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CFD simulations of a Y-junction for the implementation of hydraulic short-circuit operating mode

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Abstract. In the framework of the XFLEX HYDRO H2020 European Project, one of the demonstrators focuses on the implementation of the hydraulic short-circuit on the pump storage power plant of Grand-Maison owned by Electricité De France (EDF). The Grand-Maison power plant is a two-level plant production with one plant located above the downstream reservoir and equipped with four Pelton turbines; a second plant located downstream the reservoir and equipped with eight reversible pump-turbines. Hydraulic short circuit consists in running pumps and turbines in the meantime to balance the energy consumption of the pumps compared to the grid. Such an operating mode allows increasing the flexibility of the power plant and targeting the requirement of balancing the intermittent production due to the growing of new renewable energies such as wind and solar power plants. The hydraulic short-circuit operating mode leads to a change in the flow paths in the penstocks and junctions compared to the normal turbine or pump modes. Indeed, compared to the pump mode, this mode will lead to a flow derivation at the junction between the penstocks directed to the Pelton units and the penstocks directed to the upper reservoir. As this mode have not been scheduled at the beginning of the power plant construction, it is necessary to quantitatively assess the singular head losses generated at the junction to be able to simulate the complete behaviour of the power plant by means of a 1D model. CFD simulations are carried out with the Fluent software for several configurations of hydraulic short-circuit defined by the ratio of flow rate deviated to the Pelton turbines.

1. Introduction

The production of electricity by hydraulic power plants faces to several challenges related to the changes in the electricity market and the development of new sources of production using for instance solar and wind generation [1, 2]. Among these challenges, one is related to the increase in the flexibility production, which requires to adjust the production to the demand. Regarding the pumped-storage hydraulic power plant (PSHP) such a regulation can be achieved by using variable speed or hydraulic short-circuit (HSC) [3]. Variable speed technology has been set up

for new PSHP such as the ones of Lienthal and Nant de Drance [4] whereas the Kops II PSHP has been designed for running in HSC mode [5]. For already built PSHP, the cost of adding variable speed capacity can be prohibitive and therefore the implementation of an HSC mode is the first option to adjust the power in pump mode.

The PSHP of Grand-Maison (GM) owned by Electricité de France (EDF) is typically a power plant built in the eighty's and for which the pumps operate at a fixed point. Therefore, the HSC mode would be a mean to adjust the power during pump mode. This is one of the topic addressed in the XFLEX HYDRO: Hydropower Extending Power System Flexibility project[1]. One challenge regarding the implementation of the HSC mode is related to the head losses in the different junctions due to changes in the water ways since part of the flow in pump mode is deviated to the turbines. Hydraulic losses in junctions of various configurations have been experimentally studied for instance by Gardel et al. [6, 7, 8] more than fifty years ago. In these studies, the authors focuses on T-junctions and look at the influence on the head losses due to the direction of the flow in the junction (converging or diverging flow), the angle between the pipes, the flow repartition between the pipes, the cross-area of the pipe and the fillet radius. They proposed a set of algebraic formula to compute the head losses due to the junction. In addition, other authors such as Ito and Imai (reported in [9]), Rennels [10] or Levin and Taliev (reported in Idel'Cik [11]) have also proposed formula for T-junctions. For the Kops II power plant, a CFD studied have been carried out [12] to determine the head losses in the T-junction. The numerical results were in agreement with the experimental data excepted for a high discharge ratio between the reservoir and the pump.

