NUMERICAL INVESTIGATION OF INFLUENCE OF RUNNER GAP FOR A LOW HEAD TURBINE USING HYBRID RANS-LES TURBULENCE MODEL

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ABSTRACT

Due to their active principle, hydroelectric power plants are ideally suited to serve as regulation plants in electrical grids with a high percentage of fluctuating renewable energy. As a consequence hydro power plants are operated more and more in off design operation points where cavitation and transient phenomena, like vortex ropes in the draft tube, can occur.

The key for a good performance of low head turbines is the draft tube. In the design process of hydraulic machines simplification of the geometry, meaning the negligence of gaps as well as numerical simplifications, like circumferential averaging between stationary and rotating machine parts, can result in a falsification of the overall flow field. In particular the gap between runner and shroud can lead to a stabilization of the draft tube flow.

To analyze the gap flow influence a 4-blade propeller turbine is numerically investigated in a full load operation point. For the transient simulation two types of turbulence models are applied on a turbine with and without the existence of the runner gap. One model used is a standard RANS (Reynolds-Averaged-Navier-Stokes) turbulence model, namely the k-ω-SST model the other model is the SAS (Scale Adaptive Simulation)-SST model, a hybrid RANS-LES (Large Eddy Simulation) model. In the analyzed operation point a full load vortex develops downstream of the runner hub in the draft tube of the machine. Numerical results of integral quantities head and torque are evaluated against experimental measurements, performed in the laboratory of the Institute of Fluid Mechanics and Hydraulic Machinery at the University of Stuttgart following the IEC 60193 standard. The influence of the turbulence model and the runner gap on the shape of the vortex rope is evaluated. Velocity profiles in the draft tube cone are compared between the chosen different numerical approaches and geometries to evaluate the effect of the runner gap on the flow field in the draft tube. A comparison of the resolved turbulent structures in the draft tube is also presented.

KEYWORDS

Propeller turbine, runner gap, CFD, draft tube flow, RANS-LES

1. Introduction

In the year 2000 the European Union adopted the European Framework Directive, which advises all member states to achieve an ecologically good status of all flowing water [1]. Unused dames and wires in the member states of the European Union are moving back into the focus of energy providers. In the year 2014 about 26% of the total energy mix in Germany

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is produced by renewable energy sources. About 15% of the renewable energy is produced by hydro power, this equates to about 4% of the total energy mix [2]. The balancing of the energy grid in Europe by strengthening of renewable energy has become a challenge. The advantage of hydro power in contrary to other renewable energy like wind or photovoltaic power is the good predictability of the energy output. The compensation of fluctuations caused by wind and solar energy is furthermore another great benefit hydropower can provide. As a result, water turbines are operated more and more in off design conditions to balance the fluctuations of the electric grid. In these off design conditions various transient phenomena can develop for example vortex ropes, cavitation and so forth.

The draft tube of low head turbines like Kaplan, bulb and propeller turbines has a huge impact on the overall performance of the turbine. In the design process of turbines the accurate prediction of the draft tube flow field, in particular in off design operation points, is still a challenge. Simplifications made in the design process can lead to a falsification of the flow field. Typical simplifications in the design process are geometry simplifications like the negligence of gaps, and numerical simplifications like mixing plane approaches between stationary and rotating machine domains. These simplifications are done to reduce the computational costs of the design loops. In particular the gap flow between runner and shroud can lead to a stabilization of the draft tube flow.

A 4-blade propeller turbine with a straight draft tube is investigated in this paper, focusing on the influence of the runner gap on the draft tube flow field. Two types of transient simulations are compared, one without runner gap and another one with runner gap as in the experiment. No gaps exist at the trailing edges of the maximal opened guide vanes for the investigated operating point. The normalized gap sizes analyzed are τ=0 and τ=2 defined as:

$$\tau = \frac{s c_{cl}}{D_{ru}} \qquad (1)$$

Eq. 1 contains the runner diameter D_{ru}, the runner gap size s and a constant c_{cl} for the axial model turbine installed in a test rig at the laboratory of the Institute of Fluid Mechanics and Hydraulic Machinery. The experimental measurements are performed according to the IEC 60 193 standard [3].

