CFD study of a Francis turbine using an industrial approach including a validation with model test results

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Abstract

The goal of this study is to analyse and validate hydraulic parameters of a Francis turbine using Computational Fluid Dynamics (*CFD*). The flow through the turbine is simulated with turbulence models which meet the current industry standards. Available model test data – measured in accordance with the *IEC 60193 standard* [1] - are used to validate the *CFD* results. Different simulation methods are considered to allow thorough investigations regarding applicability, workflow and accuracy of results. In terms of time and cost optimization, a variety of simulation approaches are additionally investigated, which differ in the degree of resolution. Relevant assessment criteria for turbomachinery are considered to estimate the influence of various simulation setups and mesh variants. In-house tools are used for the analysis and visualisation of the *CFD* results.

1. Introduction

Due to the long history of development and continuous optimization of hydropower technologies in recent decades, this type of renewable energy is indispensable from a global perspective. With a share of 15% in the global electricity generation, hydropower can be considered as one of the most important energy sources worldwide. [2] The steady progress in the optimization of hydro turbines is mainly based on numerical modelling and simulation. *CFD* gained industrial importance in the 1980s and depends on efficient numerical integration methods for partial differential equations, the further development of complex turbulent flow models and the availability of computational power. [3]

New approaches for flow simulation must be investigated due to the increasing demand for water turbine developments in the small hydro sector. This is caused by the growing competitive pressure to gain a technical and also a comparative advantage in existing and future markets. For this study different simulation models and model specifications are investigated and analysed.

2. Simulation model and setup

The *CFD* program *TCAE* by *CFD SUPPORT LTD.* is used for the investigations which is based on Open-Source *CFD* Software such as *Open Foam, snappyHexMesh, Paraview*, etc. Due to its robustness, stability and accuracy [5, p. 15] all simulations are done with a *SST k- ω turbulence model* under steady state conditions. A fixed mass flow at the inlet and a fixed mean pressure at the outlet are set as boundary condition. In total, three main simulation models are used, which will be explained in detail in the following subsections.

Table 1 provides an overview of the different simulation models and Figure 1 shows the investigated simulation domains.

2.1 Full turbine model (FT)

Figure 1 a) shows the f*ull turbine model* consisting of the following four sub-domains: s*piral case including stay vanes, wicket gate, runner and draft tube.* All water-wetted turbine components are fully resolved and a mesh independence study is done with the software package *snappyHexMesh* to evaluate different meshing approaches.

2.2 Pseudo full turbine model (PFT)

The second model, which is set up and validated with model test data, can be seen in Figure 1 b). This model is identical to the f*ull turbine model* with the exception that the runner domain is represented by just one blade passage with periodic boundary conditions. This approach results in a reduction of mesh cells and therefore simulation time.

2.3 Single blade model (SB)

This simplified turbine model consists of just one blade passage. There is a short inlet and outlet domain added to the runner domain which is necessary to set the appropriate boundary conditions. With this simulation model the mesh cell number can be reduced enormously. No guide vanes are resolved in this model, but an inlet flow angle - based on appropriate operating points of the model test measurements - is set as additional boundary condition.

Table 1: Resolution of simulation models

Turbine parts	Full turbine model (*FT*)	Pseudo full turbine model (*PFT*)	Single blade model (*SB*)
Spiral case and stay vanes	full	full	not resolved
Wicket gate	full	full	simplified (1 passage without guide vane and with periodic boundary conditions)
Runner	full (15 passages)	reduced (1 passage with periodic boundary conditions)	reduced (1 passage with periodic boundary conditions)
Draft Tube	full	full	simplified (only a short draft tube cone is resolved)