The present paper focuses on one of the junctions of the Grand-Maison power plant that will be used in the future to demonstrate the ability of the power plant to run in HSC mode. This junction is rather a Y-junction than a T-junction. From the authors' knowledge no algebraic formula are available in the literature for Y-junctions. Consequently, CFD studies have been carried out for various ratio of the flow discharge between the pumps and the turbines. Prior to this work and because on site measurements are difficult to perform, a canonical T-junction has been considered to validate the methodology. The paper is divided as follow: first the two test cases are described, then the numerical settings are summarized before presenting the results and concluding the study.
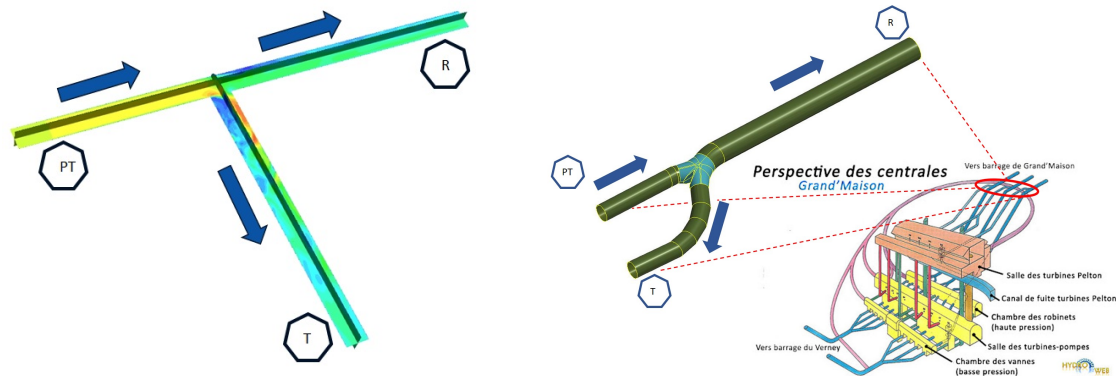
2. Test cases

The first test case is a standard 90 degree T-junction with a diverging flow (see figure 1 left). The three pipes have the same diameter of 3 meters. The pipe 1 is 27 meters long, whereas the two other pipes are 39 meters long. The fillet radii at the junction are set to 0.

The second test case if one bifurcation of the Grand Maison PSHP. This PSHP is divided in a two-level power plant: one plant with Pelton turbines is located above the level of the downstream reservoir whereas the second plant with reversible pump-turbines is located below the level of the downstream reservoir. The implementation of the HSC is scheduled between the two plant levels[2]. The present study focuses on the junction of one of the penstock at which the pipe coming from the pump-turbines divided to the pipe towards the upper reservoir and the pipe towards the Pelton turbines. The geometry of the junction is shown on the right side of figure 1. The junction itself is a Y-junction but due to the mounting of the connecting pipes, the junction is also close to a T-junction shape. The pipe towards the reservoir as a higher diameter than the one for the pipes towards the Pelton turbines or the pump-turbines.

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[1] See https://xflexhydro.net/ for an overview of the project.
[2] The reader can visit the web page describing the demonstrator for more information: https://xflexhydro.net/grand-maison

Figure 1. Two test case: configuration of the 90 degree T-junction (left) and the junction of the Grand-Maison PSHP (right) with at the bottom right a representation of the two-level power plant (courtesy of EDF). The arrows indicate the flow direction. The letter refers respectively to: the Pump-Turbine (PT), the Turbine (T) and the upper Reservoir (R).

Table 1. Average, maximum and minimum values of the y^+ for a discharge ratio $Q_T/Q_P = 0.75$ and Reynolds number in the pump pipe. RNG $k - \epsilon$ turbulence model.

Test case (Mesh)	$\mathbf{Ave(y^+)}$	$\mathbf{Max(y^+)}$	$\mathbf{Min(y^+)}$	$\mathbf{Re_D}$
90 degree T-junction	275	760	16	$6.8\ 10^6$
Junction of GM PSHP (mesh1)	75	226	3	$9.1\ 10^6$
Junction of GM PSHP (mesh2)	74	336	2	$9.1\ 10^6$

3. Numerical settings

The Fluent solver is used to solve the Reyolds-Averaged Navier-Stokes (RANS) equations that model the flow in the pipes. For the T-junction, only simulations with the RNG $k - \epsilon$ turbulence model [13] have been carried out, whereas for the junction of the GM PSHP simulations have been performed with both the RNG $k - \epsilon$ model and the realizable $k - \epsilon$ model [14]. The full set of equations is solved using a steady state solver based on the SIMPLEC algorithm described for instance in [15]. The under-relaxation factors have been set 0.2 for the pressure and to 0.3 for the momentum and the turbulent variables k and ϵ.

