DEVELOPMENT OF HIGH SPECIFIC SPEED FRANCIS TURBINE FOR LOW HEAD HPP

Jiří Obrovský*, Hana Krausová*, Jiří Špidla*, Josef Zouhar*

Nowadays we can commonly encounter with revitalizations of an original HPPs which were earlier fitted with Francis turbines. They were often placed to the locations with low head and higher discharge, which means high specific speed ($n_\mathrm{s} > 400$*). Generally it is quite complex to design Francis turbines for such high specific speed. These very old turbines usually have lower efficiency due to the earlier limited possibilities of hydraulic design. An exchange of a water turbine with another type can be quite expensive and therefore it can be more suitable to change only an old runner for a new one. In this article the design process of high specific speed turbine *$n_\mathrm{s} = 430$* is described. Optimization was done as the full-automatic cycle and was based on a simplex optimization method as well as on a genetic algorithm. For the parameterization of the runner blade, the BladeGen software was used and CFD (Computational Fluid Dynamics) analysis was run in Ansys CFX v.14 software. The final shape of the runner blade was reached after computing about 1000 variants, which lasted about 250 computational hours.*

Keywords : *Francis turbine, high specific speed, CFD, optimization method, objective function*

1. Introduction

It is necessary to consider a way of modernization of older hydro power plants fitted with high specific speed Francis turbines very carefully. Such machines have relatively large dimensions in view of produced power. This area is also covered by Kaplan turbines (see Fig. 1). Two basic ways to increase technical and economic parameters of these power plants are possible: either an exchange of a machine for another type or only an exchange of an original runner for a new one. In the selection of a way of modernization, it is needed to take into account technical limits and economic return on investment. During the change from Francis type to Kaplan type of turbine, the cavitation limits of a power plant has to be checked thoroughly and also overall economic costs of this change associated to construction work need to be considered. On the other hand, due to the present sophisticated design and flow calculation methods in hydraulic machine, it is possible to increase efficiency by replacing only the original turbine runner by up to 5 % and performance by up to 30 % as compared with original turbines subjected to the same cavitation guarantees. Annual production is critical for economic return of a runner exchange and hence a new turbine runner is designed for maximum possible discharge at a cavitation limit. Hydraulic design of such new runner must respect many hydraulic and geometric conditions and restrictions. Therefore it is suitable to find an optimum shape of runner blades using an automatic design method.

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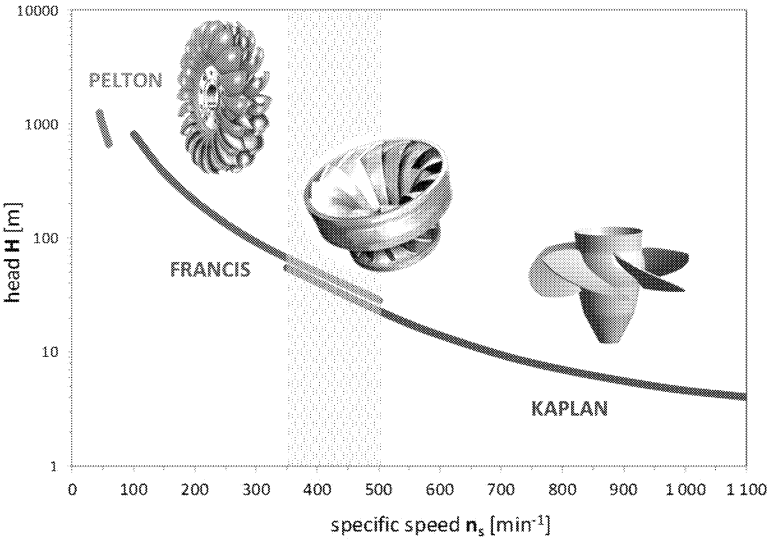

Fig.1: High specific speed area of Francis turbines

2. Mathematical background

The success in water turbine design depends mostly on an optimization procedure. In most cases an automatic optimization process with selected mathematical optimization method is used for a flow parts design (Skotak [4], [5]). Result of this procedure depends strongly on selected optimization method and an objective function.

