

## **Efficiency Scale-up in Refurbished Low Head Kaplan Turbines**

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### **ABSTRACT**

Four Kaplan turbine models were developed and tested for refurbishment of four hydro power plants on the Drava river in Slovenia. One refurbished unit on each hydro power plant was also tested by Turboinstitut using current-meters for flow measurement. Model efficiencies were scaled-up according to five common scale-up procedures (IEC 995, Hutton, Ackeret, JSME and Fay-Kvyatkovskii) and compared to prototype tested efficiencies. The analysis of results showed that scale-up procedure from IEC 995 Recommendations gives very realistic values of prototype efficiency on low head Kaplan turbines.

### **INTRODUCTION**

Turbine efficiency scale-up procedures are important for employers as well as turbine producers. It is used at tender evaluation of different producers, in wide range of turbine operation (from small through optimum to nominal flow rates). The most common recommended efficiency scale-up method in recent years is the one from the IEC 995 Recommendations. This procedure prescribes how to define turbine optimum efficiency, which is the basis for calculation of the value of efficiency scale-up  $\Delta\eta$ . Many times the producer is wondering if it will reach the guaranteed values of efficiency and nominal power. The employer can easily and accurately control the generator power but not the efficiency.

Because of this it is very useful to have back information of prototype efficiency measurements made at refurbished hydro power plants. Flow rate is the most difficult measuring parameter at site testing necessary for efficiency calculation. Turbine flow rate value is easier to obtain at Pelton and Francis turbines. More effort is necessary to do at low head Kaplan turbines which have short intake areas with large cross sections. According to our experience, one of the best absolute methods for flow rate measurement is the current-meter method with a number of fixed installed current-meters.

The comparison between model and prototype efficiencies will be shown for Fala 8, Mariborski otok, Dravograd and Vuzenica hydro power plants on the Drava River in Slovenia, respectively (see Figure 1). These hydro power plants were refurbished in recent years. Details on refurbishment are given in references [1] - [4]. The model acceptance tests of all four turbines were done in Turboinstitut's laboratory on complete homologous models in years 1993 to 1995. The employer DEM (Drava River authority) and consultants Lahmeyer International (Germany) and IBE – Consulting Engineers (Slovenia) supervised the model testing. The prototype acceptance tests were performed in years 1996 to 1998.

### **MODEL TESTING**

Model tests were performed on the Kaplan turbine test rig shown in Figure 2. The runner diameter of all four model turbines was 350 mm. Turbine models were made of welded steel plates and well finished. Bronze runner and guide vane blades were CNC-machined and

manually polished. Surface roughness  $R_a$  of guide vanes and runner blades was between 0.2 and 0.3  $\mu\text{m}$ . The average model runner tip clearance was 0.175 mm.



Figure 1: Dravograd, Vuzenica, Fala 8, and Mariborski otok HPP

The test rig is equipped with two 75 kW supply pumps and a 90 kW generator-motor. Maximum flow rate during model testing was approximately  $0.7 \text{ m}^3\text{s}^{-1}$ , head was varied between 4 and 6 m and turbine rotational speed was  $1100 \text{ min}^{-1}$  during the guaranteed efficiency testing. So the required value  $7 \cdot 10^6$  of Reynolds number of flow in model turbine, recommended by standard IEC 995, was achieved. The test rig met all the IEC 193 Recommendations for performing model acceptance tests.