Regarding the boundary conditions, an outlet discharge is fixed in each "outlet" pipe respectively, whereas the total pressure is imposed in the incoming pipe, *i.e* the pipe from the reversible pump-turbines. A no slip wall condition is imposed at the solid walls with in addition the use of a scalable wall function.

The meshes are created with the IcemCFD software. For the 90 degree T-junction, an unstructured tetrahedral mesh with 4 prism layers has been generated with 1.3 million of cells and 330'000 nodes. On the contrary, for the Grand-Maison junction, two structured meshes have been generated to better control the wall normal expansion ratio of the cells. These two meshes differ only by the number of cells in the domain but share the same height for the first cell layer closed to the solid walls. The first mesh has 4.4 million of nodes and the second mesh has 8.2 million of nodes.

For a discharge ratio $Q_T/Q_P = 0.75$ and simulations with the RNG $k - \epsilon$ turbulence model, the averaged, maximum and minimum y^+ values are gathered in table 1 with in addition the value of the Reynolds number in the pipe linked to the pump-turbines. The averaged and maximum values of the y^+ quantity for both cases lay in the logarithmic region of the boundary layer as required for RANS simulations at a high Reynolds number.

4. Results

For both test cases, the head loss coefficients between on one hand the pump and the upper reservoir (referred as K_{PR}) and another hand the pump and the turbine (referred as K_{PT}) are computed as described in [9]:

$$K_{PR} = \frac{\Delta p_{PR}}{0.5\rho C_P^2} \tag{1}$$

$$K_{PT} = \frac{\Delta p_{PT}}{0.5\rho C_P^2} \tag{2}$$

with Δp the difference between the area-averaged total pressure in a cross section of each pipe, ρ the density of the fluid and C_P the fluid velocity in the pipe linked to the pumps. In the simulations, the area-averaged total pressures are computed at the inlet/outlet boundaries, therefore the linear head-losses in each pipe are subtracted considering smooth walls. This method of calculation is inspired from the one of Gardel [6].

4.1. The 90 degree T-junction

For the 90 degree T-junction, simulations have been run for 7 discharge ratio Q_T/Q_P between $Q_T/Q_P = 0$ (pump mode) and $Q_T/Q_P = 1$ (full HSC mode). For each simulation, the head-loss coefficient is computed after than 2'000 iterations have been completed. The head-loss coefficients K_{PR} and K_{PT} are plotted on figure 2 as a function of the discharge ratio Q_T/Q_P and compared with formula available in the different references already cited.

For the head-loss coefficient K_{PR}, the agreement with the formula (excepted the one from Idel'Cik) is rather good if the discharge ratio is higher than 0.5. For a low discharge ratio $Q_T/Q_P < 0.5$, *i.e* in dominated pump mode, the gap between the simulation and the formula increases. This feature seems to be related to the used of a total pressure inlet boundary condition that imposed also a uniform velocity profile at the inlet. By imposing a developed velocity profile at the inlet of the pump pipe for $Q_T/Q_P = 0$, the head loss coefficient K_{PR} is reduced from 0.15 to 0.09 (to be compared with a value of 0.045 using the formula of Ito & Imai).

For the head loss coefficient K_{PT}, the simulations are in agreement with the formula for all the range of discharge ratio. It is noticeable that the simulations are closer to the Gardel [6, 7] and Rennels [10] formula for a discharge ratio lower than 0.75 and closer to the Ito & Imai (reported in [9]) formula for a larger discharge ratio.

4.2. The junction of the Grand-Maison PSHP

For the junction of the Grand-Maison PSHP, the operating points computed with each mesh are gathered in table 2. Each operating point has been computed with both the RNG $k - \epsilon$ model and the realizable $k - \epsilon$ model. The discharge ratio of 1.25 is simulated because the Pelton turbines have a maximum flow rate 25% higher than the one of the pump-turbines. In this case, the additional flow discharge is taken from the upper reservoir. In addition, since the junction links three pump-turbines with two Pelton turbines, the discharge ratio $Q_T/Q_P = 0.75$ and $Q_T/Q_P = 1.25$ have been computed for configurations with only a single pump-turbine and a single Pelton turbine running and with two pump-turbines and two Pelton turbines running.

