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A step forward: IEC 62097-Edition 2 - "Hydraulic Machines, Radial and Axial – Methodology for Performance Transposition from Model to Prototype"

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Abstract. Advances in the technology of hydraulic machines for hydroelectric power plants provided the background for updating and revising the efficiency scale effect methodology of IEC 60193. The fundamental step forward in IEC 62097 is the standardization of scalable losses in specific hydraulic energy, leakage losses and disk friction losses. The transposition of the hydraulic performance is driven by the dependence of friction losses on Reynolds number Re and the effect of surface roughness Ra. Since the roughness of the actual machine components differs from part to part, the performance scale effect is evaluated for each individual part separately and then is finally summed up to obtain the overall performance transposition for a complete machine. After the release of IEC 62097 Edition 1 in 2009, comments on this standard were received and open or unclear topics identified. As a result, the new innovative concepts were introduced and developed, and editorial changes were implemented in Edition 2. This paper presents the significant improvements implemented in the release of IEC 62097 Edition 2 related to the performance transposition methodology for hydraulic machines through: a) addressing the shift in n_{ED} and Q_{ED} in the performance scaling from the model to prototype; b) identifying two-step efficiency transposition as the primary method for deriving prototype efficiency based on the model test results; c) specifying recommended roughness measurement techniques and minimum prototype roughness values; d) readjusting scalable losses and leakage losses for models with peak efficiency exceeding the assumed maximum hydraulic efficiency specified in the standard; e) improved structure of the IEC 62097 standard document and "Excel" workbook providing clear and user friendly guidelines for the performance transposition calculations. The release of Edition 2 is a clear step forward in advancing the performance transposition methodology for radial and axial hydraulic machines.

1. Introduction

The IEC 62097 methodology for calculating prototype efficiencies based on model test results is supported by experimental work and theoretical research on flow analysis, it has been simplified for

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practical reasons, and is agreed upon as a convention. This methodology represents the present state of knowledge on the transposition of performance from model to a homologous prototype.
The fundamental step forward in IEC 62097 is the standardization of scalable losses. With previous performance transposition calculations, hydraulic surfaces were assumed to be smooth and a loss distribution factor V was defined as a fixed value for given machine type. As a result of such an approach, designs of hydraulic machines which are not adequately optimized would benefit from their lower technological level. This is certainly not correct, since a low efficiency design typically produces high non-scalable losses, like incidence losses, whereby the amount of scalable losses is approximately constant for all hydraulic machines of a given type, geometrical size, specific speed and roughness of hydraulic surfaces.
A new basic feature of the IEC 62097 standard is the separate consideration of losses in specific hydraulic energy, leakage losses and disk friction losses. Above all, the transposition of the hydraulic performance is not only driven by the dependence of friction losses on Reynolds number Re, but also the effect of surface roughness Ra has been accounted for.
Since the roughness of the actual machine components differs from part to part, the performance scale effect is evaluated for each individual part separately and then is finally summed up to obtain the overall performance transposition for a complete machine.
IEC 62097 – Background of Edition 2
After release of IEC 62097 Edition 1 in 2009, comments on this standard were received and open or unclear topics identified. The initial intent was to create an Amendment-1 for clarification of these topics (4/265/CDV), however the amount of information included in Amendment-1 to address the comments exceeded the IEC prescribed limits for the size of an Amendment. It was thus decided to produce and circulate a Second Edition of the Standard IEC-62097 (02-2009). This Edition 2, which integrates Amendment-1, has been completed and is being circulated as a FDIS as it was initially intended for Amendment-1. Additional work has been completed to fully address the Amendment-1 comments and to ensure proper alignment of Edition 2 with IEC-60193.

2. Technical points of Edition 2

For Edition 2, editorial changes were implemented and the following significant additional information was introduced as described below.

2.1. Impact of n_{ED} and Q_{ED} shift on performance transposition

While IEC 60193 does not account for the shift in n_{ED} and Q_{ED} for determining the performance transposition between the model and homologous prototype, IEC 62097 Edition 2 considers the implications of this shift on the prototype performance. This difference in the performance transposition methodology between IEC 60193 and IEC 62097 is addressed by Annex E of Edition 2, which defines when it is necessary or appropriate to apply one Standard or the other. Once a particular Standard is selected, it prevails over the other one.