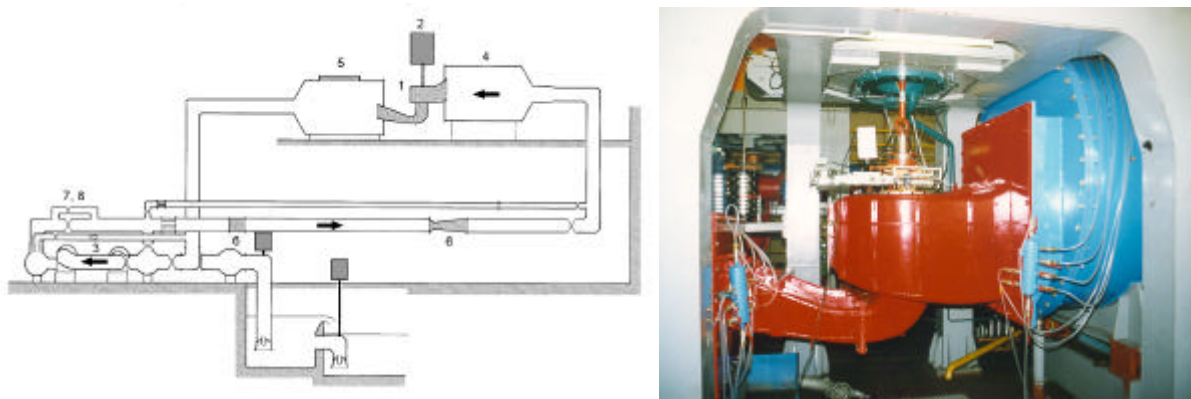


Figure 2: Kaplan turbine test rig in Turboinstitute and model turbine for Vuzenica HPP

The flow rate, head and suction head measurements were performed by motorised mercury manometers with the error of less than 0.2 mm of mercury column. The torque measurement was realised with fixed force meter and compensation calibrated weights. The force meter was calibrated with weights of class M 1. An optical device and counter was used for turbine rotational speed measurement with estimated error of 0.5 min<sup>-1</sup>. Measuring system was a Burr-Brown data acquisition plate build into a PC. The sampling time of each measuring point was 45 s.

Measurement error analysis gave the next values:

- systematic uncertainty of efficiency measurement (flow rate 0.20 %, head 0.10 %, torque 0.10 %, rotational speed 0.05 %)

$$f_{hs} = \frac{e_{hs}}{h} = \sqrt{(f_{Q_s}^2 + f_{E_s}^2 + f_{M_s}^2 + f_{N_s}^2)} = \sqrt{0,2^2 + 0,1^2 + 0,1^2 + 0,05^2} = \pm 0,25\%$$

- random uncertainty i. e. repeatability of efficiency measurement (flow rate 0.07 %, head 0.03 %, torque 0.05 %, rotational speed 0.01 %)

$$f_{hr} = \frac{e_{hr}}{h} = \sqrt{(f_{Q_r}^2 + f_{E_r}^2 + f_{M_r}^2 + f_{N_r}^2)} = \sqrt{0,07^2 + 0,03^2 + 0,05^2 + 0,01^2} = \pm 0,092\%$$

- total uncertainty of efficiency measurement

$$f_{ht} = \sqrt{(f_{hs}^2 + f_{hr}^2)} = \sqrt{0,25^2 + 0,092^2} = \pm 0,27\%$$

## SITE TESTING

On four mentioned refurbished hydro power plants field acceptance tests were performed on the first refurbished unit of each HPP. In tender the employer requested prototype acceptance tests with absolute flow measurement with current-meters. The measurements were executed according to standards IEC No. 41, ISO 3354, ISO 3455 and ISO 7194. Good accuracy in flow measurement was achieved with the use of large number of current-meters simultaneously on a fixed current-meters support. Recommended number of current-meters (IEC 41) is

$$23 \cdot \sqrt[3]{A} < z < 36 \cdot \sqrt[3]{A} \quad \text{or} \quad z_{min} < z < z_{max}$$

where A is the area of the measuring section in square metres. Actually used number of current meters was:

- Dravograd HPP:  $z_{used} = 196 = 1,09 z_{min}$
- Vuzenica HPP:  $z_{used} = 224 = 1,14 z_{min}$
- Fala HPP:  $z_{used} = 196 = 1,00 z_{min}$
- Mariborski otok HPP  $z_{used} = 224 = 1,14 z_{min}$

The position of current-meter support in measuring cross section was checked with computational fluid dynamics. Program package CFX-TASCflow was used to compute inclination angle between current-meter shaft which is perpendicular on measuring plane and flow streamlines. For mentioned hydro power plants it did not exceed 5°. Inclination between current-meter shaft and flow streamlines gains additional error to velocity measurement if current-meter does not measure velocity component perpendicular to measuring plane

accurately. The used current-meters measure the perpendicular velocity component with systematic error +0,3 % (current-meter rotates 0,3 % faster as it should) at inclination angle 10°. This was determined during current-meter calibration [5].