The operation point analyzed in this paper has the characteristic values $n_1' = n_1'_{opt}$ and $Q1' = 1.13\ Q_1'_{opt}$. In the draft tube a full load vortex develops downstream the runner hub due to the velocity distribution at the runner outlet. The developing vortex shape for a full load vortex can be symmetric or asymmetric and in some cases the vortex starts to pulsate [4].

2. Numerical Setup

The transient simulations of the propeller turbine are performed with the commercial CFD code Ansys CFX version 16.0. For the computational model of the turbine no geometry simplification are carried out. For the investigations of the influence of the runner gap on the flow field in the draft tube, the gap between runner and hub is deliberately neglected in one computational model. For all computations a mass flow boundary condition is set. At the outlet of the expansion tank a static pressure boundary condition is set.

Besides analyzes of the gap of the runner, influences of the turbulence model on flow field, vortex shape and integral quantities are also investigated. The compared turbulence models are a k-ω-SST model and a SAS-SST model. The computational model and the evaluation position for the time averaged velocity profiles in the draft tube cone are illustrated in Fig. 1.

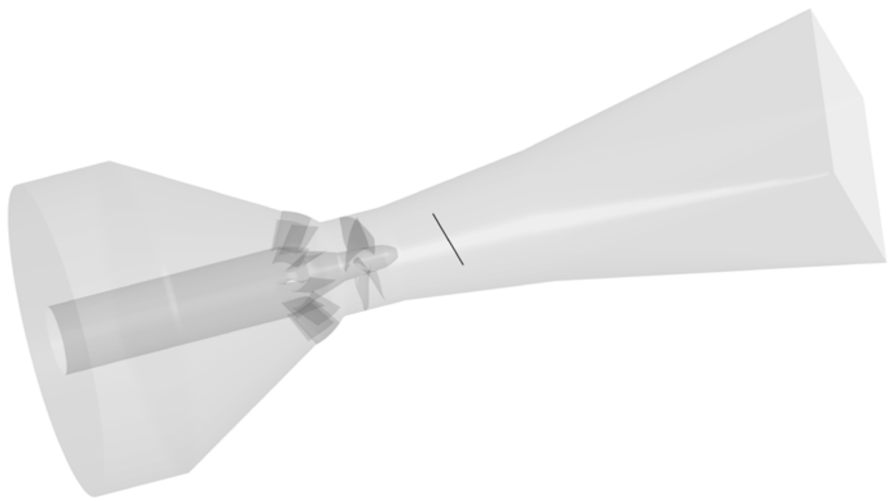

Fig.1 Hydraulic contour of the propeller turbine with marked evaluation line for the velocity profile

For the temporal discretization a second order backward Euler scheme is used. For the SAS model a bounded central differencing scheme is applied for the spatial discretization [4]. The spatial discretization of the turbulence quantities is carried out by using a first order scheme, whereas for temporal discretization a second order scheme is used [5].

All simulations are carried out in model size with a grid density of about 30 million elements in total for all components. The guide vane and the draft tube mesh, including an expansion tank, are equal for all presented results. The runner mesh differs due to the gap between runner and shroud. The number of elements as well as the averaged y^+ values for each component are listed in Tab 1.

Tab.1 Number of elements and averaged y^+ for the tubine parts

	mesh 1 (τ=0)		**mesh 2 (τ=2)**	
Turbine part	elements	y^+_{mean}	elements	y^+_{mean}
Guide vanes	5.2M	1.2	5.2M	1.2
Runner	11.3M	2.2	11.9M	3.3
Draft tub with expansion tank	14.3M	1.0	14.3M	1.0
Total	30.8M		31.3M	

3. Turbulence models

For the investigated gap widths of τ=0 and τ=2 the k-ω-SST model as well as the SAS-SST model are applied for turbulence modelling. The k-ω-SST model represents the standard model in the field of turbo machinery for turbulence modelling. The SAS-SST model is a hybrid turbulence model which can switch between RANS and LES mode.