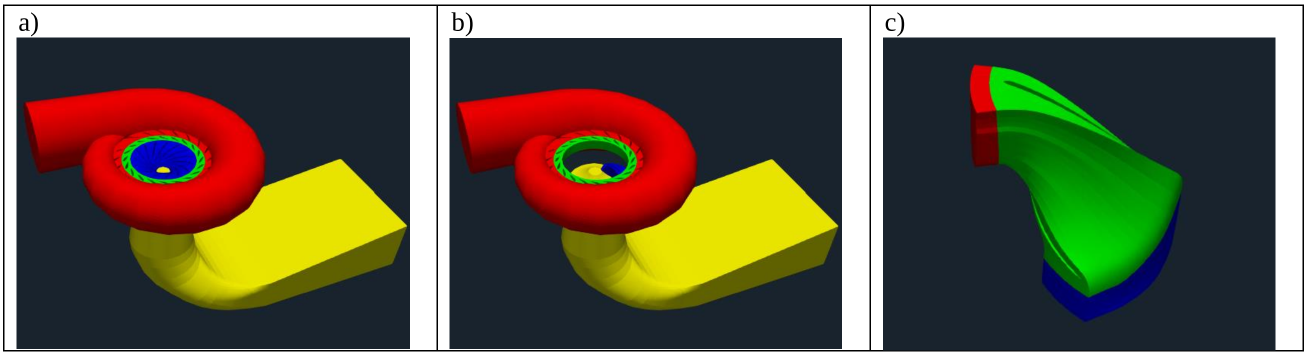

Figure 1: Different simulation domains: a*) full turbine model (*FT*)*; b) p*seudo full turbine model (PFT)*; c) s*ingle blade model (SB*)

3. Results

This section summarizes the main results of the different simulation approaches.

3.1 *Mesh independence study*

A mesh independence study is done with *snappyHexMesh*. Here the aim is to determine a mesh with high quality concerning typical mesh criteria [5] (*aspect ratio, y+- value, skewness, volume change*, etc.), less mesh cells to reduce the simulation time, good convergence behaviour and good accuracy regarding *CFD*-efficiencies. Figure 2 shows the correlation between the number of mesh cells and the determined *CFD*-efficiencies. The basis of the shown relative efficiencies in Figure 2 is the optimum hydraulic turbine efficiency of the model test.
For this study 27 different mesh variants (*V16 to V35-3*) are investigated for the *full turbine model*. The mesh cell numbers of the variants vary between five (e.g.. *V41, V42*) to 32 million mesh cells (e.g. *V27, V26*).
It can be seen in Figure 2 that meshes with a high resolution do not necessarily tend to have a more accurate efficiency compared to the test rig measurements. Different mesh criteria have a bigger influence on the simulation results than the total number of mesh cells. With the focus on an industrial approach the mesh settings of variant *V35-3* are used for further investigations. For the variant *V35-3* the deviation of the calculated *CFD*-efficiency compared to model test data is in an acceptable range, typical mesh criteria are fulfilled, numerical convergence targets are met and the mesh cell number with about 10 million mesh cells (for the *FT-model*) as well as the simulation time is low in comparison to other mesh variants.