Current-meter calibrations were performed in the towing tank of Ship building institute, Zagreb, Croatia in a period before site testing. During calibration current-meters were mounted on the profiles of the same cross-section shape as have current-meter carrier on site. Most of the measured calibration points were within the range of  $\pm 0.2$  % around the calibration lines computed with linear regression. Four current-meters were calibrated for comparison also in the Calibration Laboratory of the Swiss National Hydrological and Geological Survey, Bern, Switzerland. Useable measuring range of used current-meters with 125 mm spiral pitch was  $0,05 \dots 4 \text{ ms}^{-1}$ .

Velocity profiles were after measurement immediately visually checked on computer screen and corrected if particular current-meter fails operation. Flow integration and determination of boundary layer coefficient  $m$  was programmed exactly as stated in the ISO 3354–Second edition 1988–07–15 standard. Repeatability of flow measurement under stable operating conditions was better than  $\pm 0,1$  %.

Measurement error analysis gave the next values:

- systematic uncertainty of efficiency measurement (head (or specific energy)  $\pm 0,1$  %, energy counter  $\pm 0,2$  %, voltage transformer  $\pm 0,5$  %, current transformer  $\pm 0,5$  %, flow rate  $\pm 1,0$  %)

$$f_{hs} = \frac{e_{hs}}{h} = \sqrt{(f_{Es}^2 + f_{Pecs}^2 + f_{Pvts}^2 + f_{Pcts}^2 + f_{Qs}^2)} = \sqrt{0,1^2 + 0,2^2 + 0,5^2 + 0,5^2 + 1,0^2} = \pm 1,24\%$$

- random uncertainty of efficiency measurement

$$f_{hr} = \frac{e_{hr}}{h} = \sqrt{(f_{Er}^2 + f_{Pr}^2 + f_{Qr}^2)} = \sqrt{0,05^2 + 0,15^2 + 0,1^2} = \pm 0,19\%$$

where  $f_{Er}, f_{Pr}, f_{Qr}$  are random uncertainties for head (or specific energy), turbine power and flow,