Contrary to the T-junction, the number of iterations completed before analysing the results are respectively equal to 6'000 for the simulations using the mesh 1 and 12'000 for the simulations using the mesh 2. Since oscillations of the area-averaged total pressure are observed for large discharge ratios, the head-loss coefficients are calculated using an iteration-averaged total pressure over the last 3'000 iterations for the simulations with the mesh 1 and 4'000 iterations for the simulations with the mesh 2 (a comparison with an unsteady simulation is shown in
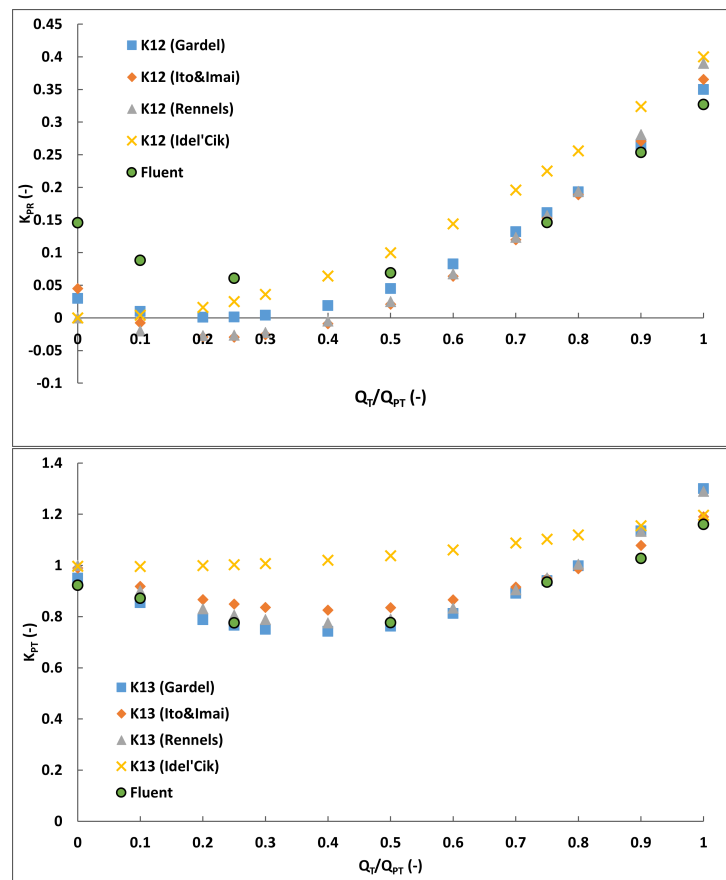
Figure 2. 90 degree T-junction, variation of the head-loss coefficients K_{PR} (top) and K_{PT} (bottom) as a function of the discharge ratio Q_T/Q_P. RNG $k - \epsilon$ turbulence model.

Table 2. GM junction, operating points computed for each mesh.