The task of an optimization method is to optimize certain properties of a system which are described by parameters, usually represented as a vector. In most technical applications, these methods serve for minimization of an objective function (in this case called 'cost' function) which can be accompanied by some constraints.

To design shape of the runner blade, a combination of two methods was chosen. Each of them has different character of the found extreme. A global optimization method allowed exploring of parametric space and determining the regions where the minimum could be found. To detect specific value of extreme, a local optimization method was used.

2.1. Genetic optimization method

Differential evolution (DE) belongs to the class of genetic algorithms which use biology-inspired operations of mutation, crossover and selection on a population to minimize an objective function.

DE solves an optimization problem by evolving a population of *NP* individuals in *D*-dimensional parametric space which are randomly generated between lower and upper bounds defined by user :

$$X_i(t) = [x_{i,1}(t), \ldots, x_{i,D}(t)] \ , \quad i = 1, \ldots, NP. \tag{1}$$

In order to expand the search space, operation of mutation is used. Different forms of creating mutant vector exist, but the most common is DE/rand/1. This type uses one mutation constant F called scaling factor which has values from range $[0, 2]$, respectively $[-2, 2]$.

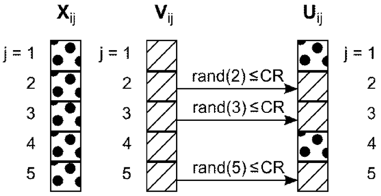

Fig.2: Illustration of crossover for 5 individuals

The next possibility how to increase diversity of a population is crossover. During binomial crossover some parameters of the donor vector $\mathbf{v}_{ij}$ are copied to the target vector $\mathbf{x}_{ij}$ and the trial vector $\mathbf{u}_{ij}$ is created (see Fig. 2). How many parameters will be changed, depends on the crossover probability CR which reaches values from 0 to 1.

The last operation is selection. It works on Darwin's phrase 'survival of the fittest', so it is based on comparing the values of the objective function. If the cost function of the trial vector is less or equal to the value of the objective function of the target vector, then the trial vector is a new part of the target vector for the next generation. Otherwise, the target vector enters to the next generation. The population is getting better and hence the objective function value is non-decreasing.

The process repeats until some stopping criterion is reached (Storn [7]).

2.2. Simplex optimization method

The simplex method belongs to the direct search class of local methods which do not require derivatives. The algorithm is using a geometric figure called 'simplex' consisting of $n+1$ vertices in an n-dimensional space.

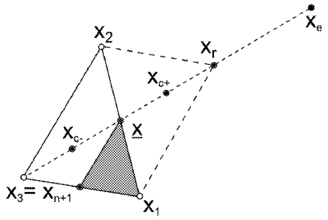

Fig.3: Simplex movements: $\underline{x}$ centroid, x_r reflection, x_e expansion, $x_{\mathrm{c}-}$ inner contraction, $x_{\mathrm{c}+}$ outer contraction, the shaded triangle – shrinkage operation

For two variables ($n = 2$), the simplex is a triangle and objective function f is evaluated at each of its vertices x_1, x_2, x_3. An example of two-dimensional simplex is given in Fig. 3. Firstly, the vertices are arranged in descending order according to the objective function values. The worst vertex $x_n + 1$ is discarded and replaced by a point with lower objective function value. This point is created by four operations namely reflection, expansion, contraction (inner and outer) and shrinkage operation (Haftka [1]).

Huge advantage of this method is very fast convergence.

3. Optimization process

As mentioned, the hydraulic design of the runner blade was based on the automatic optimization process. This process was composed of the parameterization of the runner blade, the automatic mesh generation, CFD calculations with post-processing and the own optimization cycle with defined objective function.