- total uncertainty of efficiency measurement

$$f_{ht} = \sqrt{(f_{hs}^2 + f_{hr}^2)} = \sqrt{1,24^2 + 0,19^2} = \pm 1,25\%$$

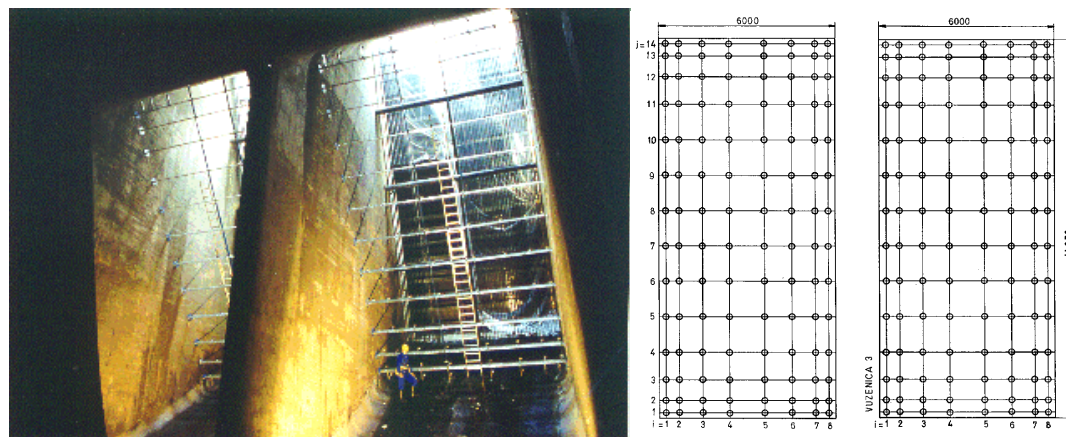
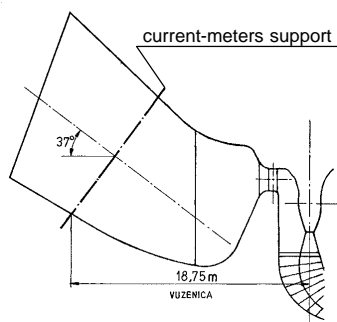
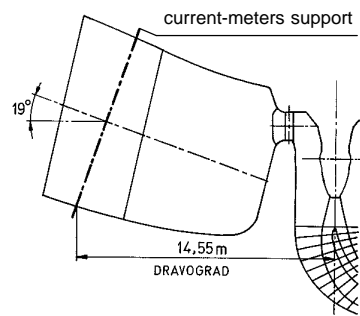


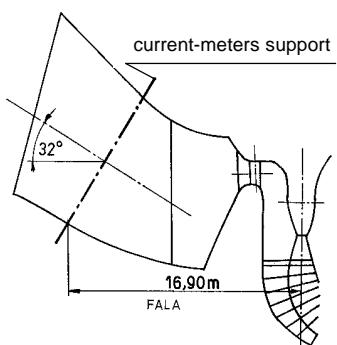
Figure 3: Vuzenica HPP: current-meters support



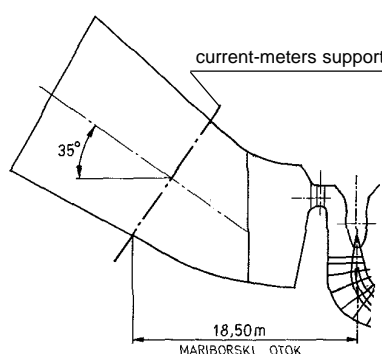
Vuzenica HPP  
 area = 2×6,00m×11,37m  
 No. of current meters z = 224



Dravograd HPP  
 area = 2×5,10m×10,20m  
 No. of current meters z = 196



Fala HPP  
 area = 2×6,00m×11,50m  
 No. of current meters z = 196



Mariborski otok HPP  
 area = 2×6,00m×11,50m  
 No. of current meters z = 224

Figure 4: Current-meters measuring sections

Surface roughness of the prototype runner blades was  $R_a < 6 \mu\text{m}$ . The average prototype runner tip clearance was 2.5 mm.

## SCALE-UP PROCEDURES FOR KAPLAN TURBINES

Many scale-up procedures for evaluation of prototype efficiency from tested model efficiency have been developed in the past. But the most used was the Hutton formula (1) before the year 1991 when new IEC 995 [6] procedure was recommended.

$$\Delta h_{Hutton} = 0,7 \cdot (1 - h_{M, opt}) \cdot \left[ 1 - \left( \frac{Re_M}{Re_P} \right)^{0,2} \right] \quad (1)$$

We used the Hutton formula for calculation of the efficiency scale-up in optimum of the turbine (1) and then we added this value to the model efficiency in each point. The difference between model and prototype efficiency of the turbine is constant in each tested point when Hutton formula is used. This formula is based on an assumption that 70 % of turbine losses

are friction losses and 30 % are losses related to changes of kinetic energy. The Ackeret formula (2) proposes 50 % of friction losses and 50 % of kinetic energy losses.

$$\Delta h_{Ackeret} = 0,5 \cdot (1 - h_{M, opt}) \cdot \left[ 1 - \left( \frac{Re_M}{Re_P} \right)^{0,2} \right] \quad (2)$$

