed terms	26
3.4.6 Pressure terms	27
3.4.7 Specific energy terms	27
3.4.8 Height and head terms	30
3.4.9 Power and torque terms.....	32
3.4.10 Efficiency terms	34
3.4.11 General terms relating to fluctuating quantities	35
3.4.12 Fluid dynamics and scaling terms ^{a)}	37
3.4.13 Dimensionless terms	38
3.4.14 Terms relating to additional performance data	39
4 Nature and extent of guarantees related to hydraulic performance.....	40
4.1 General.....	40
4.1.1 Design data and coordination	40
4.1.2 Definition of the hydraulic performance guarantees	40
4.1.3 Guarantees of correlated quantities	41
4.1.4 Form of guarantees	41
4.2 Main hydraulic performance guarantees verifiable by model test.....	41
4.2.1 Guaranteed quantities for any machine.....	41
4.2.2 Specific application.....	42
4.3 Guarantees not verifiable by model test	43
4.3.1 Guarantees on cavitation erosion	43
4.3.2 Guarantees on maximum momentary overspeed and maximum momentary pressure rise	44
4.3.3 Guarantees covering noise and vibration	44
4.4 Additional performance data	44
5 Execution of tests	45
5.1 Requirements of test installation and model.....	45
5.1.1 Choice of laboratory	45
5.1.2 Test installation	45
5.1.3 Model requirements	46
5.2 Dimensional check of model and prototype	49
5.2.1 General	49
5.2.2 Explanation of terms used for model and prototype.....	49
5.2.3 Purpose of dimensional checks.....	49
5.2.4 General rules.....	50

5.2.5	Procedure.....	51
5.2.6	Application for different types of machines.....	52
5.2.7	Methods	52
5.2.8	Accuracy of measurements.....	61
5.2.9	Dimensions of model and prototype to be checked	62
5.2.10	Permissible maximum deviations in geometrical similarity between prototype and model for turbines, pumps and pump-turbines	66
5.2.11	Surface waviness and roughness.....	71
5.3	Hydraulic similitude.....	74
5.3.1	Theoretical basic requirements and similitude numbers	74
5.3.2	Conditions for hydraulic similitude as used in this document.....	74
5.3.3	Similitude requirements for various types of model tests.....	75
5.3.4	Reynolds similitude.....	76
5.3.5	Froude similitude	77
5.3.6	Other similitude conditions.....	80
5.4	Test conditions	81
5.4.1	Determination of test conditions.....	81
5.4.2	Minimum values for model size and test conditions to be fulfilled	82
5.4.3	Stability and fluctuations during measurements	83
5.4.4	Adjustment of the operating point	83
5.5	Test procedures.....	83
5.5.1	Organization of tests.....	83
5.5.2	Inspections and calibrations	86
5.5.3	Execution of tests	88
5.5.4	Faults and repetition of tests.....	93
5.5.5	Final test report	94
5.6	Introduction to the methods of measurement.....	95
5.6.1	General	95
5.6.2	Measurements related to the main hydraulic performance guarantees	95
5.6.3	Measurements related to additional data	97
5.6.4	Acquisition and processing of data	97
5.7	Physical properties	97
5.7.1	General	97
5.7.2	Acceleration due to gravity	97
5.7.3	Physical properties of water.....	98
5.7.4	Physical conditions of atmosphere.....	104
5.7.5	Density of mercury.....	104
6	Main hydraulic performances: methods of measurement and results.....	105
6.1	Data acquisition and data processing.....	105
6.1.1	Overview	105
6.1.2	General requirements	105
6.1.3	Data acquisition.....	105
6.1.4	Component requirements.....	107
6.1.5	Check of the data acquisition system.....	110
6.2	Discharge measurement	112
6.2.1	General	112
6.2.2	Choice of the method of measurement.....	112
6.2.3	Accuracy of measurement	113
6.2.4	Primary methods	114