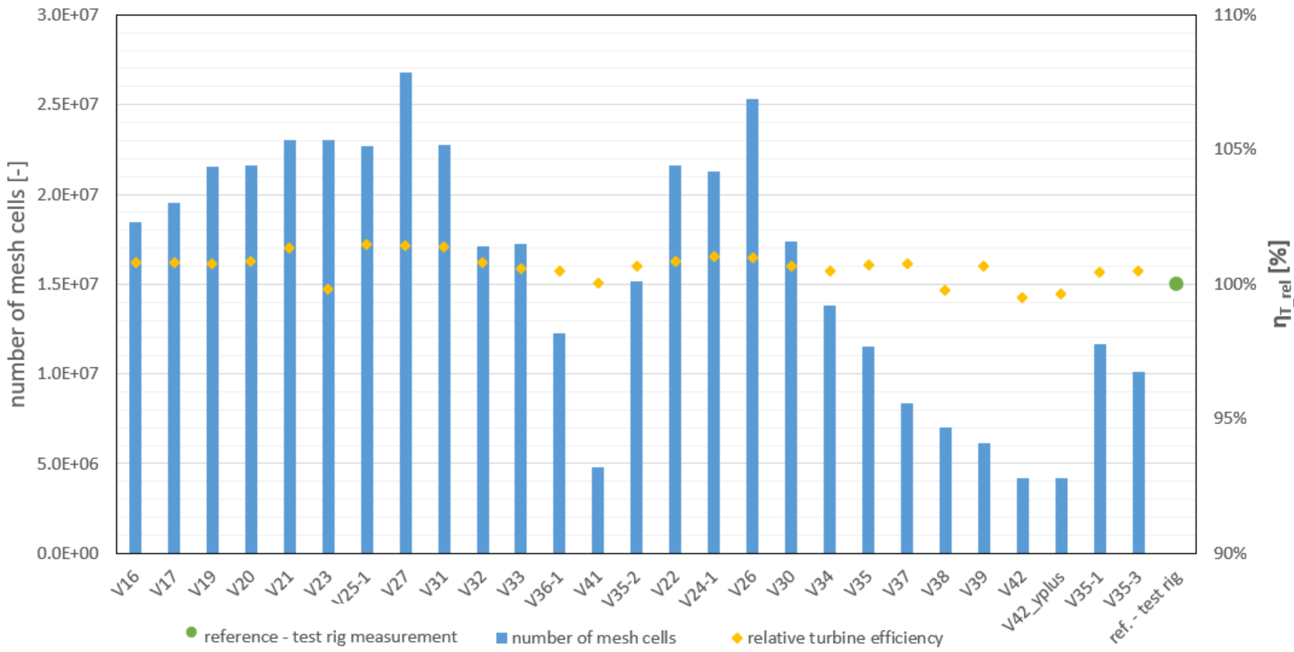

Figure 2: Correlation between mesh cells and relative hydraulic turbine efficiencies for different CFD mesh variants

The mesh settings *V35-3* applied to all three simulation models (*FT*, *PFT*, *SB*) result in different mesh cell numbers due to different domain sizes. The full turbine model meshes for variant *V35-3* can be seen in Figure 3. In Table 2 the mesh cell numbers per simulation domain are listed.

Table 2: mesh resolution of simulation models

Simulation model	Number of mesh cells [-]	Mesh cell ratio [-] (basis *FT*)
Full Turbine (FT)	10.058.679	100 %
Pseudo Full Turbine (PFT)	6.096.312	60.6 %
Single Blade (SB)	293.528	2.9 %

The mesh variant V35-3 for the *Full Turbine Model (FT)* can be seen in Figure 3.

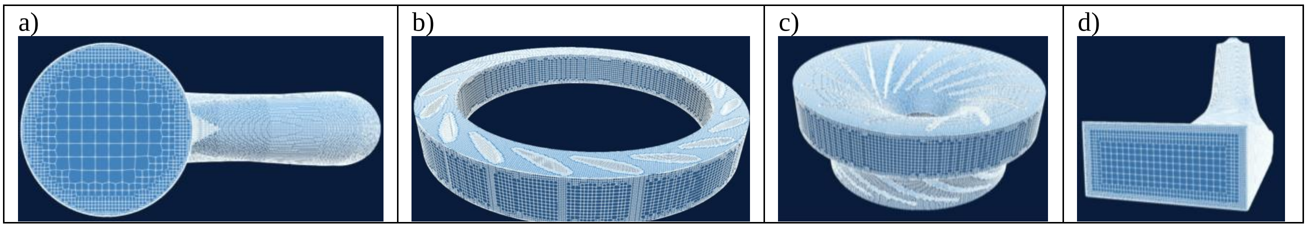

Figure 3: Mesh variant V35-3 of independence study for *FT*-model; a) spiral case mesh; b) guide vane mesh; c) runner mesh; d) draft tube mesh

3.2 Hill chart and hydraulic turbine efficiency

Hill charts are generated based on *CFD* simulations for the *pseudo full turbine model* (*PFT*) and for the *single blade model (SB).* Here, 96 operating points are simulated per hill chart with *CFD* and an in-house-software tool is used for the data processing utilizing a cubic spline interpolation method. The *PFT*-hill chart can be seen in Figure 4. With the *PFT* approach the mesh size of the selected mesh variant *V35-3* has been reduced by about 40% and for the *SB* approach by about 97% and therefore the simulation times are significantly lower compared to the benchmark *FT*-model. The *PFT*- hill chart can be seen in Figure 4 using following non-dimensional relationships:

$$\psi_{rel} = \frac{\psi}{\psi_{opt}} \quad (1) \quad with \quad \psi = \frac{2\,g\,H_n}{\pi^2\,n^2\,D_2^2} \quad and \quad \varphi_{rel} = \frac{\varphi}{\varphi_{opt}} \quad (3) \quad with \quad \varphi = \frac{4\,Q}{\pi^2\,n\,D_2^3} \quad (4)$$