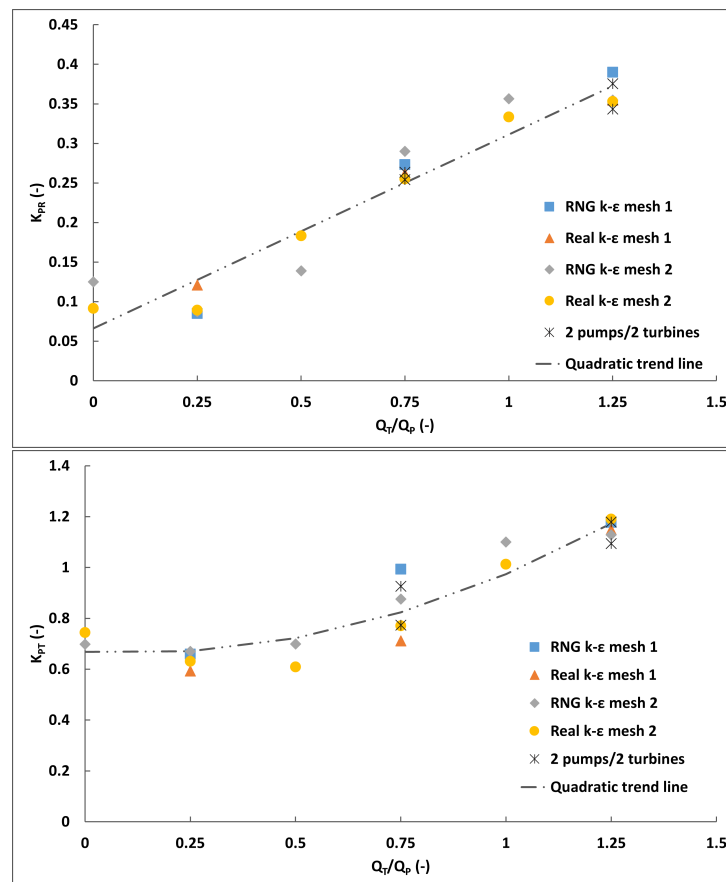| Q_T/Q_P	Number of pump/turbine in operation	mesh 1	mesh 2
0	1/1	n	y
0.25	1/1	y	y
0.5	1/1	n	y
0.75	1/1	y	y
0.75	2/2	n	y
1	1/1	n	y
1.25	1/1	y	y
1.25	2/2	n	y
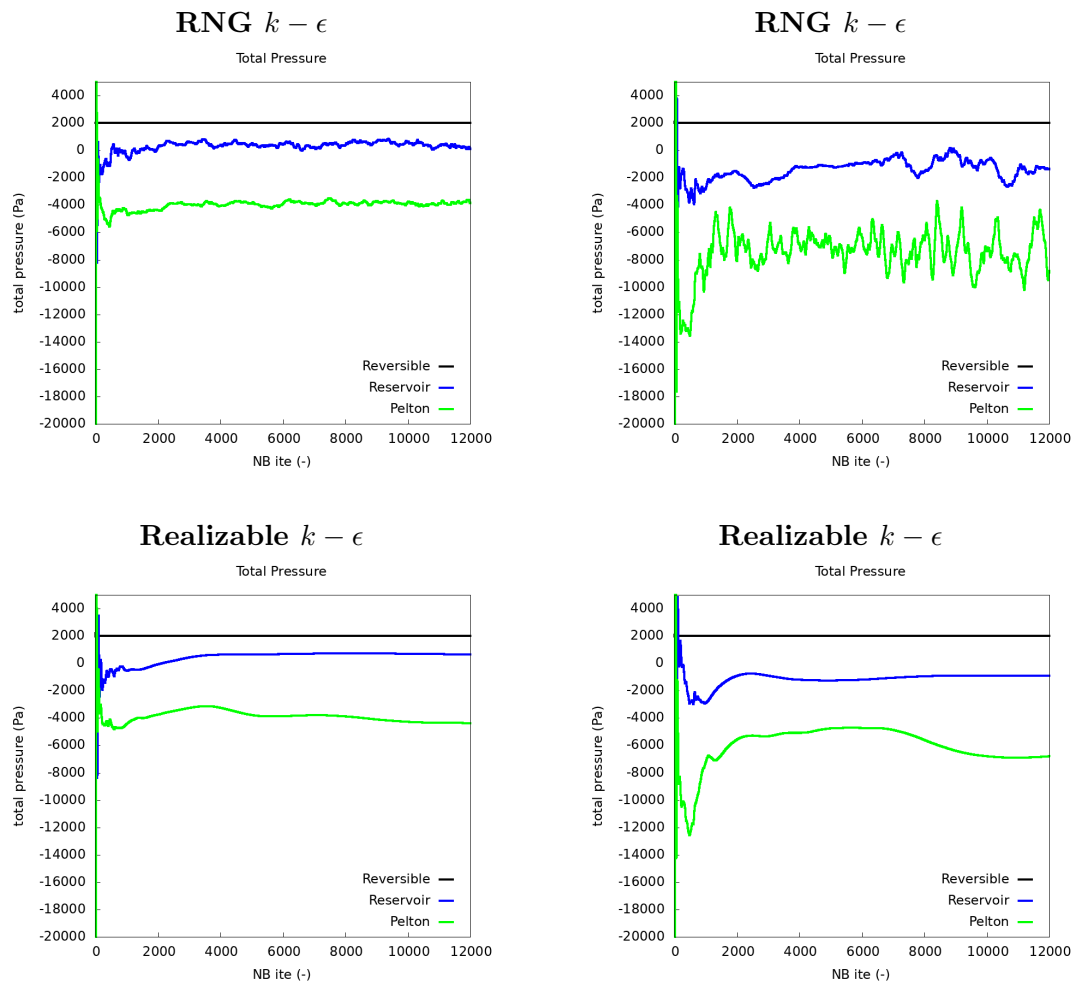
Figure 3. GM junction, mesh 2, evolution of the total pressure at the inlet and outlets of the computational domain for a discharge ratio $Q_T/Q_P = 0$ (left) and $Q_T/Q_P = 1$ (right).