6.2.5	Secondary methods	115
6.3	Pressure measurement	118
6.3.1	General	118
6.3.2	Choice of pressure-measuring section	119
6.3.3	Pressure taps and connecting lines	119
6.3.4	Apparatus for pressure measurement	121
6.3.5	Calibration of pressure measurement apparatus	128
6.3.6	Vacuum measurements	129
6.3.7	Uncertainty in pressure measurements	129
6.4	Free water level measurement (see also ISO 4373)	129
6.4.1	General	129
6.4.2	Choice of water level measuring sections	130
6.4.3	Number of measuring points in a measuring section	130
6.4.4	Measuring methods	130
6.4.5	Uncertainty in free water level measurement	131
6.5	Determination of E and $NPSE$	132
6.5.1	General	132
6.5.2	Determination of the specific hydraulic energy E	133
6.5.3	Simplified formulae for E	135
6.5.4	Determination of the net positive suction-specific energy $NPSE$	142
6.6	Shaft torque measurement	144
6.6.1	General	144
6.6.2	Methods of torque measurement	144
6.6.3	Methods of absorbing/generating power	145
6.6.4	Layout of arrangement	145
6.6.5	Checking of system	150
6.6.6	Calibration	150
6.6.7	Uncertainty in torque measurement (at a confidence level of 95 %)	151
6.7	Rotational speed measurement	152
6.7.1	General	152
6.7.2	Methods of speed measurement	152
6.7.3	Checking	152
6.7.4	Uncertainty of measurement	152
6.8	Computation and presentation of test results	153
6.8.1	General	153
6.8.2	Power, discharge and efficiency in the guarantee range	158
6.8.3	Computation of steady-state runaway speed and discharge	171
6.9	Error analysis	176
6.9.1	Definitions	176
6.9.2	Determination of uncertainties in model tests	178
6.10	Comparison with guarantees	182
6.10.1	General	182
6.10.2	Interpolation curve and total uncertainty bandwidth	183
6.10.3	Power, discharge and/or specific hydraulic energy and efficiency in the guarantee range	184
6.10.4	Runaway speed and discharge	188
6.10.5	Cavitation guarantees	189
7	Additional performance data – Methods of measurement and results	191
7.1	Introduction to additional data measurement	191

7.1.1	General	191
7.1.2	Test conditions and test procedures	192
7.1.3	Uncertainty in measurements	192
7.1.4	Model to prototype conversion	192
7.2	Fluctuating quantities	193
7.2.1	Data acquisition and processing for measurement of fluctuating quantities	193
7.2.2	Pressure fluctuations	197
7.2.3	Shaft torque fluctuations	213
7.3	Axial and radial thrust	214
7.3.1	General	214
7.3.2	Hydraulic axial thrust	215
7.3.3	Radial thrust	223
7.4	Hydraulic loads on control components	226
7.4.1	General	226
7.4.2	Guide vane torque	227
7.4.3	Runner blade torque	233
7.4.4	Pelton needle force and deflector torque	237
7.5	Testing in an extended operating range	241
7.5.1	General	241
7.5.2	Four quadrants	241
7.5.3	Operating modes (see Figure 116)	243
7.5.4	Scope of tests	244
7.5.5	Methods of testing in the extended operating range	246
7.6	Differential pressure measurement in view of prototype index test	248
7.6.1	General	248
7.6.2	Purpose of test	249
7.6.3	Execution of test	249
7.6.4	Analysis of test results	249
7.6.5	Transposition to prototype conditions	250
7.6.6	Uncertainty	250
Annex A (informative)	Dimensionless terms	251
Annex B (normative)	Physical properties, data	253
Annex C (informative)	Summarized test and calculation procedure	261
C.1	General	261
C.2	Agreements to be reached prior to testing	261
C.3	Model, test facility and instrumentation	262
C.3.1	Model manufacture and dimensional checks	262
C.3.2	Test facility instrumentation and data acquisition system	262
C.4	Tests and calculation of the model values	262
C.4.1	Test types	262
C.4.2	Measurement of the main quantities during the test	263
C.4.3	Uncertainty of the measured quantities	263
C.4.4	Calculation of the quantities related to the main hydraulic performance	263
C.4.5	Calculation of the dimensionless factors or coefficients and of the Thoma number	263
C.4.6	Determination of δ_{ref} for the transposition of efficiency	264
C.4.7	Calculation of efficiency and power coefficients referred to Re_M^*	264