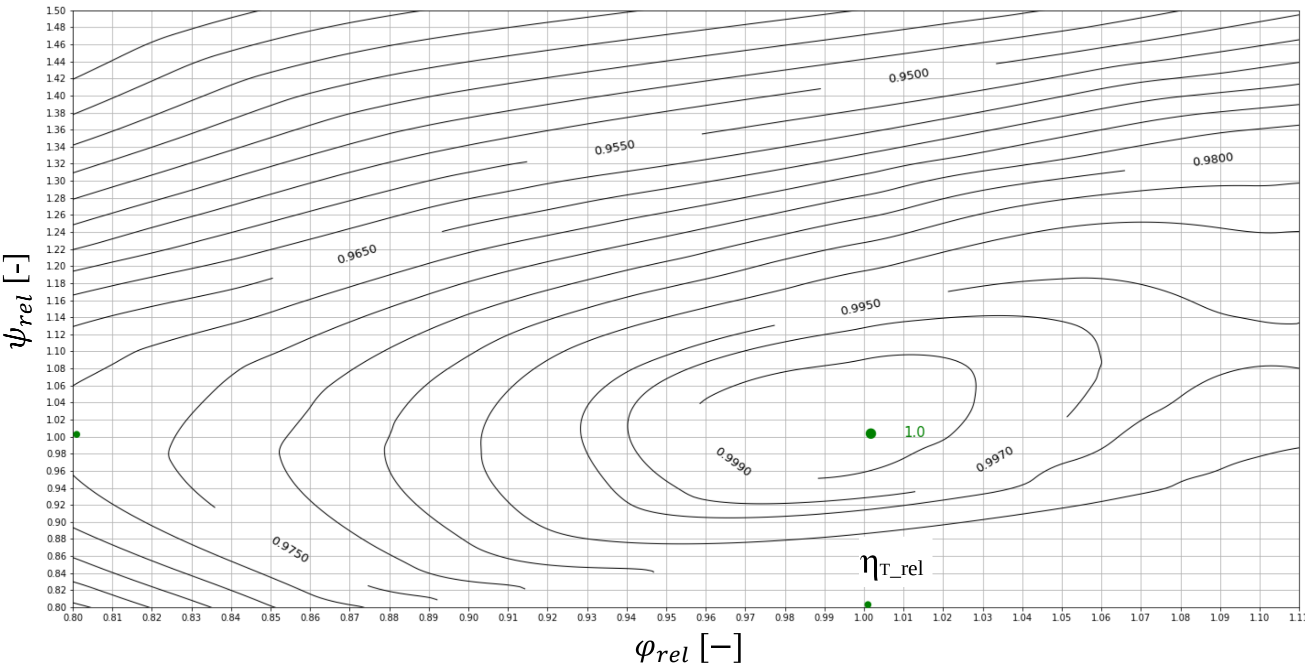

Figure 4: Efficiency hill chart of *pseudo full turbine model* (*PFT*)

Figure 5 shows the hydraulic turbine efficiency of the model test compared to *CFD* results. The mentioned in-house hill chart tool is used for the generation of the efficiency curves by intersecting the generated hill charts. The reference of the relative efficiencies is again the maximum efficiency of the model test data and the results are plotted over the non-dimensionless flow (φ_{rel}). The trend of both simulation models matches very well with model test measurements. However, there are slight differences in the magnitude. The mean deviation of *PVT* results compared to model test data is 0.98 % in the investigated operating range ($0.5 \leq \varphi_{rel} \leq 1.2$ and ψ_{rel}=1). A minor efficiency overprediction exists in full load and a moderate deviation in the part load. The deviation in the part load is in an operating range where the draft tube vortex is dominant [5]. *SB*- model leads to constantly higher efficiencies caused by a reduced simulation domain and the systematic neglection of losses for spiral case, stay vanes, guide vanes and draft tube.