3.1. k-ω-SST

The k-ω-SST model is a two-equation eddy viscosity turbulence model using the Boussinesq hypothesis to solve the turbulent quantities [7]. The Boussinesq hypothesis implies that the Reynolds stress tensor τ_{ij} is proportional to the mean strain rate tensor S_{ij}, which can be written as:

$$-\rho\overline{u_i^{'}u_j^{'}} = \mu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}+\frac{2}{3}\frac{\partial U_k}{\partial x_k}\delta_{ij}\right)-\frac{2}{3}\rho k\delta_{ij} \tag{2}$$

Through the combination of the k-ε with the k-ω turbulence models no additional damping function for the viscous sublayer is necessary. For the core flow the SST model switches from the k-ω formulation which is used for the flow in the sublayer to a k-ε formulation to avoid the common problems of the k-ω model of being too sensitive to inlet free stream turbulence properties.

3.2. SAS-SST

The hybrid approach of the SAS-SST turbulence model allows the resolution of smaller turbulence quantities in the flow field. Therefore the SAS-SST mode enables unsteady RANS to operate in the SRS (Scale Resolving Simulation) mode [8]. Through the provided information of the von Karman length scale L_{vK} a dynamically adjustment of resolved turbulence structures for the SAS model is possible, resulting in a LES like behavior whereas RANS capabilities are still provided [9]. The essential quantity for the turbulence model to switch to SRS mode is the von Karman length scale, which is introduced by an additional source term QSAS in the transport equation of the turbulence eddy frequency of the RANS SST model described in Eq. (3) [10] [11] [12].

$$\frac{\partial \rho\omega}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho U_j \omega\right)=\alpha\frac{\omega}{k}P_k-\rho\beta\omega^2+Q_{SAS}+$$
$$+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\omega}\right)\frac{\omega}{x_j}\right]+\left(1+F_1\right)\frac{2\rho}{\sigma_{\omega 2}}\frac{1}{\omega}\frac{\partial}{\partial x_j}\frac{\partial\omega}{\partial x_j} \qquad (3)$$

The source term Q_{SAS} is defined as:

$$Q_{SAS}=\max\left[\rho\zeta_2\kappa S^2\left(\frac{L}{L_{vK}}\right)^2\omega-C\frac{2\rho\kappa}{\sigma_\phi}\max\left(\frac{1}{\omega^2}\frac{\partial\omega}{\partial x_j}\frac{\partial\omega}{\partial x_j},\frac{1}{k^2}\frac{\partial k}{\partial x_j}\frac{\partial k}{\partial x_j}\right),0\right] \qquad (4)$$

with the von Karman length scale L_{vK} and the turbulent length scale L. The von Karman length scale is defined as:

$$L_{vK}=\kappa\left|\frac{\overline{U}'}{\overline{U}''}\right|, \overline{U}''=\sqrt{\frac{\partial^2\overline{U_i}}{\partial x_k^2}\frac{\partial^2\overline{U_i}}{\partial x_j^2}}, \overline{U}'=S=\sqrt{2S_{ij}S_{ij}}, S_{ij}=\frac{1}{2}\left(\frac{\partial\overline{U_i}}{\partial x_j}+\frac{\partial\overline{U_j}}{\partial x_i}\right) \qquad (5)$$

The reduction of the turbulence eddy viscosity enables the generation of smaller turbulent structures which leads to a turbulence cascade down to grid limit. Similar to the Smagorinsky LES model a limiter is introduced to the turbulence eddy viscosity. The grid limiter is necessary due to the insufficient damping of the SAS-SST for small turbulent structures [10]. An advantage of the SAS-SST model over DES-type models is the ability to operate in RANS mode if the grid density and the time step are not fine enough.

4. Results

For the evaluation of the results a comparison of different quantities is carried out. The integral quantities torque and head are compared with measurements performed in the closed loop in the laboratory of the Institute of Fluid Mechanics and Hydraulic Machinery. The vortex structure in the draft tube, velocity profiles in the draft tube cone, turbulence quantities in the draft tube are analyzed for all numerical approaches. Moreover, the effect of the runner gap on the listed evaluation quantities is investigated. The evaluation spot for the velocity profiles is shown in Fig. 1. After achieving a periodic flow behavior, a time averaging of the flow quantities is performed over 60 runner revolutions to evaluate the integral quantities and the velocity profiles.