C.4.8	Correction of the model-measured values taking into account the influence of cavitation	264
C.5	Calculation of prototype quantities	264
C.6	Plotting of model or prototype results	264
C.7	Comparison with the guarantees	265
C.8	Final protocol	265
C.9	Final test report	265
Annex D (normative)	The scale effect on hydraulic efficiency for reaction machines	266
D.1	Basic statements and assumptions	266
D.2	Efficiency transposition formulae.....	266
D.2.1	Derivation of the general formula for efficiency transposition	266
D.2.2	Amount of relative scalable losses in the range of guaranteed efficiencies	267
D.2.3	Determination of the effect of scaling on the efficiency of the model	269
D.2.4	Determination of the formula for the transposition of efficiency from model to prototype	271
Annex E (informative)	Comparison of the hydraulic efficiency transposition methods of IEC 60193 and IEC 62097 for reaction machines	273
E.1	IEC 60193 transposition method	273
E.1.1	Applications	273
E.1.2	Limitations	273
E.2	IEC 62097 transposition method	274
E.2.1	Applications	274
E.2.2	Limitations	274
Annex F (normative)	Computation of the prototype runaway characteristics taking into account friction and windage losses of the unit	275
Annex G (informative)	Example of determination of the best smooth curve: method of separate segments	276
G.1	General.....	276
G.2	Principle of the method	276
G.3	Choice of the minimum width of the intervals	278
G.4	Determination of the intervals	278
Annex H (informative)	Examples of analysis of sources of error and uncertainty evaluation	279
H.1	General.....	279
H.2	Example of analysis of sources of error and of uncertainty evaluation in the measurement of a physical quantity	279
H.2.1	General	279
H.2.2	Errors arising during calibration	280
H.2.3	Errors arising during the tests.....	281
H.3	Example of calculation of uncertainty due to systematic errors in the determination of the specific hydraulic energy, mechanical runner/impeller power and hydraulic efficiency	281
H.3.1	General	281
H.3.2	Discharge	282
H.3.3	Pressure.....	282
H.3.4	Specific hydraulic energy.....	282
H.3.5	Power	283
H.3.6	Hydraulic efficiency	283
H.4	Example of calculation of uncertainty due to systematic errors in the determination of the net positive suction specific energy	284

H.4.1	General	284
H.4.2	Discharge	284
H.4.3	Pressure	284
H.4.4	Net positive suction specific energy	284
Annex I (normative)	The scale effect on hydraulic efficiency for Pelton turbines	286
I.1	General.....	286
I.2	Similarity considerations	286
I.3	Transposition formula	288
Annex J (normative)	Analysis of random errors for a test at constant operating conditions	289
J.1	General.....	289
J.2	Standard deviation	289
J.3	Confidence levels	290
J.4	Student's <i>t</i> distribution	290
J.5	Maximum permissible value of uncertainty due to random errors.....	291
J.6	Example of calculation	292
Annex K (normative)	Calculation of plant Thoma number σ_{pl}	293
K.1	Definition of σ_{pl} , <i>NPSE</i> and <i>NPSH</i>	293
K.2	Data needed to calculate σ_{plc}	294
Annex L (informative)	Flux diagram of specific hydraulic energy, flow and power	296
Annex M (informative)	Synchronous and asynchronous components of pressure signals	299
Annex N (informative)	Natural frequency of the hydraulic system	301
Annex O (informative)	Calculation of axial force components	302
O.1	General.....	302
O.2	Calculating the force acting on the runner crown (F_2)	302
O.2.1	General	302
O.2.2	Pressure specific energy losses due to seal clearance	302
O.2.3	Pressure specific energy losses through the centrifugal zones between the stationary and rotating parts	304
O.2.4	Pressure specific energy losses in a pressure relief/equilibrium pipe	305
O.2.5	Additional specific energy losses	306
O.3	Calculating the force acting on the runner band (F_3).....	307
Bibliography.....		308
Figure 1–	Schematic representation of a hydraulic machine.....	22
Figure 2 –	Guide vane opening and angle	22
Figure 3 –	Reference diameter and bucket width	24
Figure 4 –	Determination of σ_0 and σ_1 for typical cavitation curves.....	29
Figure 5 –	Reference level of machine	31
Figure 6 –	Flux diagram for power and discharge.....	33
Figure 7 –	Illustration of some definitions related to oscillating quantities.....	36
Figure 8 –	Procedure for dimensional checks, comparison of results "steel to steel" and application of tolerances for model and prototype	51
Figure 9 –	Example of spiral case and distributor dimensions to be checked.....	54
Figure 10 –	Example of draft tube dimensions to be checked	54