3.1. Parameterization of the runner blade

For the parameterization of the runner blade the commercial BladeGen v.14 software was used. This software was implemented to the optimization cycle in the 'batch mode'. Number of the parameters depends on used method of parameterization. The first method uses the user-defined equation for spanwise distribution of the runner shape. It means that only the blade shape on the hub and on the shroud of the runner was directly defined. Total number of parameters was 26. This method was mainly used together with the genetic optimization algorithm due to less number of parameters. The user-defined spanwise distribution dialog is shown in Fig. 4. For the second method, the equation was removed and the classic design using the number of streamlines between the hub and the shroud was applied. Total number of the streamlines was 13 and the four streamlines were directly chosen for the shape design of the blade in optimization and the rest was interpolated. Total number of parameters was 36 and this method was mainly used for the final shape optimization using simplex method. In both of methods, the meridional shapes of leading edge and trailing edge of the runner blade were optimized. Bezier curves served for the description of the shape. The GUI (Graphical User Interface) of the BladeGen software is shown in Fig. 4.

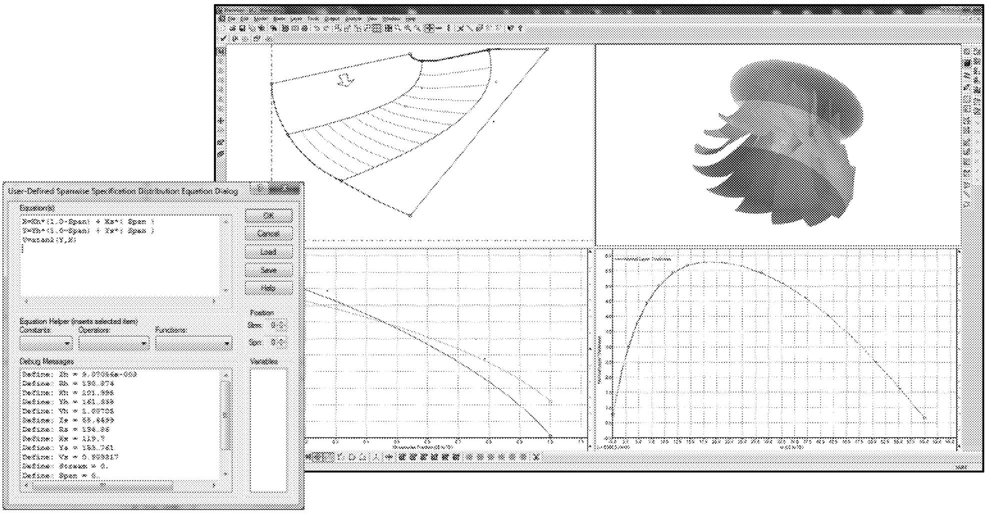

Fig.4: The design of the runner blade in BladeGen 14

3.2. CFD model for the optimization

The blade profile created in the BladeGen software was applied for an automatic mesh generation and the mesh of the blade was analyzed using CFD model. This model, used for the full-automatic analysis, consisted of three main parts and is shown in Fig. 5. The small inlet volume constituted the part for the inlet velocity profile prescription. The runner blade segment represented the second part and the full draft tube was joined as the third important part of the CFD model. In case of high specific speed turbine, the flow in the draft tube can affect the total efficiency of the turbine by several percent (Skotak [6]).

Therefore, it is necessary to optimize the runner joined with the draft tube. As mentioned, the inlet velocity profile was prescribed at the inlet of the model. This profile was exported from the CFD analysis of the entire spiral case with stay vanes and guide vanes. It was composed of the velocity components (radial u, axial w, circumferential v) as well as of the turbulence components (turbulence kinetic energy *TKE*, turbulence eddy dissipation *TED*). As you can see in Fig. 6, the velocity profile is asymmetrical between the hub and shroud. This disproportion is given by the nature of the flow near the shroud where the radial velocity is significantly increasing. The inlet volume and the runner segment were meshed in the ANSYS TurboGrid v.14 software and the hexahedral mesh was comprised of 200k elements. The draft tube was meshed in the PDC GridPro v.5.1 software and its mesh was created in two variants. The first mesh, used for the optimization, contained 110k hexahedral elements. The second one, used for the entire turbine unit analysis, had 500k hexahedral elements. Number of the runner blades was 13 and the suction diameter of the model runner was 0.32 m.