2.2. Minimum roughness

Although excessively smooth prototype hydraulic surfaces with roughness lower than certain threshold values could not yield additional efficiency gains, the minimum prototype roughness threshold values were not specified in Edition 1. This led to artificially high transposed values of efficiency for extremely smooth prototype surfaces and neglected the physical effect of the boundary layer.
Therefore minimum recommended prototype roughness values for new radial, diagonal and axial machines are introduced in Edition 2. The prototype specific hydraulic energy is the criteria for the different roughness values. Also for the model a recommended roughness range is introduced, as is shown in Table 2.

Table 1. Minimum recommended prototype roughness for new radial or diagonal machines.

		Specific hydraulic energy, *E* (J/kg)				
Roughness (μm) applied on		**300**	**850**	**1400**	**3000**	**8000**
Spiral casing	Ra_{SP}	≥ 5,0	≥ 3,2	≥ 3,2	≥ 3,2	≥ 3,2
Stay vane channel	Ra_{SV}	≥ 5,0	≥ 3,2	≥ 1,6	≥ 1,6	≥ 1,6
Guide vane channel	Ra_{GV}	≥ 1,8	≥ 1,4	≥ 1,0 [a]	≥ 0,8 [a]	≥ 0,8 [a]
Runner channel	Ra_{RU}	≥ 1,8	≥ 1,4	≥ 1,0 [a]	≥ 0,8 [a]	≥ 0,8 [a]
Draft tube	Ra_{DT}	≥ 5,0	≥ 3,2	≥ 3,2	≥ 3,2	≥ 3,2
Rotating part	Ra_{TR}	≥ 5,0	≥ 3,2	≥ 1,6	≥ 1,6	≥ 1,6
Stationary part	Ra_{TS}	≥ 5,0	≥ 3,2	≥ 1,6	≥ 1,6	≥ 1,6

[a] There are indications that small *Ra* values may deteriorate within a few months. Further studies are required in order to better understand the phenomena taking place with the surface finish once a machine is in operation for a few months.

NOTE: Roughness values for intermediate specific hydraulic energy shall be linearly interpolated.

Table 2. Recommended roughness range for the model.

Component	**SP**	**SV**	**GV**	**RU**	**DT**	**TR**	**TS**
Ra_{COM} (μm)	0,4 – 1,6	0,4 – 1,6	0,2 – 0,8	0,2 – 0,8	0,4 – 1,6	0,4 – 1,6	0,4 – 1,6

2.3. Hydraulic efficiency transposition

For hydraulic efficiency transposition between the model and homologous prototype, Edition 2 prescribes a two-step transposition as the standard primary method:

(1) first step is the conversion of the tested model performance to the performance of the reference model characterized by fixed Reynolds number and fixed values of surface roughness;
(2) second step is the conversion of the reference model efficiency to the prototype conditions.

This method suits especially well for comparison between different models. A one-step efficiency transposition method, i.e. conversion of tested model efficiency directly to the prototype conditions, is also introduced in Edition 2 but it can be used only indicatively for efficiency transposition from the tested model to the prototype at the optimum point.

The following formulae describe the two-step hydraulic efficiency transposition:

$$\frac{\eta_{hM^*}}{\eta_{hM}} = \frac{\eta_{EM^*} \cdot \eta_{TM^*} \cdot \eta_{QM^*}}{\eta_{EM} \cdot \eta_{TM} \cdot \eta_{QM}} = \left(1 + \Delta_{E_{M \to M^*}}\right) \cdot \left(1 + \Delta_{Q_{M \to M^*}}\right) \cdot \left(1 + \Delta_{T_{M \to M^*}}\right)$$

$$\frac{\eta_{hP}}{\eta_{hM^*}} = \frac{\eta_{EP} \cdot \eta_{TP} \cdot \eta_{QP}}{\eta_{EM^*} \cdot \eta_{TM^*} \cdot \eta_{QM^*}} = \left(1 + \Delta_{E_{M^* \to P}}\right) \cdot \left(1 + \Delta_{Q_{M^* \to P}}\right) \cdot \left(1 + \Delta_{T_{M^* \to P}}\right)$$