Figure 11 – Example of the dimensions to be checked on a bulb unit.....	55
Figure 12 – Example of the dimensions to be checked on the runner/impeller of a radial flow machine	56
Figure 13 – Runner/impeller of radial flow machine: examples of locations for blade profile measuring sections for templates or measuring points for CMM	57
Figure 14 – Runner/impeller of radial flow machine: check of outlet width and blade profiles by means of templates as illustrated on a Francis runner	57
Figure 15 – Runner/impeller of radial flow machine: check of inlet and outlet widths between blades (example of a pump-turbine runner).....	58
Figure 16 – Runner/impeller of axial flow machine: example of locations for blade profile measuring sections for templates or measuring points for CMM	58
Figure 17 – Runner/impeller of axial flow machine: definition of blade adjustment and of blade profile tolerances.....	58
Figure 18 – Pelton turbine: example of dimensions to be checked on the distributor and the housing of vertical and horizontal shaft machines	59
Figure 19 – Pelton turbine: example of dimensions to be checked on the buckets and nozzles	60
Figure 20 – Definition of waviness and surface roughness	72
Figure 21 – Low specific hydraulic energy turbine example of recommended maximum surface roughness values on the runner blades (pressure side and suction side).....	73
Figure 22 – Relation between the setting level z_p of a Francis turbine and the cavitation reference level z_c	78
Figure 23 – Dependence of σ values on level z for model and prototype	78
Figure 24 – Acceleration due to gravity g ($m \cdot s^{-2}$).....	98
Figure 25 – Density of distilled water ρ_{wd} ($kg \cdot m^{-3}$).....	101
Figure 26 – Time multiplexing data acquisition system.....	106
Figure 27 – Bus operated data acquisition system	107
Figure 28 – Time delay	108
Figure 29 – Typical low-pass filter attenuation characteristics	109
Figure 30 – Different measurement chains and their recommended checkpoints	111
Figure 31 – Examples of pressure taps	120
Figure 32 – Types of pressure manifolds: a) with separate connecting lines to manifold and b) with ring manifold.....	121
Figure 33 – Examples of experimental setup of liquid column manometers	123
Figure 34 – Dead weight manometer with compensation by pressure or force transducer (example of experimental set-up)	126
Figure 35 – Pressure weighbeam (example of experimental set-up).....	127
Figure 36 – Stilling well.....	130
Figure 37 – Point and hook gauges.....	131
Figure 38 – Example showing main elevations, heights and reference levels of the test rig and model machine.....	134
Figure 39 – Determination of specific hydraulic energy through differential pressure measuring instrument	137
Figure 40 – Determination of specific hydraulic energy of the machine through separate measurement of gauge pressures	138
Figure 41 – Determination of specific hydraulic energy of the machine through separate measurement of pressures by water column manometers.....	139

Figure 42 – Pelton turbines with vertical axis: determination of specific hydraulic energy of the machine	140
Figure 43 – Pelton turbines with horizontal axis: determination of specific hydraulic energy of the machine	141
Figure 44 – Low-head machines: determination of specific hydraulic energy of the machine using free water levels	142
Figure 45 – Determination of net positive suction energy <i>NPSE</i> and net positive suction head <i>NPSH</i>	143
Figure 46 – Balance arrangement	146
Figure 47 – Balance arrangement with gear	147
Figure 48 – Balance arrangement with two separate frames	147
Figure 49 – Arrangement with machine bearings and seals not in balance	147
Figure 50 – Arrangement with lower bearing and seal not in balance	148
Figure 51 – Arrangement with intermediate bearing and seal not in balance	148
Figure 52 – Arrangement using a torquemeter	148
Figure 53 – Arrangement using a torquemeter with machine bearings and seals in balance	149
Figure 54 – Arrangement using a torquemeter with machine bearings and seals not in balance	149
Figure 55 – Choosing the appropriate transposition method	153
Figure 56 – Single-regulated (Francis) model turbine: performance hill diagram (discharge factor versus speed factor)	155
Figure 57 – Single-regulated (Francis) model turbine: performance hill diagram (energy coefficient versus discharge coefficient)	155
Figure 58 – Double-regulated (Kaplan) model turbine: performance hill diagram	156
Figure 59 – Single-regulated (radial) model pump: performance diagram	156
Figure 60 – Double-regulated model pump: performance diagram	157
Figure 61 – Pelton model turbine: performance hill diagram (example for a six-nozzle machine)	157
Figure 62 – Single-regulated (radial) model pump-turbine: general four-quadrant diagram	158
Figure 63 – Reaction machines: procedure for calculating test results in view of comparison with guarantees	159
Figure 64 – Single-regulated turbine: three-dimensional surface of hydraulic efficiency and curves of performance at E_{nD} constant	161
Figure 65 – Single-regulated pump: performance curves	162
Figure 66 – Double-regulated turbine: performance curves at E_{nD} constant	163
Figure 67 – Double-regulated pump: performance curves at E_{nD} constant	164
Figure 68 – Non-regulated turbine: performance curves	165
Figure 69 – Non-regulated pump: performance curves	166
Figure 70 – Efficiency curve correction in order to take into account cavitation influence (e.g. tubular machines at overload operation)	167
Figure 71 – Francis model turbine: cavitation curves	167
Figure 72 – Model pump: cavitation curves	167
Figure 73 – Francis model turbine cavitation curves: examples of limits for application of transposition formula	169
Figure 74 – Runaway curves for a single-regulated turbine (Francis)	172