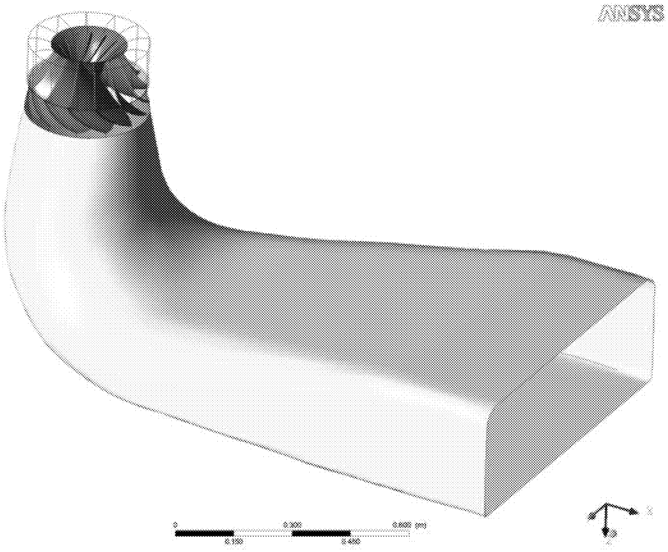

Fig.5: The CFD model for the optimization process

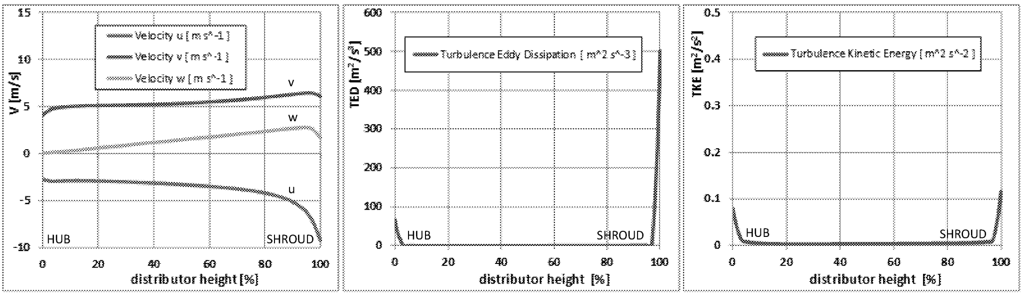

Fig.6: The velocity and turbulence profile components for the runner inlet boundary condition

3.3. Optimization cycle and the objective function

The own optimization cycle was controlled by the in-house software created in the Visual Studio.NET software. This utility controlled all optimization parts. The scheme of the optimization cycle is shown in Fig. 7. The optimization is started with some initial geometry of the blade or with randomly generated initialization parameters. The whole full-automatic cycle was composed of the mesh generation, CFD analysis, results analysis and the objective function evaluation. Then the modification of the geometry is performed and the cycle is repeated. It is able to calculate more operational points in one cycle to extend the optimized operational area of the turbine. The number of calculated points depends on the hardware capacity and license options. The optimum operational point and the maximum power output are mostly optimized operational points. In our case, one cycle of the optimization lasted about 15 minutes. The method of genetic algorithm (DE) with a population of 10 individuals was used for the first part of optimization and about 700 variants of the runner blade were calculated. After the next 300 variants, the final geometry was reached using the Simplex Nelder-Mead algorithm.