IEC 995 scale-up procedure consists of equations (3) and (4). Value  $V_{ref}$  for Kaplan turbines is 0.8.

$$\Delta h_{IEC} = d_{ref} \left[ \left( \frac{Re_{ref}}{Re_M} \right)^{0,16} - \left( \frac{Re_{ref}}{Re_P} \right)^{0,16} \right] \quad (3)$$

$$d_{ref} = \frac{1 - h_{M, opt}}{\left( \frac{Re_{ref}}{Re_M} \right)^{0,16} + \frac{1 - V_{ref}}{V_{ref}}} \quad (4)$$

According to EdF experiences [7], the Fay-Kvyatkovskii formula (5) gives the best results. Efficiency scale-up values calculated with this formula are different in each tested point.

$$\Delta h_{F.K.} = \left( 1 - 0,18 \frac{Q_i}{Q_{opt}} \right) \cdot (1 - h_M) \cdot \left[ 1 - \left( \frac{Re_M}{Re_P} \right)^{0,2} \right] \quad (5)$$

Scale-up effects have been studied a lot in Japan. Their standard JSME S 008 – 1989 proposes equations (6) and (7).  $V^*$  is loss distribution coefficient for overall efficiency.

$$\Delta h_{JSME} = V^* \cdot (1 - h_{M, opt}) \cdot \left[ 1 - 1,1 \cdot \left( \frac{D_M}{D_P} \right)^{0,18} \right] \quad (6)$$

$$V^* = 1,04 - 0,22 \cdot \log_{10} n_{Q, opt} \quad (7)$$

There are tendencies to use scale-up procedures [8] - [10] which are more simple than IEC 995 (3) and (4). The suitable one is the formula of Spurk and Grein [8].

$$\Delta h_{S.G.} = (h_{\infty} - h_M) \cdot \left[ 1 - \left( \frac{Re_M}{Re_P} \right)^n \right] \quad (8)$$

A large base of highly accurate model and prototype testing data is necessary to define infinite efficiency  $\eta_{\infty}$  (it is function of  $n_q$ ) and power coefficient  $n$ .

## TESTED PROTOTYPE AND MODEL EFFICIENCIES

Comparison between turbine efficiencies calculated from model test results and efficiencies tested on prototypes were made for one constant gross head for each HPP (see diagrams in Figures 5 and 6). During the prototype testing the gross head was constant, but the efficiencies were calculated with net head. There were no pressure taps for measuring head on the hydro power plants, so the net head was calculated according to standard IEC 41 (gross head is diminished for the value of hydraulic losses and changes of kinetic energy between

turbine input and output cross sections). The values of model efficiency which correspond to a certain constant gross head were obtained from model hill diagram. Efficiency differences for scale-up were calculated with equations in previous chapter. In cases of IEC, Hutton, Ackeret and JSME scale-up procedures, constant values of  $\Delta\eta$  were added to model values. In case of Fay-Kvyatkovskii procedure  $\Delta\eta$  was different in each point. Values of  $\Delta\eta$  normalised to IEC 995 value are in Table 1.

Table 1: Efficiency scale-up values normalised to IEC 995 values

	$n_Q$	IEC $Dh/Dh_{IEC}$	JSME $Dh/Dh_{IEC}$	Hutton $Dh/Dh_{IEC}$	Ackeret $Dh/D7h_{IEC}$	Fay-Kvyatk. $Dh/Dh_{IEC}$
Fala 8	160,1	1	0,54	1,02	0,73	1,20
Vuzenica	171,9	1	0,55	1,03	0,73	1,20
Mar. otok	167,9	1	0,55	1,03	0,73	1,20
Dravograd	158,5	1	0,59	1,03	0,74	1,30