Figure 75 – Runaway curves for a single-regulated turbine (six-nozzle Pelton)	172
Figure 76 – Runaway speed determined by extrapolation: example for a single-regulated turbine (Francis).....	172
Figure 77 – Influence of Thoma number on runaway speed and discharge of a single-regulated turbine (Francis).....	173
Figure 78 – Influence of the Thoma number on runaway speed and discharge of a double-regulated turbine (Kaplan).....	174
Figure 79 – Influence of the Thoma number on the off-cam runaway curves of a double-regulated turbine (Kaplan).....	174
Figure 80 – Example of calibration curve	178
Figure 81 – Single-regulated machine.....	184
Figure 82 – Double-regulated machine	184
Figure 83 – Single-regulated turbine: comparison between guarantees and measurements	185
Figure 84 – Non-regulated turbine: comparison between guarantees and measurements	186
Figure 85 – Non-regulated pump: comparison between guarantees and measurements	187
Figure 86 – Francis turbine runaway speed and discharge curves: comparison between guarantees and measurements	189
Figure 87 – Model turbine cavitation curve and comparison with the guarantee on the influence of the cavitation on the efficiency	190
Figure 88 – Typical data acquisition system.....	194
Figure 89 – Frequency response of analogue anti-aliasing filter.....	195
Figure 90 – Suggested locations of transducers.....	200
Figure 91 – Pump diagram with exploration paths.....	202
Figure 92 – Turbine hill-chart with exploration paths.....	203
Figure 93 – Normal pump mode operation of an $n_{QE} = 0,102$ pump-turbine model	205
Figure 94 – Zero discharge operation (10 % guide vane opening) of an $n_{QE} = 0,102$ pump-turbine model	205
Figure 95 – Part load operation of an $n_{QE} = 0,321$ Francis turbine model: $Q_{nD}/Q_{nDopt} = 0,719$	206
Figure 96 – Higher part load operation of an $n_{QE} = 0,226$ Francis turbine model: $Q_{nD}/Q_{nDopt} = 0,764$	207
Figure 97 – Full load operation of an $n_{QE} = 0,173$ Francis turbine model: $Q_{nD}/Q_{nDopt} = 1,218$	208
Figure 98 – Example of waterfall diagram of pressure fluctuations in the draft tube of a Francis turbine, transducer p_1	209
Figure 99 – Example of summarized diagram of pressure fluctuations in the draft tube of a Francis turbine, transducer p_2	210
Figure 100 – Interaction of the external system with sources of pressure fluctuations from the hydraulic machine.....	211
Figure 101 – Definition of coordinate system	214
Figure 102 – Individual elements of axial force acting on a radial machine.....	216
Figure 103 – Typical testing arrangement for axial thrust measurement.....	218
Figure 104 – Typical calibration arrangement for axial thrust measurement	219