the appendix) . The iteration-history of the area-averaged total pressure in each pipe, for simulations with the mesh 2, is shown on figure 3 for a discharge ratio of respectively 0 and 1. For a discharge ratio of 0, almost no oscillations are observed for both the RNG and the realizable $k - \epsilon$ turbulence models. For a discharge ratio of 1, the RNG $k - \epsilon$ turbulence model is characterised by large oscillations of the total pressure mainly in the pipe towards the Pelton turbines. On the contrary, the realizable $k - \epsilon$ turbulence model is almost stable.

The head-loss coefficients for each flow configuration and each turbulence model are plotted on figure 4. In overall, a qualitative agreement is observed between the simulations whatever the mesh, the turbulence model or the number of pump-turbines and Pelton turbines in operation. Discrepancies between the turbulence models reaches approximately 25% in two cases:

- for the head loss coefficient K_{PR} and a discharge ratio of 0.5. For a discharge ratio of 0.25, the difference is only observed with the mesh 1.
- for the head loss coefficient K_{PT} and a discharge ratio of 0.75. However, it is noticeable that the simulations using the refined mesh (mesh 2) predict a lower difference.

In addition, it is interesting to mention that the head losses in the junction due the operation in HSC mode represent less 0.5% of the total head of the power plant. By considering all the simulated points, a quadratic trend line has been derived for both head loss coefficients K_{PR}

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Figure 4. Variation of the head-loss coefficients K_{PR} (top) and K_{PT} (bottom) as a function of the discharge ratio Q_T/Q_P. Grand-Maison junction.

and K_{PT} with respectively a coefficient of determination equal to 0.93 and 0.89. However, a linear tendency for K_{PR} has also a coefficient of determination equal to 0.93.

The contours of the magnitude of the velocity field C in a x-y plane (see figure 5) show the pseudo-unsteadiness of the flow in the case of the RNG $k - \epsilon$ model compared to the realizable $k - \epsilon$ model. However, the contour patterns as well as the magnitude of the velocity are in overall the same between the two models.

The contours of the eddy viscosity μ_t in a x-y plane are plotted for three discharge ratio: 0.25, 0.75 and 1.25 on figure 6. Strong differences between the two turbulence models are observed even for discharge ratios for which the head loss coefficients are close. The realizable $k - \epsilon$ provides a higher value of the eddy viscosity for the discharge ratio of 0.25 et 0.75 by factor of 2 to 10 compared to the RNG $k - \epsilon$ model mainly in the pipe towards the reservoir. Another surprising feature is the clip of the eddy viscosity in the pipe towards the reservoir with the RNG $k - \epsilon$ model for the discharge ratio of 0.75. These differences should be related to the use of a non constant C_μ by the realizable $k - \epsilon$ model. Indeed, no differences (figures are not shown here due to a lack of place) have been observed in the turbulent kinetic energy k, the turbulent dissipation rate ϵ and the strain rate S quantities that are used in the formulation of the two models.