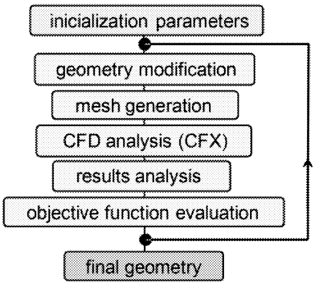

Fig. 7: The optimization scheme

The objective function is very important part of the optimization and significantly affects the result of the optimization. In our case, the objective function f contained several terms and each of term had its own weighting factor (Skotak [5]). The sum of N operational points is included.

$$f = \sum_{i=1}^{N} (w_{\mathrm{H}}\, f_{\mathrm{H}} + w_{\mathrm{E}}\, f_{\mathrm{E}} + w_{\mathrm{K}}\, f_{\mathrm{K}} + w_{\mathrm{S}}\, f_{\mathrm{S}}) \ . \tag{2}$$

– The head term – f_{H}

$$f_{\mathrm{H}} = \frac{|H_{\mathrm{t}} - H_{\mathrm{tTEO}}|}{H_{\mathrm{tTEO}}} \ , \tag{3}$$

H_{tTEO} – required (theoretical) pressure head.

– The efficiency term – f_{E}

$$f_{\mathrm{E}} = 1 - \frac{T_{\mathrm{R}}\, \omega}{Q\, \varrho\, g\, H} \ , \tag{4}$$

H – pressure head, Q – discharge, T_{R} – runner torque, ω – angular velocity, ϱ – water density, g – gravity acceleration.

– The cavitation term – f_{K}

$$f_{\mathrm{K}} = 1 - \frac{\sum (p_{\mathrm{va}} - p_{\mathrm{S}})\, S}{\sum p_{\mathrm{va}}\, S} \ , \quad \text{for } p_{\mathrm{S}} < p_{\mathrm{va}} \tag{5}$$

p_{va} – saturated water vapor pressure, p_{S} – static pressure.

– The swirl intensity term – f_S

$$f_\mathrm{S} = \left| \left(\frac{1}{R_0} \, \frac{r\,v}{w} \right) - S_\mathrm{rREQ} \right| \;, \tag{6}$$

S_rREQ – required swirl intensity downstream the runner, R_0 – suction radius of the runner, v – circumferential velocity, w – axial velocity, r – integration radius.

4. Additional CFD models

After the optimization was performed and some variant was found, the additional CFD model had to be performed to verify the parameters of optimized runner.

4.1. Cavitation analysis

The same model from the optimization process was used for prediction of cavitation parameters. Only some differences were done. Firstly, the two-phase steady state model was chosen for the calculation. Then the quality of the draft tube mesh was improved and the final draft tube mesh contained 500k hexahedral elements. The draft tube is especially important in a case of cavitation analysis, because of increasing losses in this component. The optimum operational point and the maximum power output were chosen as the points for cavitation analysis. The evaluation of cavitation consisted of two steps. Firstly, the dependence of cavitation coefficient on the turbine efficiency was created. Secondly, the cavitation area was visually checked by virtue of pressure distribution on the blade and isosurface with described density. The cavitation coefficient of the optimized runner is shown