Figure 105 – Axial force factor versus discharge factor at different constant specific hydraulic energies in pump mode.....	221
Figure 106 – Axial force factor versus speed factor measured at different guide vane openings in the four quadrants of a pump-turbine	221
Figure 107 – Typical arrangements for radial thrust measurement (horizontal or vertical shaft)	224
Figure 108 – Design examples for torque measuring guide vanes	228
Figure 109 – Guide vane torque factor versus guide vane angle measured at different constant specific hydraulic energies in turbine mode.....	230
Figure 110 – Guide vane torque factor versus guide vane angle measured at different constant specific hydraulic energies in pump mode.....	231
Figure 111 – Guide vane torque factor versus speed factor measured at different constant guide vane angles in the four quadrants of a pump-turbine	231
Figure 112 – Example for runner blade torque measuring arrangement using telemetry	234
Figure 113 – Performance and hydraulic runner blade torque characteristics of an axial turbine measured at one constant runner blade angle β and various constant guide vane angles α	236
Figure 114 – Pelton needle force factor as a function of relative needle stroke	240
Figure 115 – Example of four quadrants operation of a radial-type pump-turbine	242
Figure 116 – Chart illustrating the various operating modes	244
Figure 117 – S-shape characteristics in turbine brake mode	247
Figure 118 – Characteristic of a pump with positive slope range in a limited discharge range	247
Figure 119 – Example of graphical representation of index test data.....	250
Figure D.1 – Efficiency change in hydraulically similar operating conditions A and B having different Re values	267
Figure D.2 – Variation of relative scalable losses	268
Figure D.3 – Transposition curve for model efficiency using best efficiency point.....	270
Figure D.4 – Efficiency increase from constant Re_{M^*} to constant Re_P	271
Figure D.5 – Efficiency increase from different Re_M to constant Re_P	272
Figure F.1 – Single-regulated turbine: determination of the maximum runaway speed of the prototype taking into account the friction and windage losses of the unit	275
Figure G.1 – Principle of the method of separate segments	277
Figure G.2 – Example of determination of intervals	277
Figure I.1 – Influence of Froude number	287
Figure I.2 – Influence of Weber number	288
Figure I.3 – Influence of Reynolds number	288
Figure K.1 – Definition for determination of net positive suction energy, $NPSE$, and net positive suction head, $NPSH$, of a prototype machine ($E_{LS} \neq 0$).....	293
Figure L.1 – Turbine	296
Figure L.2 – Pump	297
Figure M.1 – a) Representation of asynchronous pressure pulsation and location of pressure transducers, and b) synchronous and c) asynchronous parts of the pressure signal.....	300
Figure O.1 – Crown seal clearance	304
Figure O.2 – Crown radius	305
Figure O.3 – Pressure relief pipe	306

Figure O.4 – Runner band seal	307
Table 1 – Permissible maximum deviations	68
Table 2 – Maximum recommended prototype surface roughness R_a	73
Table 3 – Similitude numbers	74
Table 4 – Similitude requirements for various types of model tests	76
Table 5 – Minimum values for model size and test parameters	82
Table 6 – Coefficients of the Herbst and Roegenner formula	100
Table 7 – Minimum test specific hydraulic energy	102
Table 8 – Nomenclature for Figure 46 to Figure 54	146
Table 9 – Variables defining the operating point of a machine	154
Table 10 – Summary of errors that determine total measurement uncertainty	179
Table 11 – Definition of individual force elements of axial thrust	217
Table 12 – Non-hydraulic forces influencing radial thrust measurement	225
Table 13 – Definition of quadrants and operating modes	242
Table B.1 – Acceleration due to gravity g ($\text{m}\cdot\text{s}^{-2}$)	253
Table B.2 – Density of distilled water ρ_{Wd} ($\text{kg}\cdot\text{m}^{-3}$) (1 of 2)	254
Table B.3 – Kinematic viscosity of distilled water ν ($\text{m}^2\cdot\text{s}^{-1}$)	256
Table B.4 – Vapour pressure of distilled water p_{va} (Pa)	257
Table B.5 – Density of dry air ρ_a ($\text{kg}\cdot\text{m}^{-3}$)	258
Table B.6 – Ambient pressure p_{amb} (Pa)	259
Table B.7 – Density of mercury ρ_{Hg} ($\text{kg}\cdot\text{m}^{-3}$)	260
Table D.1 – V_{ref} values	269
Table I.1 – Numerical data for surface tension σ^*	287
Table J.1 – Confidence levels	290
Table J.2 – Values of Student's t	291
Table J.3 – Computation of the estimated standard deviation and the uncertainty for eight observations	292
Table K.1 – Summary of calculated σ_{plc} values and other relevant data	295

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES –
MODEL ACCEPTANCE TESTS**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 60193 has been prepared by IEC technical committee 4: Hydraulic turbines.

This third edition cancels and replaces the second edition published in 1999. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) update to methods/measuring tools currently used for checking dimensions on both model and prototype;
- b) update to requirements of accuracy in the dimensional check procedure as a result of new technology;