Based on the observations above, the level of the eddy viscosity does not have a strong influence on the head loss coefficients at least if the eddy viscosity is sufficiently high. This statement
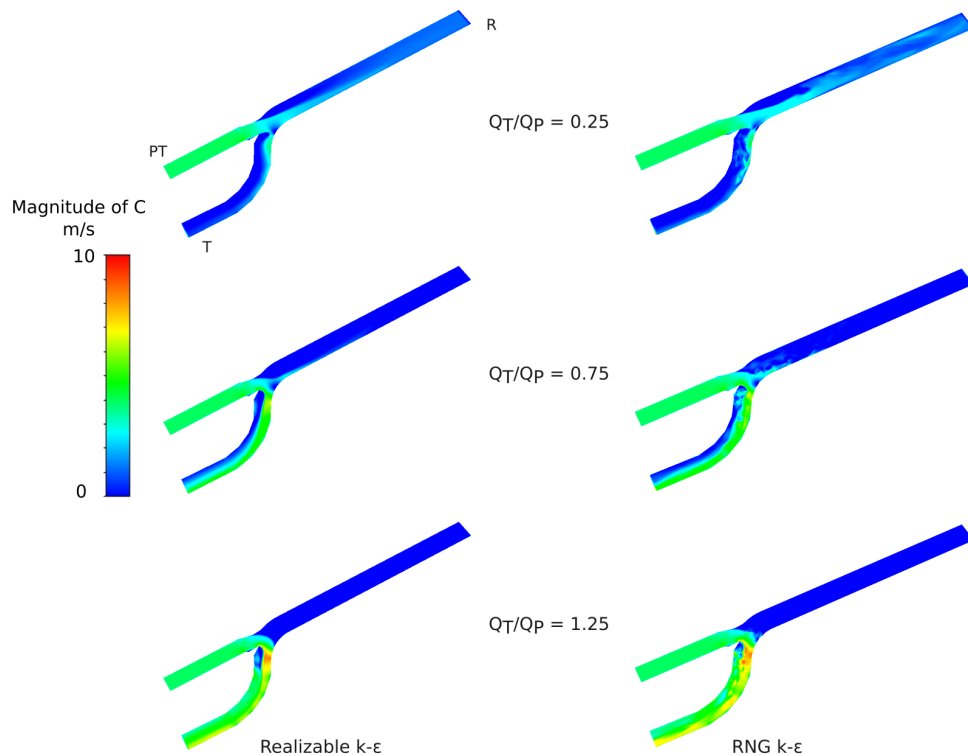
Figure 5. Contour of the magnitude of the velocity C in a x-y plane. Grand-Maison junction. Simulation on mesh 2.

has been confirmed by computing the flow without any turbulence model (laminar option is the Fluent solver), which leads for a discharge ratio of 0.75 to lower head loss coefficients by a factor 10 for K_{PR} and 2.5 for K_{PT}.

5. Conclusion

In the framework of the XFLEX HYDRO project, the implementation of the hydraulic short-circuit operating mode is scheduled on the Grand-Maison PSHP operated by EDF. Among the different tasks that need to be achieved before providing such a service, one of them focuses on the estimation of the head-losses in the junctions in HSC mode.

The assessment of the head-losses has been carried out by CFD analyses since on site measurement are too challenging. The methodology applied in the simulations have been validated successfully on a T-junction at 90 degrees for which algebraic formula derived from various experimental works are available. The simulations of the Grand-Maison junction have been carried out with two different meshes and two RANS turbulence models (realizable and RNG $k - \epsilon$). The results are consistent whatever the mesh or the turbulence models used and a global tendency for the head loss coefficients between on one hand the pump and the upper reservoir and on another hand the pump and the Pelton turbines have been derived. The losses in the junction represent less than 0.5% of the head and no unsteady phenomena has been observed. In addition, the number of pump-turbines and Pelton turbines that operate in the HSC mode has no influence on the dimensionless head-loss coefficients.