4.1. Integral quantities

The integral quantities head and torque are compared with the experimental measurement since the discharge is the inlet boundary condition in all numerical setups. All quantities are normalized using the experimental results and listed in Tab. 2. For all numerical approaches head and torque are overpredicted. The head of the simulation using the hybrid SAS-SST

turbulence model is even more overestimated compared to the RANS turbulence model, independent of the gap size. For the torque the differences between the two analyzed turbulence models is almost identical, even though the torque is overpredicted by all computations.
The influence of the gap can be seen on the torque as well as on the head. Due to the runner gap the torque at the runner reduces independent of the used turbulence model, but is still overestimating the results of the experiment. The head of the simulations with runner gap is also reduced, even though there still is a rather big difference between the two investigated turbulence models.

Tab.2 Normalized integral quantities, head and torque

	τ=0		τ=2	
	SST	SAS	SST	SAS
Head $(H_{cfd}-H_{exp})/H_{exp}$ [%]	3.2	5.8	2.4	4.4
Torque $(T_{cfd}-T_{exp})/T_{exp}$ [%]	4.5	4.3	2.6	2.6

4.2. Velocity profiles

The evaluation of the velocity profiles is performed in the cone of the draft tube close behind the runner trailing edge (see Fig. 1). The analyzed meridional, circumferential and radial velocity components are time averaged and presented in Fig. 2.