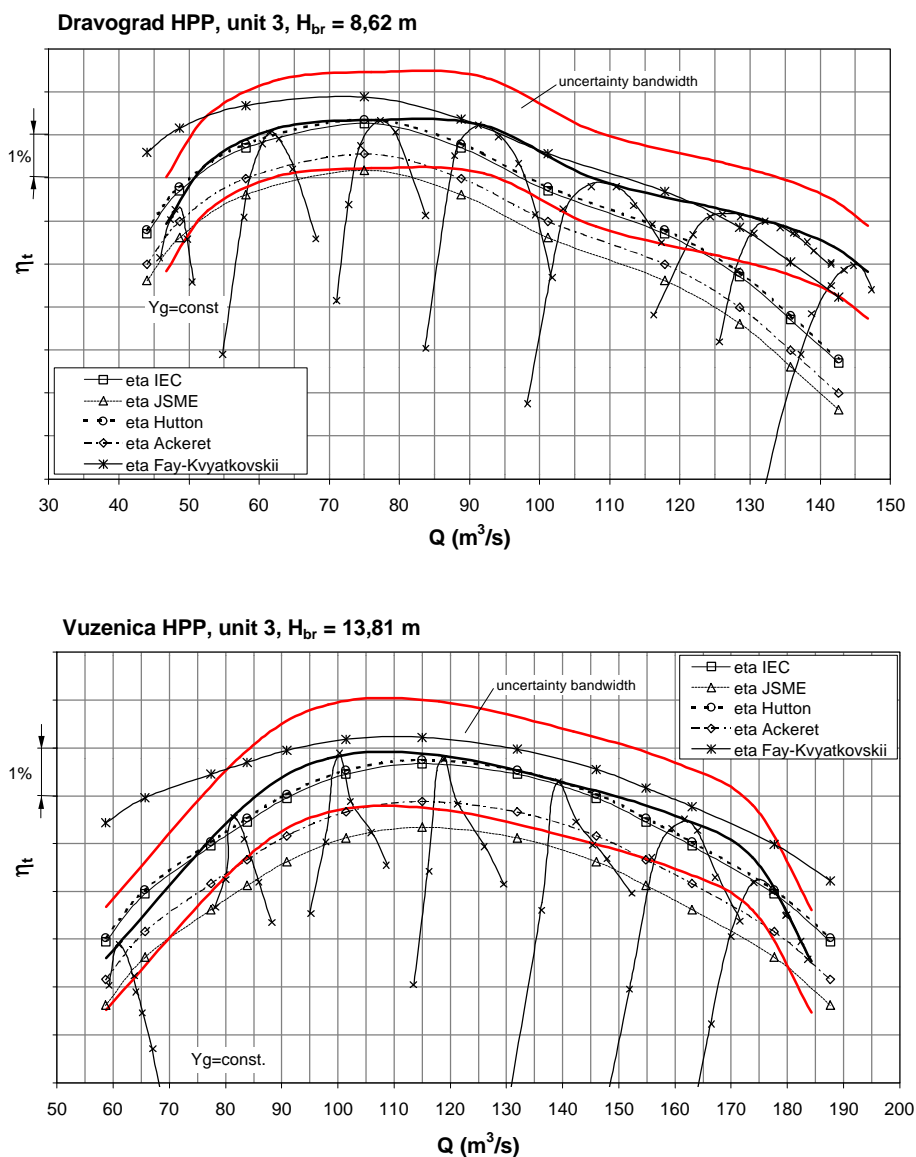


Figure 5: Tested prototype efficiency and model scale-up curves (Dravograd HPP and Vuzenica HPP)