A deeper analysis of the results provided by the two turbulence models shows a strong difference in the eddy viscosity level, which can explain some discrepancies observed between them mainly for a discharge ratio of 0.5 and 0.75.
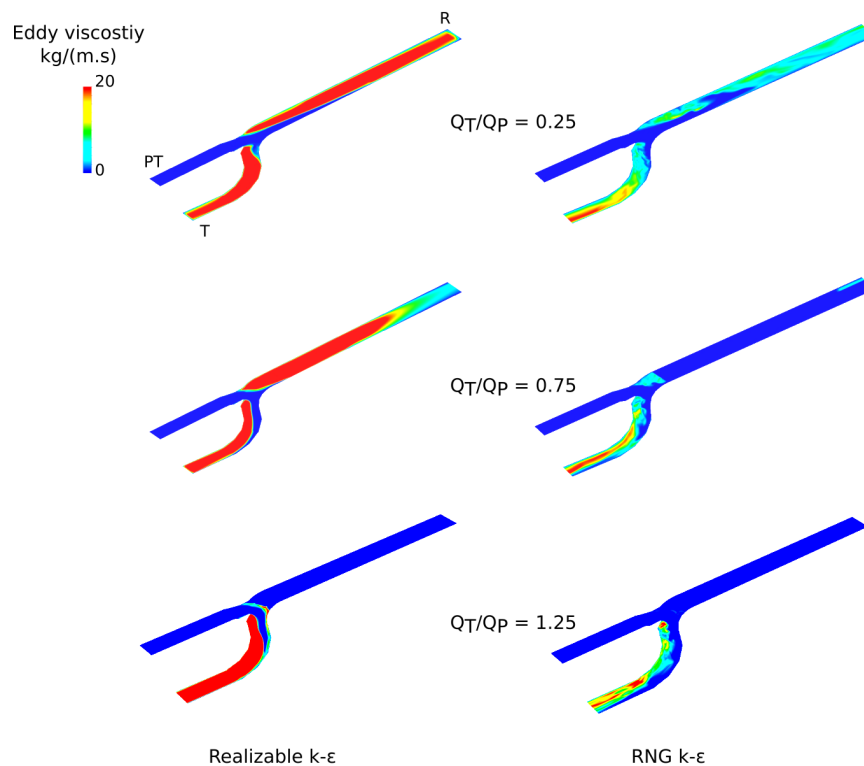
Figure 6. Contour of the eddy viscosity μ_t in a x-y plane. Grand-Maison junction. Simulation on mesh 2.

Appendix

An unsteady simulation with the RNG $k - \epsilon$ model on the mesh 2 and for a discharge ratio of 1 has bee carried out. The simulation has been run over 40 s with a time step set to 0.002 s, which required almost 10 more CPU resources than a steady simulation. The time-history of the area-averaged total pressure is displayed on figure A1. The head loss coefficients are computed by averaging the area-averaged total pressure over the last 20 s. The values for K_{PR} and K_{PT} are respectively of 0.343 and 1.184. Compared to the steady simulations the difference are lower than 10%, which is sufficient for the present test case since the losses are small compared to the available head. Therefore, the pseudo-averaging method used with the steady simulations is justified.
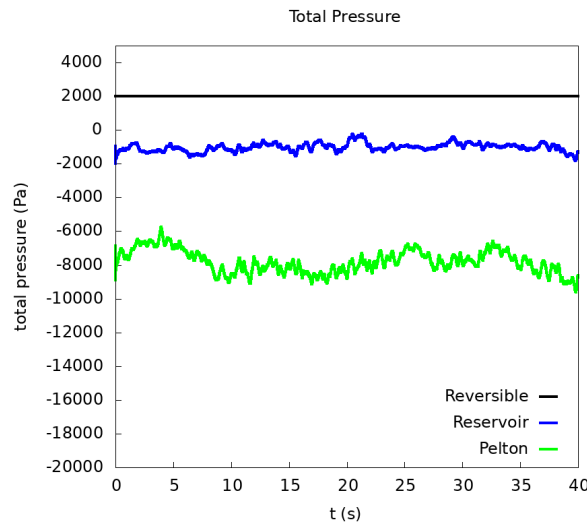
Figure A1. Time-history of the area-averaged total pressure at the inlet and outlets of the computational domain for a discharge ratio $Q_T/Q_P = 1$. RNG $k - \epsilon$ model on the mesh 2. Grand-Maison junction.

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