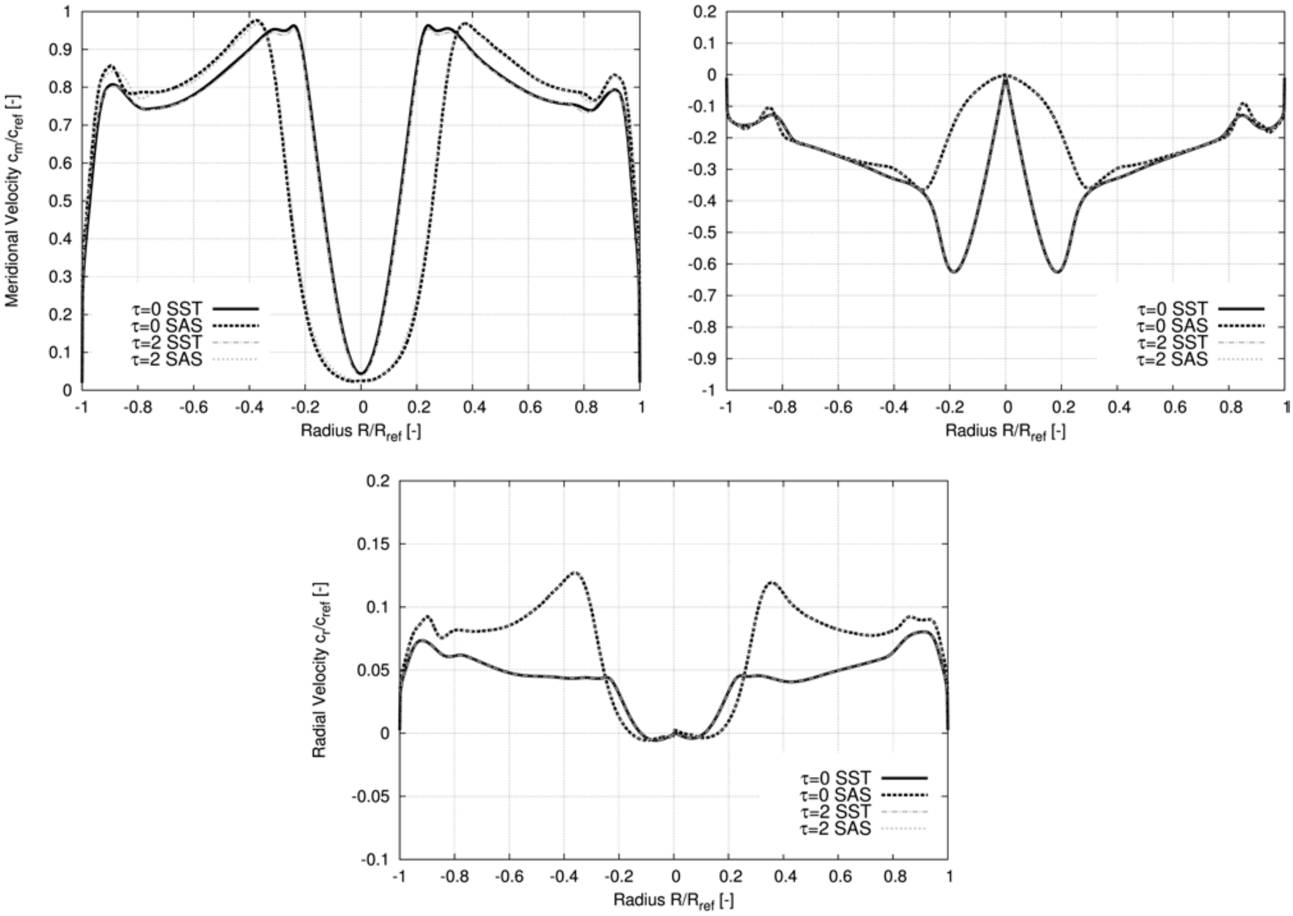

Fig.2 Time averaged velocity profiles for the SST and the SAS model with and without runner gap

Differences between the SST and the SAS turbulence model are visible in all velocity components. The size of the stagnation region where the full load vortex develops can be seen in the meridional and circumferential velocity component. A significant difference of the size of the stagnation region can be observed between the k-ω-SST and the SAS-SST model. The computation using the SAS-SST turbulence model show a larger stagnation region downstream the runner hub compared to the k-ω-SST model. The runner gap has a minor effect on the velocity profiles at the measuring position in the draft tube cone. Explicit influences of the gap flow can be seen close behind the runner in the downstream flow in all velocity components and is extenuated more and more to the evaluation spot. In an additional evaluation spot in the draft tube diffusor the effect of the gap flow on the velocity profile is vanished.

4.3. Vortex rope

The full load vortex for the analyzed operation point arises from a low pressure zone downstream the runner hub and is visualized in Fig. 3 by a pressure isosurface. The shape of the vortex rope differs between the two numerical approaches, whereas the influence of the runner gap on the shape is negligible. The vortex rope of simulation using the k-ω-SST model looks like a classical full load vortex, which is positioned downstream the runner hub in the middle of the draft tube in a symmetrical shape. Computations with the SAS-SST provide differing results. The vortex rope is developing in a shape resembling a corkscrew, looking like a part load vortex. The described difference of the results applying different turbulence models is according to the velocity profiles presented in Fig. 2. The dimensions of the low pressure zone are larger when using the SAS-SST model compared to the k-ω-SST model. The hub contour in the experiment is varied. Observations indicate that vortex rope is developing in the shape as calculated with the SAS model. Further validation of the shape and the velocity profiles are necessary.