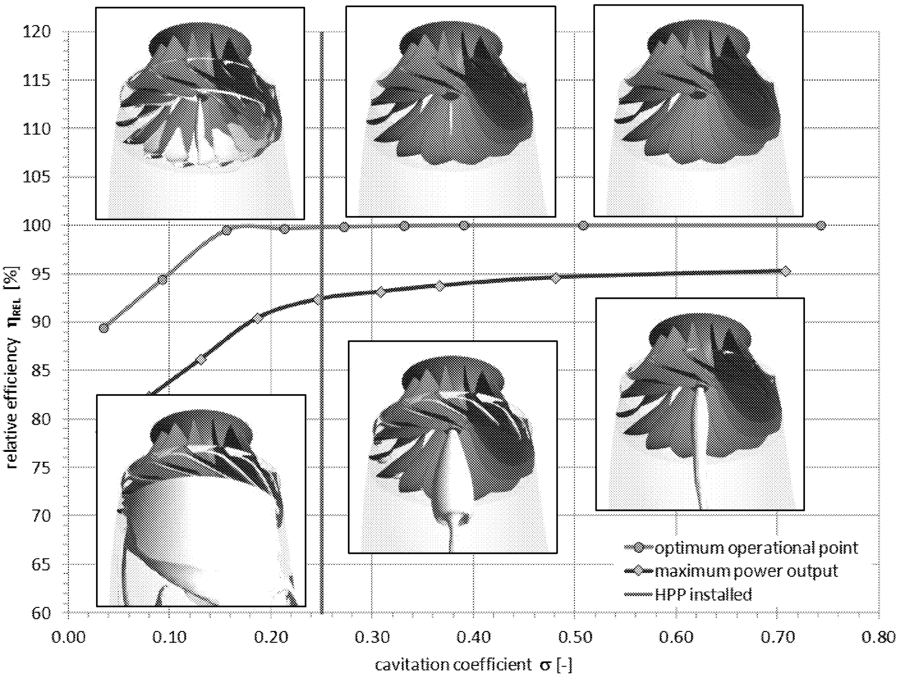

Fig.8: The dependency of the cavitation coefficient of the optimized runner

in Fig. 8. The isosurface of cavitation area in the runner for different cavitation coefficient is observed.

The fundamental equations for the cavitation coefficient calculation are given as follows (IEC):

$$\sigma = \frac{NPSH}{H} \,, \tag{7}$$

$$NPSH = \frac{p_{\mathrm{abs2}} - p_{\mathrm{va}}}{\varrho\, g} + \frac{v_2^2}{2\, g} - (z_{\mathrm{r}} - z_2) \,, \tag{8}$$

σ – cavitation coefficient, $NPSH$ – net positive suction head, p_{va} – saturated water vapor pressure, H – net head, p_{abs2} – absolute outlet pressure, v_2 – outlet velocity magnitude, $(z_{\mathrm{r}} - z_2)$ – reference dimension.

4.2. Turbine unit analysis

The model of entire turbine was used for the verification of the optimized runner. This model allows creating a preliminary hill chart of the turbine unit (Obrovsky [2]). The CFD model consisted of three main components. The spiral case with 12 stay vanes and 24 guide vanes was modelled by using hexahedral and tetrahedral meshes. It generally had 2150k elements. The runner segment with hexahedral mesh was used from the optimization procedure. The entire draft tube model was taken from the cavitation analysis and contained 500k hexahedral elements. The entire CFD model of turbine was comprised of 2850k elements.

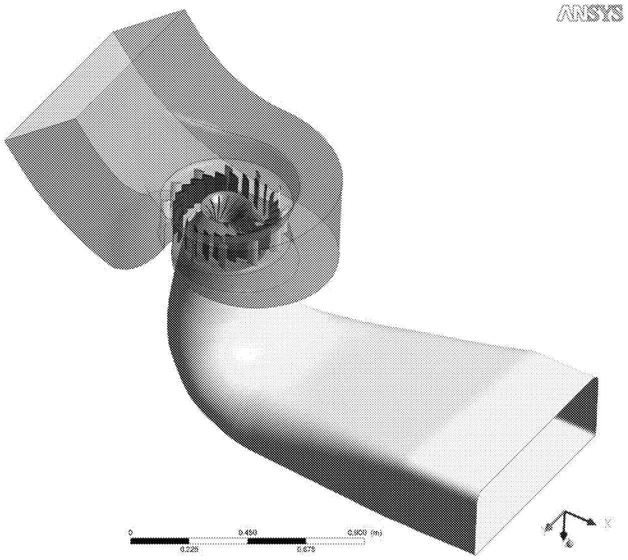

Fig.9: The CFD model of the turbine unit

About five operational points were calculated for each guide vane opening. Together, six guide vane openings were computed to check whole operational area of the turbine. The interfaces among components of the turbine were set up as circumferential averaged interface – stage. The CFD model of the turbine unit is shown in Fig. 9. The results of the steady state CFD analysis do not include additional losses as friction losses of the outer side of the runner discs and volumetric losses (Sado [3]). The dependency of the relative efficiency on the relative discharge of the turbine for the rated net head is shown in Fig. 10. The streamlines downstream the runner for the minimum discharge, optimum operational point and maximum power output are observed.