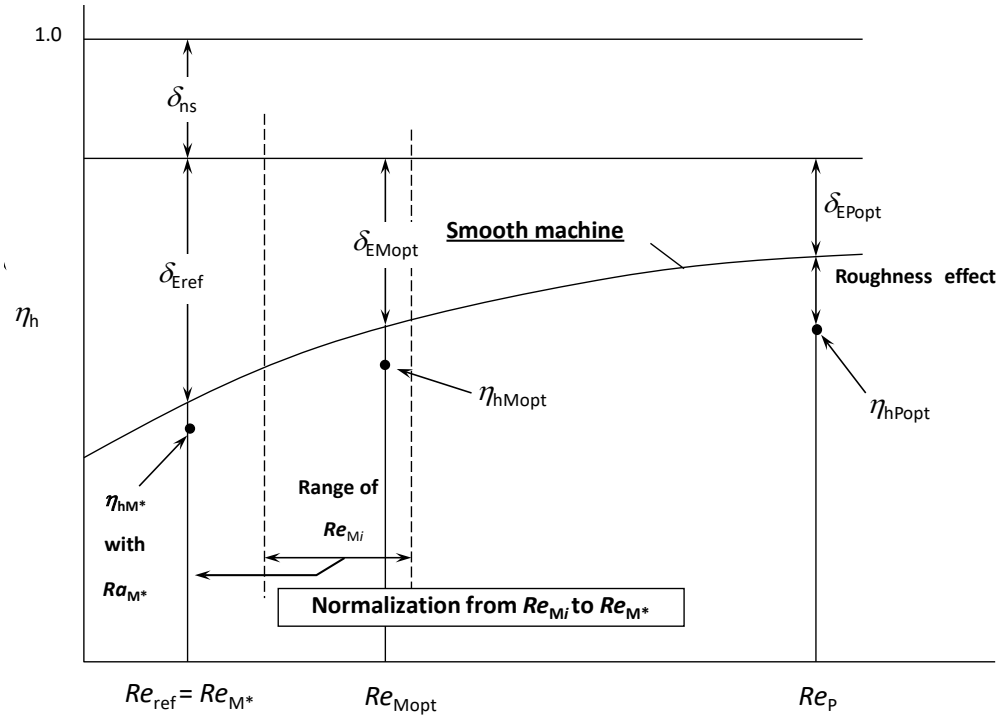


Figure 1. Normalization of test data from Re_{M_i} to Re_{M^*} and Re_{M^*} to Re_P.

2.4. Roughness measurements

Roughness measurement techniques and measurement tolerances were not described in sufficient detail in Edition 1. Therefore, available additional information on the model and prototype roughness measurements has been collected and presented in a separate chapter of Edition 2. Also normative references to ISO 4287, ISO 4288 and ISO 13565 were inserted.

However, for roughness measurements of hydraulic machine water passages, more studies and more data collection are needed before recommending a detailed procedure; this is intended to be covered by Edition 3.

2.5. Elaboration of the assumed maximum efficiency concept

This concept was not well explained in Edition 1, which led to confusion. So a description is added in chapter 7 “Transposition to prototype” of Edition 2 to explain how this new concept works and why it needs to be used.

In accordance with this concept, if maximum hydraulic efficiency of a tested model exceeds the assumed maximum hydraulic efficiency stated in IEC 62097, the values of:

i) scalable hydraulic energy loss index for each component passage of a machine, dECOref,
ii) the scalable disk friction loss index, dTref,
iii) leakage loss

are uniformly decreased by multiplying them by a coefficient, kcorr, defined as follows:

