Numerical analysis of the behaviour of a Deriaz versus a Francis reversible turbine in terms of their energy efficiency and fish-friendly characteristics

I. Kassanos
National Technical Univ. of Athens
9 Heroon Polytechniou, 15780
Athens, GREECE

V. Alexopoulos
Drakos Polemis Pumps
Kryoneri, 14568
Athens, GREECE

J.S. Anagnostopoulos
National Technical Univ. Athens
9 Heroon Polytechniou, 15780
Athens, GREECE

Intro

This work investigates the capability of a Deriaz type hydroturbine to operate in both pumping and generating mode with high efficiency and improved fish friendly performance, compared to a similar reversible Francis turbine. Deriaz turbines could be used for pumped-storage power plants of small or large size, as they are applicable to a wide head and flow rate ranges. They can be installed in place of relatively low head reversible Francis turbines, where their double regulation capability would be advantageous in variable loading operation, in terms of energy efficiency. Moreover, the design of their mixed flow runner, with longer and smaller number of blades and smoother flow direction variations may be beneficial to passing fish.

The present work aims at the comparative investigation of a Deriaz and a Francis reversible turbine, regarding both their efficiency and impact on passing fishes mortality. The reference design of the two machines is determined based on literature data and preliminary numerical simulations, so as to be suitable to pump-turbine operation. Commercial CFD software is used for the numerical simulation and analysis of the flow in the reference design of a Deriaz and a Francis turbine, for both operation modes, assumed to be installed alternatively in a pumped-storage power plant of particular characteristics (hydraulic head, storage capacity, and operation program). Furthermore, a numerical model is developed in order to track the passing fish fauna through the pump-turbines and to estimate the impact of the flow characteristics and runner design on their survivability. This is carried out by monitoring the flow field properties (e.g. pressure variation rate, shear stresses, etc.) along a streamlined trajectory. The collected data are then used to quantify the probability of the injury/mortality of a passing fish, based on relevant biological indexes from the literature. The actual size (length) of a fish is also taken into consideration in order to estimate the blade strike probability.

The results show that the efficiency of the Deriaz turbine in full load conditions is similar to that of the Francis turbine in both operating modes, whereas its fish friendly behavior is better. These advantages become more substantial in partial load operation (whenever it is imposed or allowed), and hence the Deriaz turbine may be considered as a promising alternative for such units, especially when the injury and fatality of the passing fish passing is an important environmental issue.

1. Background

The turn to a decentralised energy model and the increase of renewable energy sources with increased intermittency in the power generation mix, poses a great challenge for the stability of the electricity network. Pumped storage installations can provide an important solution allowing the mass deployment of intermittent renewable energy stations while maintain grid flexibility and provide fast response services. Furthermore, the development of micro or small scale grid applications, such as in non-interconnected islands is becoming increasingly important [1]. Especially in islands where increased wind potential may be present, the installation of new wind turbine capacity may only be financially justified when combined with an energy storage system [2]. In small scale applications, utilizing the potential from small rivers, creeks or canals, large variability of the hydraulic conditions may be observed. This poses a challenge in the performance characteristics of the hydraulic machinery, which are designed to operate at specific hydraulic conditions. In small scale pump storage installations, variable operation and flexibility may be even more important due to limitations imposed by available storage capacity. Reversible pump-hydroturbines of are used in many pumped storage plants due to the lower construction and installation cost compared to ternary sets (separate pump and turbine). However, the operation range, overall efficiency and flexibility of the former solution is inferior.

On the other hand, a significant envrinmental impact of conventional hydraulic machinery is the increased fish mortality [3]. Several studies in the past have focused on the determination of the effects on fish passing through hydraulic machinery, and the identification of the various injury and mortality mechanisms [4-8]. Recently, numerical tools have been employed to assess the biological performance of hydraulic turbines and allow the design of turbines with efficient operation, and at the same time, increased fish friendly characteristics. These tools can be used in the early stages of the turbine/pump design, even with simplified models suitable for industrial usage [9-12]. By utilizing these numerical tools and incorporating fish friendly metrics and analyses during the design stages of new hydroelectric equipment, it is possible to evaluate the fish friendly characteristics and determine the relative effect on environmental performance of design modifications.

The Deriaz turbine is an alternative reaction type turbine, with double regulation, similar to a Kaplan machine. It typically consists of a spiral casing and a distributor to control the runner inlet conditions and power output. The rotation of the runner blades allows the operation of the turbine at extended operating conditions with high efficiency [13], while improved part load characteristics are also observed [14]. Since it was initially proposed, the Deriaz turbine has been installed predominantly in pump-storage applications, with numerous installation between the 50s and 60s. However, the complexity of the mechanical design regarding the double regulation, the ascociated higher costs and the proven reliability of other reaction turbines have hindered the mass deployment of the Deriaz turbine. Recently, the increasing importance of flexible turbine operation combined to the inherent advantages of the Deriaz turbine, have lead to a renewed interest in ths type of turbine. However, very few studies can be found in the literature where numerical tools have employed for flow modelling and performance analysis of these machines [1, 15-17]. Moreover, their environmental performance has not yet been studied. In the present work, such numerical tools are used to evaluate and compare the hydraulic and fish friendly performance of a Francis turbine and a Deriaz turbine, for the same operating conditions.