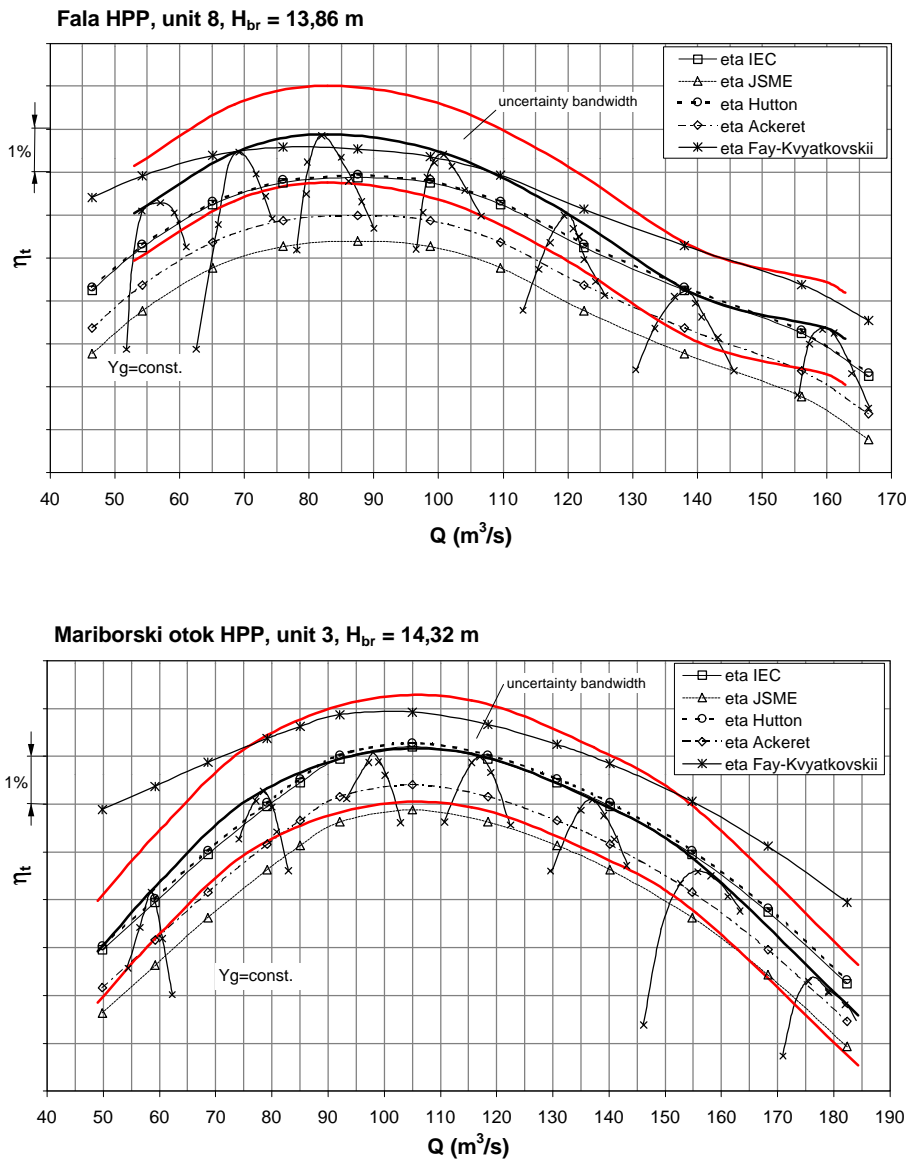


Figure 6: Tested prototype efficiency and model scale-up curves (Fala HPP and Mariborski otok HPP)

It can be seen from the Table 1 that IEC 995 and Hutton procedures give practically the same values for efficiency scale-up. The differences between them are only 2 or 3 %. The Ackeret and JSME formulas are very pessimistic. The difference at the first is up to 27 % and at the second up to 45 %, respectively. The formula preferred by EdF is very optimistic and the difference in turbine optimum is up to 30 %.

Around the prototype “on cam” curves is the uncertainty bandwidth calculated as recommended in the IEC 41.

Figure 5 for Dravograd HPP shows for:

- IEC and Hutton - relatively good agreement with prototype tested curves in the optimum region; at greater flow rates out of uncertainty bandwidth,

- Ackeret and JSME - pore agreement; practically in all region out of uncertainty bandwidth,
- Fay-Kvyatkovskii - practically all inside uncertainty bandwidth and it is the closest to the tested prototype curve except in the region left to the optimum.