$$k_{corr} = \frac{(1 - \eta_{hopt})}{(1 - \eta_{hA\,max})}$$

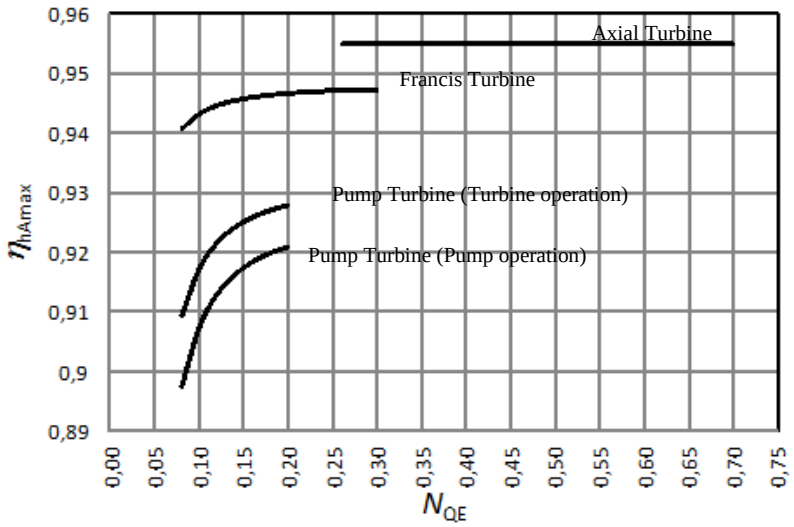


Figure 2. Assumed maximum hydraulic efficiency $\eta_{hAmax} = (1 - \delta_{Eref}).(1 - \delta_{Tref}).\eta_Q$.

3. Improved structure in Edition 2

3.1. Document structure

As shown in the table below, the following additional chapter and annexes are added in Edition 2 to explain the main concepts, improve the document clarity and identify the limits of its application:

(1) New chapter detailing the central topic of surface roughness;
(2) Annex E providing comparison and limitations of IEC60193 and IEC 62097 efficiency transposition methods;
(3) Annex G with detailed description of using the "Excel" workbook attached with Edition 2;
(4) Annex H presenting an example of calculation with the "Excel" workbook.

Table 3. Comparison of document structure for Edition 1 and Edition 2.

Edition 2	**Edition 1**
0 INTRODUCTION	INTRODUCTION
1 Scope	1 Scope
2 Normative references	2 Normative references
3 Terms, definitions, symbols and units	3 Terms, definitions, symbols and units
4 Scale-effect formula	4 Scale-effect formula
5 Surface roughness of model and prototype	5 Standardized values of scalable losses and pertinent parameters
6 Standardized values of scalable losses and pertinent parameters	6 Calculation of prototype performance
7 Transposition to prototype	7 Calculation procedure
8 Calculation procedure	
Annex A (informative) Basic formulae and their approximation	Annex A (informative) Basic formulae and their approximation
Annex B (informative) Scale effect on specific hydraulic energy losses of radial flow machines	Annex B (informative) Scale effect on specific hydraulic energy losses of radial flow machines
Annex C (informative) Scale effect on specific hydraulic energy losses of axial flow machines	Annex C (informative) Scale effect on specific hydraulic energy losses of axial flow machines
Annex D (informative) Scale effect on disk friction loss	Annex D (informative) Scale effect on disc friction loss
Annex E (informative) Comparison of IEC 60193 and IEC 62097 hydraulic efficiency transposition methods for reaction machines	
Annex F (informative) Leakage loss evaluation for non-homologous seals	Annex E (informative) Leakage loss evaluation for non homologous seals
Annex G (normative) Guide for detailed calculations	
Annex H (informative) Example of a calculation with "Excel" workbook	
Bibliography	Bibliography

3.2. "Excel" workbook attached with Edition 2

The layout of the "Excel" workbook is changed to use it either for a) efficiency transposition at an individual test point from tested model to reference model and then from reference model to prototype or for b) direct transposition from tested model to prototype at the optimum point.
Simplification in the workbook structure is done, consisting of 5 sheets called "Input Form", "Hydraulic Perf. (Results)", "Specific Energy Eff.", "Power Eff." and "Volumetric Eff".
The "Assumed maximum hydraulic efficiency" is shown in the sheet "Hydraulic Perf. (Results)".

Results of step-up calculation

Project :	Example for IEC 62097 - STEP 1 Pump Turbine in turbine mode	**Ref. No. :**	2017
Date :	2017		
Type of machine	Pump-turbine (Turbine mode)		**Step 1 of the '2 step Method'**

Efficiency step-up ratio and step-up increment of hydraulic efficiency

Type of turbine	Pump-turbine (T)		ν_B (m²/s)	1,0036E-06
N_{QE}	0,1442		Re_B	7,0000E+06
D_B (mm)	280,0		ρ_B (kg/m³)	998,244