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2. Methodology and Case study

2.1 Indicators for passing fish injury/mortality

In order to compare the fish friendliness of Francis and Deriaz reversible machines, the two most important biological performance indicators are used in this study: barotrauma and shear stress, which quantify the probability of exposure a passing fish to injury. The fish collision with the rotating blades is also taken into account.

The probability of fatal injury of a fish due to a abrupt decrease in static pressure along its trajectory (barotrauma) is expressed by the LRP index [23], defined as the logarithm of the ratio of the acclimation pressure, p_a, of the fish to the minimum static pressure, P_{min}, that it will encounter inside the machine.

$$LRP = ln\frac{P_a}{P_{min}} \tag{1}$$

As it has been found, this is the most crucial variable (versus, for example, the rate of pressure reduction) for the effect of the pressure field formed in the turbomachine on the viability of the passing fish [8]. The probability of fatal injury of a fish due to a sharp decrease in pressure can be estimated by empirical relationships [8]. Here, in order to make a comparative evaluation of the two hydraulic turbomachines, a minimum static pressure value threshold was used for both cases. The volume of the flow field enclosed by this iso-pressure surface is a fish impact indicator. A similar, more representative indicator could be the percentage of fish trajectories passing through this low-pressure volume.

The high values of shear stresses that develop in hydrodynamic machines can also cause injury to a passing fish [4]. The shear stress acting on a fish is analogous to the local fluid velocity gradient and local viscosity, which depends mainly on the fluid turbulence intensity (turbulent viscosity). As with the low pressure region, a flow volume can be defined here, which is enclosed by the 3D iso-surface of a threshold shear value.

The most dangerous moment of fish passage is when they enter the rotating runner, where their collision with the blades leading edge is usually fatal. This probability can be approximated by the Von Raaben's deterministic model:

$$P_{bl} = \frac{l \cdot cos\theta \cdot N \cdot n/60}{V_n} \tag{2}$$

where l is the fish length, N the number of blades and n the rotation speed (rpm) of the runner, V_n is the flow (and, approximately, the fish) velocity component perpendicular to the inlet surface of the runner, and θ is the angle between V_n and total velocity, V (Fig. 1a). It can be observed the the value of cosθ maximizes in pump operation, when the flow enters the runner without rotation ($\theta \approx 0$).

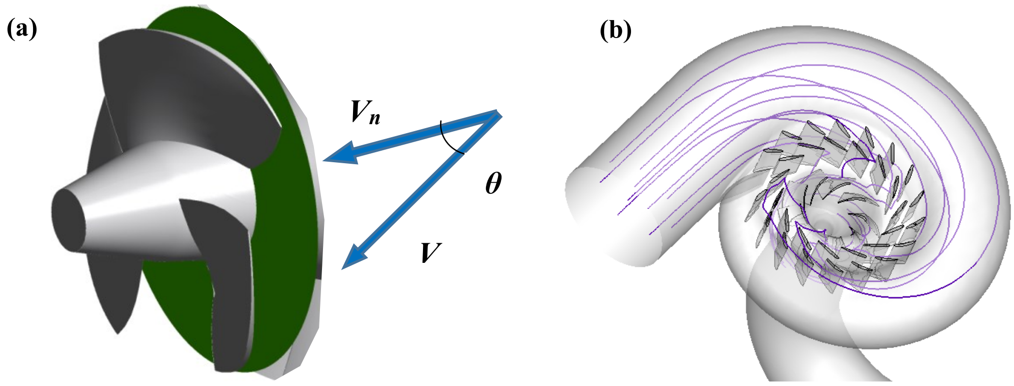

Fig. 1. Variables of Von Raaben relation (left), and indicative particle trajectorie in a turbine (right).

In the present study all the above indicators are computed by tracking of a statistically adequate number (of the order of 10^4) of flow particles in the flow field obtained by numerical simulation, starting from different points, evenly distributed at the entrance section of the machine (Fig. 1b). The results of Von Raaben relation are given here for a reference fish size (length) of 20 cm.

2.2 Flow modelling

The 3-dimensional computational domain considered in this analysis consists of the spiral casing, distributor, runner and suction/discharge cone. The same spiral casing, wicket gate and cone was used for both turbines to evaluate the effect of the different runner type at similar operating conditions, in turbine and pump mode.
The numerical grid (Fig.2) contains approximately 7.9 mil. tetrahedral cells in both cases.

The commercial code Ansys Fluent™ is used to solve the incompressible RANS equations using the k-ω sst turbulence model. The flow equations were solved in a coupled manner, while a second order discretization in space was employed. The numerical simulations were carried out at the design flow, as also at off design conditions using the Moving Reference Frame (MRF) model [18]. Specifically, in turbine operation, the inlet velocity is prescribed correspondingly to the design flow rate and inlet velocity triangle, while a zero pressure boundary condition is applied at the outlet. On the contrary, in pump operation the rotational speed of the runner is reversed, a zero pressure boundary condition was applied at the inlet, and a mass flow boundary condition at the outlet of the computational domain. Based on the applied boundary conditions, the hydraulic head in both pump and turbine operations is a result of the computation. Finally, a no-slip boundary condition is applied on all internal walls.