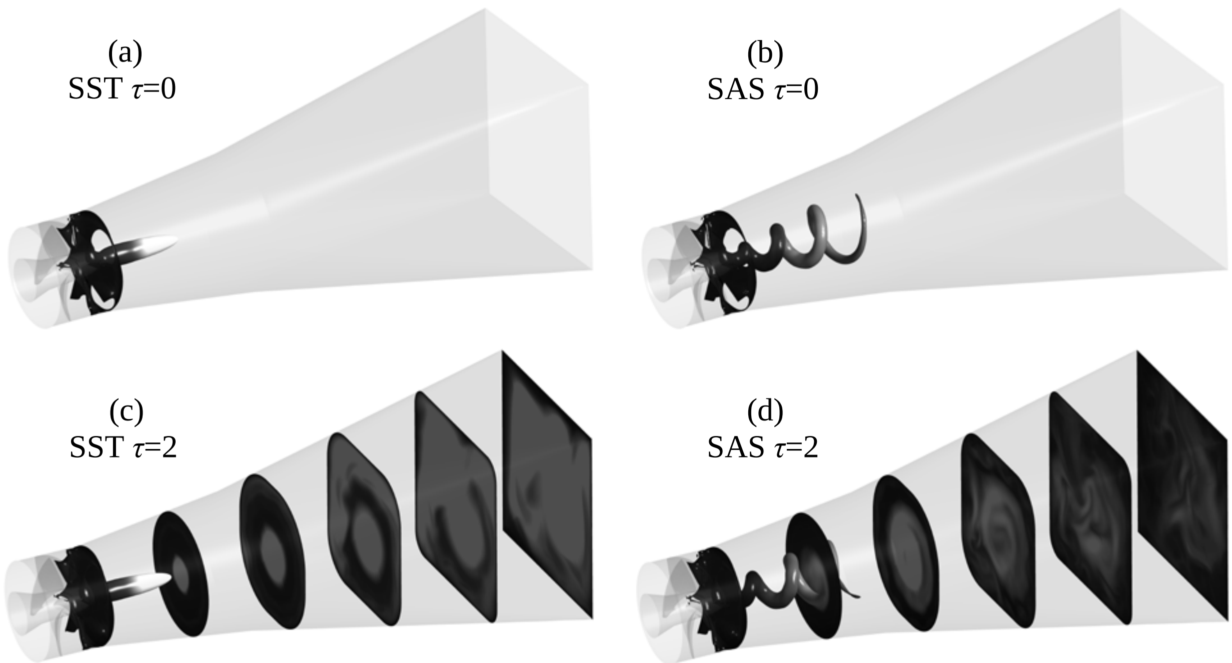

Fig.3 Shape of the vortex rope in the draft tube for the SST and the SAS model with and without runner gap with additional planes in the draft tube (c), (d) colored by the viscosity ratio 0-2000

4.4. Turbulence evaluation

The ability of the SAS-SST model to resolve smaller flow structures than the k-ω-SST model can be seen in Fig. 4. The flow structures in the cone of the draft tube are generally smaller than in the diffusor, this is irrespective of the turbulence model. To display the LES content of the turbulence model there are several options. In this paper two are illustrated. On one hand there is the velocity invariant Q and on the other hand the viscosity ratio, which is also illustrated in Fig. 3 [13]. The k-ω-SST model shows large flow structures with high values of the viscosity ratio. The breakdown of the vortex rope in the diffusor, due to the change of the geometry from round to rectangular, increases the scales of the resolved turbulent structures. Influences of the gap size on resolved structures in the entire draft tube for the investigated gap sizes cannot be observed. Further investigations with additional gap widths and grid densities are planned for a detailed evaluation.

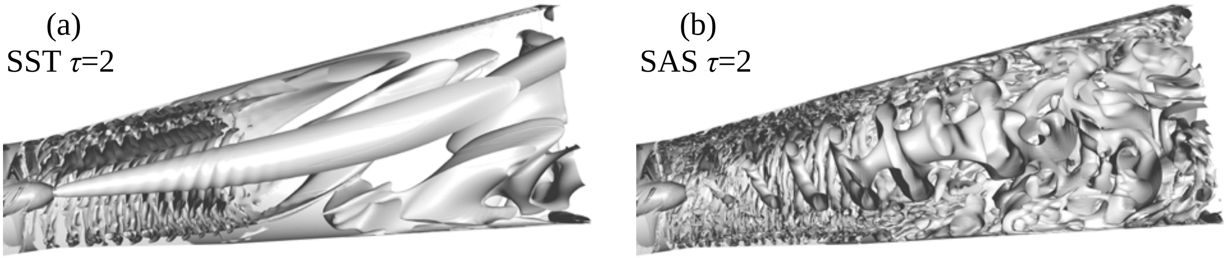

Fig.4 Isosurface of the velocity invariant Q=1 for the SST and the SAS model

5. Conclusion and Outlook

Simulations of a full load operation point of an axial propeller turbine with and without runner gap are performed with grids of approximately 30 million elements applying two different turbulence models. The computed integral quantities torque and head are overestimated independent of the turbulence model and the runner gap. The hybrid RANS-LES turbulence model overpredicts the head even more than the standard RANS model. With negligence of the gap the torque and head are veering away from the results of the experimental measurement. The shape of the vortex rope diversifies significantly between the two investigated turbulence models. A straight vortex rope downstream the runner hub develops using a k-ω-SST turbulence model. When applying the SAS-SST turbulence model a vortex rope in the shape of a corkscrew is reassembling downstream the runner hub in the middle of the draft tube. The differences of the vortex rope can also be seen in the time averaged velocity profiles, evaluated in the cone of the draft tube. The described differences can be seen in all investigated velocity components. The runner gap has minor influences on the analyzed velocity profiles, due to the position of the evaluation spot. The hybrid turbulence model is capable to resolve smaller turbulent structures in the draft tube than the RANS model. An effect of the gap on the turbulent structures in the draft tube cannot be registered.

Additional gap sizes and grid densities are planned to investigate to get a better understanding of the effects of the runner gap on the flow field in the draft tube.

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