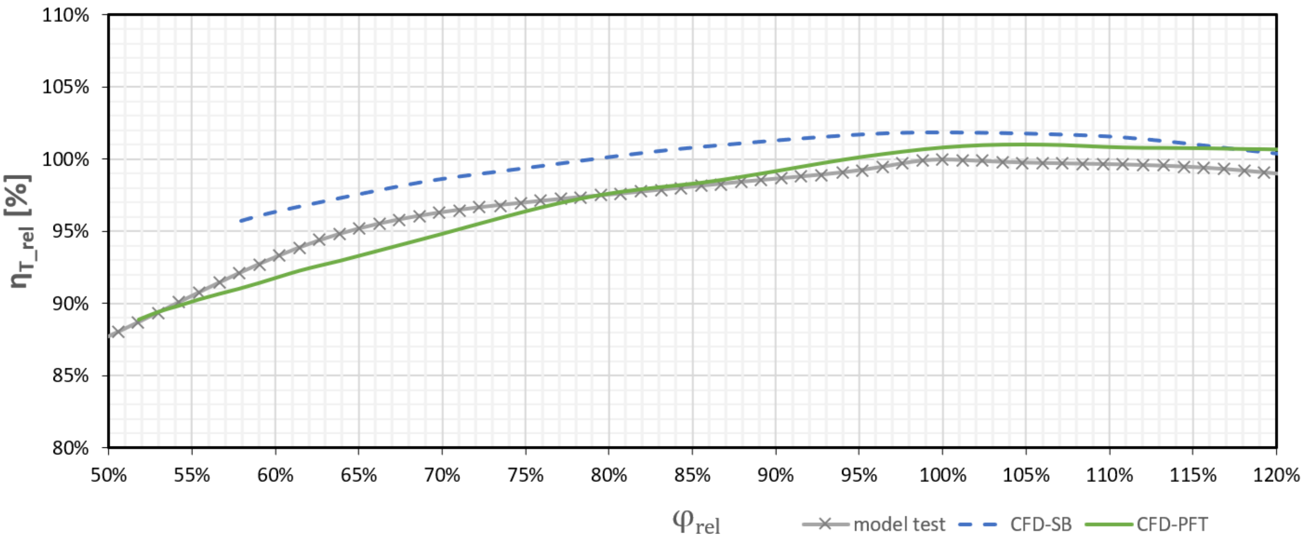

Figure 5: Comparison of efficiencies of model test data, *CFD-pseudo full turbine model* (*PFT*) and *CFD single blade model (SB)*

7. Conclusion and Discussion

This study summarises the comparison between high accurate test rig measurements with simplified *CFD* simulation setups. Three different simulation models are investigated (f*ull turbine (FT), pseudo full turbine (PFT), single blade (SB)*). A mesh independence study is done for *FT* to determine mesh approaches with few mesh cells respectively simulation time but good convergence behaviour and accuracy of calculated *CFD*-efficiency. The mesh sizes of the *PFT* and *SB* are 40% and even 97% smaller compared to *FT*. Hill charts are drawn with in-house tools for the *PFT* and *SB* approaches based on 96 different operating points per model. The efficiency is well predicted for the *PFT* and overpredicted for the *SB* simulations. The main reason for the overprediction of the *SB* approach with only one simulated passage is the neglection of hydraulic losses generated by spiral case, stay vanes, guide vanes and draft tube. Further investigations must be done to combine a *SB* simulation with flow dependent, calculated losses for turbine parts which are not included in the simulation domain. For further studies a transient simulation approach is recommended for deep part load ranges.

Nomenclature

Symbol	Term	Unit
ψ	non-dimensional net head	-
φ	non-dimensional flow rate	-
ψ_{rel}	Ψ relative to ψ_{opt}	
φ_{rel}	φ relative to φ_{opt}	
ψ_{opt}	ψ for optimum η	
φ_{opt}	φ for optimum η	
g	gravity	m/s^2
H_n	net head	m
Q	flow rate	m^2/s
D_2	outlet diameter turbine runner	m
η	Efficiency	-
η_{T_rel}	Hydraulic turbine efficiency relative to η_{T_opt} of model test data	-
η_{T_opt}	Maximum measured hydraulic model test efficiency	-

References

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