Figure 5 for Vuzenica HPP shows for:

- IEC and Hutton - very good agreement with tested curves; practically inside  $\pm 0.5$  % uncertainty bandwidth,
- Ackeret – on the lower limit of the uncertainty bandwidth,
- JSME – out of uncertainty bandwidth,
- Fay-Kvyatkovskii – slightly above the tested curve; at low flow rates values are unreal.

Figure 6 for Fala HPP shows for:

- IEC and Hutton – under the tested curve except in nominal regime; inside the uncertainty bandwidth,
- Ackeret and JSME - in all tested region outside the uncertainty bandwidth,
- Fay-Kvyatkovskii - good agreement with prototype tested curves in the optimum region; at lower and greater flow rates above the tested curve but inside the uncertainty bandwidth.

Figure 6 for Mariborski otok HPP shows for:

- IEC and Hutton - very good agreement with tested curve,
- Ackeret and JSME – under the tested curve,
- JSME – also out of uncertainty bandwidth,
- Fay-Kvyatkovskii – above the tested curve but not completely inside the uncertainty bandwidth.

The infinity efficiency  $\eta_{\infty}$  for supposed power coefficient  $n$  from tested model and prototype curves according to Spurk and Grein [8] (see Equation (8) and Figure 7) was also calculated.

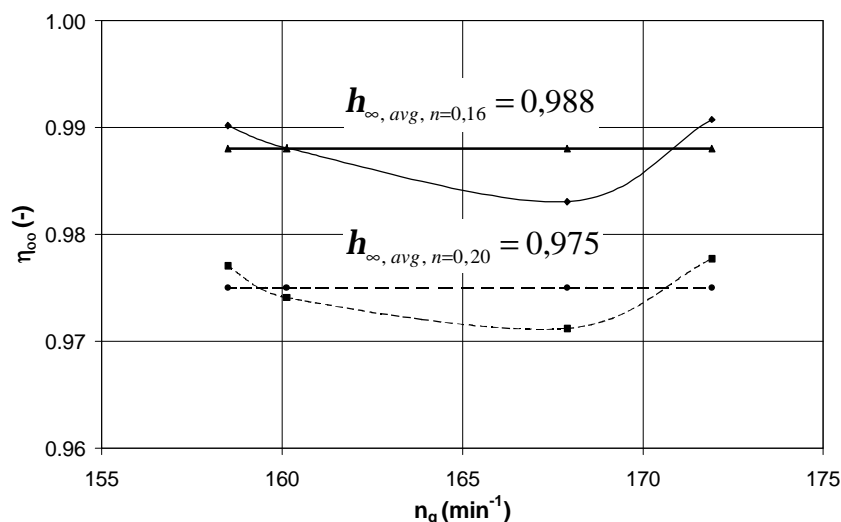


Figure 7: Infinite efficiency  $h_{\infty}$

## CONCLUSIONS

Model and prototype efficiency testing with highly accurate methods (the absolute method on prototype) enables verification of different efficiency scale-up formulas which are recommended by the international standards.

The IEC 995 efficiency scale-up formula gave the best results in comparison with the Ackeret, JSME and Fay- Kvyatkovskii formulas for low pressure Kaplan turbines of specific speed  $n_q = 160$  to  $170 \text{ min}^{-1}$  in optimum. Equally good as the IEC 995 formula is the Hutton formula.

Scale-up formulas of JSME S 008 and Fay-Kvyatkovskii are not suitable for efficiency scale-up of turbines of the mentioned  $n_q$ .

The values of infinite efficiency according to Spurk and Grein are  $\eta_{\infty, \text{avg}} = 0.998$  for power coefficient  $n = 0.16$  and  $\eta_{\infty, \text{avg}} = 0.975$  for  $n = 0.20$ .

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