Step-up of Optimum Point of the REFERENCE MODEL (subscript B)			**Step-up of the individual test point of the REFERENCE MODEL (subscript B)**	
n_B (Hz)	28,523		n_B (Hz)	28,523
$Q_{1B\,opt}$ (m³/s)	0,532	These values of Turbine B can be selected and copied in Turbine A in the sheet 'Input form' for step 2	Q_{1Bi} (m³/s)	0,337
$E_{B\,opt}$ (J/kg)	754,92		E_{Bi} (J/kg)	486,50
$\eta_{hB\,opt}$ (%)	92,248		η_{hBi} (%)	80,216
t_{WB} ( )	20,00		t_{WB} ( )	20,00
$P_{mB\,opt}$ (kW)	369,53		P_{mBi} (kW)	131,32

$\eta_{hA\,opt}$ (%)	92,000	η_{hAi} (%)	80,000
$\Delta_{EA->B\,opt}$	0,00200	$\Delta_{EA->Bi}$	0,00200
$\Delta_{QA->B\,opt}$	0,00000	$\Delta_{QA->Bi}$	0,00000
$\Delta_{TA->B\,opt}$	0,00070	$\Delta_{TA->Bi}$	0,00070
$\Delta\eta_{hB\,opt}$ (%)	0,248	$\Delta\eta_{hBi}$ (%)	0,216

Scalable losses and leakage losses defined in the code:

Scalable spec. hyd. energy loss, δ_{Eref}	4,850	(%)
Leakage loss, $(100-\eta_Q)$	1,000	(%)
Scalable disk friction loss, δ_{Tref}	1,822	(%)
Assumed max. hydraulic efficiency for A, η_{hAmaxA}	92,483	(%)

Figure 3. Calculation example, table "Hydraulic Perf. (Results)".

4. Application of Edition 2 methodology

The performance transposition methodology of IEC 62097 Edition2 was successfully used for optimization of the model design and establishing efficiency and energy production guarantees for the large greenfield Francis turbine-generator unit project, which is presently under construction. The Edition 2 methodology formed the basis of the competitive model testing strategy for this project. In accordance with this strategy, three turbine models with the same runner diameter built by different suppliers were delivered to the independent laboratory EPFL – LMH, where roughness of the model hydraulic components was measured. Each model was tested at the independent laboratory and the model performance normalized to reference model conditions and prototype hydraulic performance calculated using prescriptions of IEC 62097 Edition 2. Performance normalization was completed for the following reference model parameters:

Reference Reynolds number, $Re_{ref} = 7 \times 10^6$

Reference model water density, $\rho_{ref} = 1000$ kg/m^3

Table 4. Reference arithmetical mean roughness, Ra_{ref}, of turbine model components.

Spiral case	0.8 µm
Stay vane channels	0.8 µm
Wicket gate channels	0.4 µm
Runner blade, crown, and band (inner surfaces)	0.4 µm
Runner crown and band (outer surfaces)	0.8 µm
Draft tube	0.8 µm
Stationary parts (headcover, discharge/bottom ring) facing the runner outer surfaces	0.8 µm

This methodology allowed a utility company to perform a direct comparison of the performance characteristics of each supplier's design. The turbine design with the best performance characteristics at the normalized reference model parameters was selected for the prototype turbine procurement. Manufacturing of the turbine components for the above greenfield project is currently in progress.

5. Conclusion

The release of IEC 62097 Edition 2 presents significant improvement of the performance transposition methodology for hydraulic machines through:

1) addressing the shift in n_{ED} and Q_{ED} in the performance scaling from the model to prototype;
2) identifying two-step efficiency transposition as the primary method for deriving prototype efficiency based on the model test results;
3) specifying recommended roughness measurement techniques and minimum prototype roughness values;
4) readjusting scalable losses and leakage losses for models with peak efficiency exceeding the assumed maximum hydraulic efficiency specified in the standard;
5) improved structure of the IEC 62097 standard document and "Excel" workbook providing clear and user friendly guidelines for the performance transposition calculations.

The release of Edition 2 is a clear step forward in advancing the performance transposition methodology for radial and axial hydraulic machines.

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[1] IEC 62097(2009) Hydraulic machines, radial and axial – performance conversion method from model to prototype
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[3] JSME Standard S008(1999) Performance Conversion Method for Hydraulic Turbines and Pump-TurbinesA reference

Notes: Product names mentioned herein may be trademark of their respective companies.