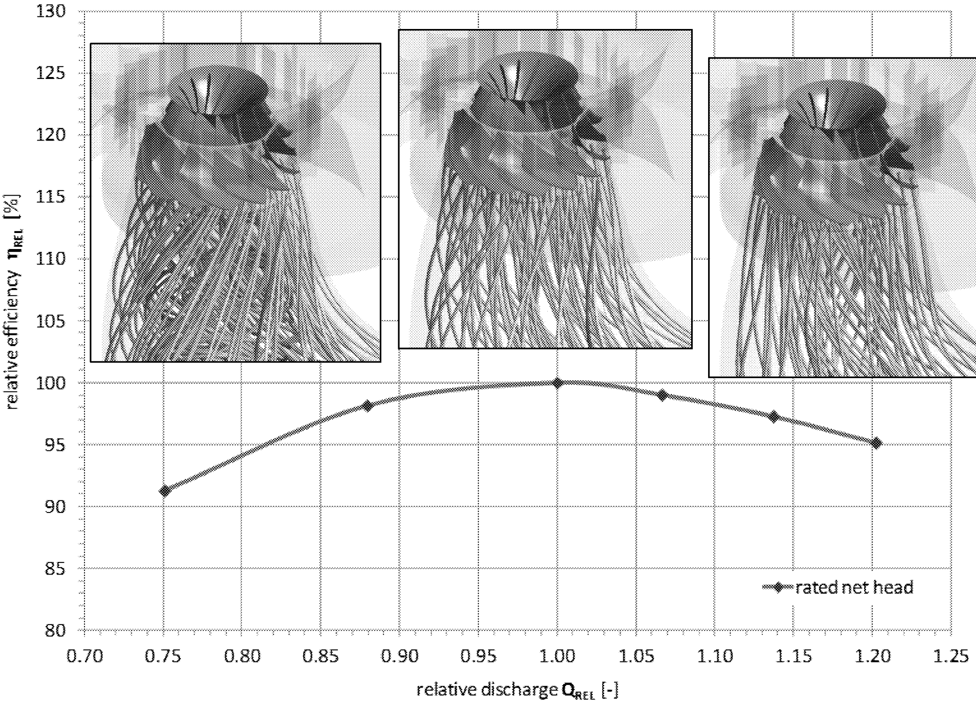

Fig. 10: The dependency of the efficiency on the discharge for the rated net head of the turbine

The fundamental equations for the unit parameters calculation are following:

$$n_{11} = \frac{n\,D}{\sqrt{H}}\ , \tag{9}$$

$$Q_{11} = \frac{Q}{D^2\,\sqrt{H}}\ , \tag{10}$$

$$\eta = \frac{T_\mathrm{R}\,\omega}{Q\,H\,\varrho\,g}\ , \tag{11}$$

n_{11} – unit speed, Q_{11} – unit discharge, η – turbine efficiency, n – runner speed, H – net head, Q – discharge, D – runner diameter, T_R – runner torque, ω – angular velocity, ϱ – water density, g – gravity acceleration.

5. Conclusions

This paper introduces the design process of the high specific speed turbine by using CFD analysis. The three main parts of this process are following:

- The auto-optimization process of the runner design
- The CFD model for the turbine cavitation prediction
- The CFD model of the entire turbine unit for preliminary verification.

On the basis of the CFD analysis, the influence of the efficiency in dependence on cavitation coefficient for the maximum power output of the turbine is presented. The mildly flat characteristic of the turbine in dependence on the discharge for the rated net head of the turbine can be also observed.

The model tests of the optimized runner will be carried out in the new Hydraulic Laboratory of CKD Blansko Engineering during the year 2013. Development and acceptance tests of hydraulic machine physical models are performed in accordance with the international standard IEC 60193.

The presented approach of the runner design allows optimizing the hydraulic shape of a blade directly for a specific HPP including the influence of original turbine flow parts.

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