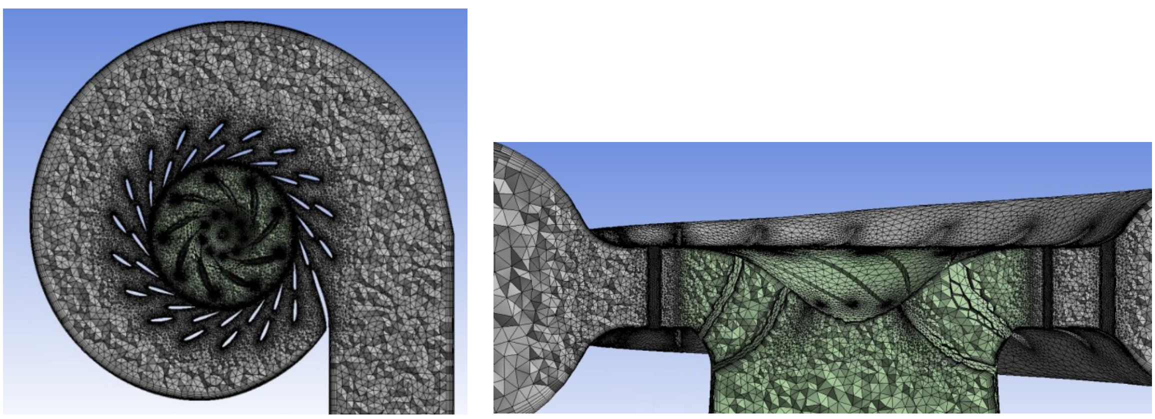

Fig. 2. Pictures of the computational mesh used for the simulations.

2.3 Case study

The geometry of the two runners studied in this work is shown in Fig.3, and the main dimensions are summarised in Table 1, along with the design conditions. The Deriaz turbine runner is comprised of 5 blades, while 9 blades are used in the Francis turbine runner. Typically, the number of runner blades in Francis turbines is selected between 9 and 17 blades, depending on the specific speed of the turbine and cavitation considerations [19]. Similarly for Deriaz turbines, the number of runner blades ranges between 5 and 12 blades [20]. Reducing the number of blades increases the pressure differential between the pressure and suction sides of the blade making the runner susceptible to cavitation, and at at the same time the structural integrity of the runner blades may be also compromised. On the other hand, however, with increasing number of blades the flow blockage and friction losses are increased. The number of blades is selected here so as to minimise the fish strike probability (Eq. 2), and at the same time to allow for efficient energy exchange. For a fair comparison, the blades of Deriaz rotor are considered fixed, like Francis.

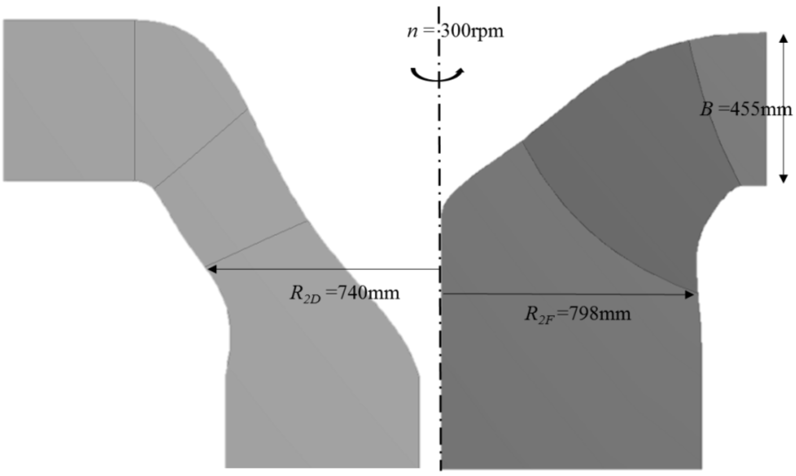

Fig. 3. Comparative meridional view of the two machines: Deriaz (left) and Francis (right).

Table 1. Main characteristics of the reversible machines.

	Francis	Deriaz
Rotor radius, R_2 [mm]	798	745
Guide vanes height, B [mm]	455	455
Number of blades, N [-]	9	5
Rotational speed, n [rpm]	300	300
Turbine head, H_T, [mwc]	27.5	27.5
Turbine flow rate, Q_T [m^3/s]	12.4	12.4
Pump flow rate, Q_p [m^3/s]	10.5	10.5

3. Results and discussion

3.1. Machines performance

The characteristic performance curves of the two machines in both turbine and pump operation are produced by the numerical simulations at the design points and at some off-design operation conditions, and they are plotted in Fig. 4. The H-Q curves in Fig. 4a coincide at the design point of turbine operation (Table 1), according to the adopted procedure for reversible operation modelling, whereas the slope of the Deriaz curve is higher and leads to smaller head at partial load operation.

In pumping operation, Deriaz machine exhibits lower head in the entire range (Fig. 4c), which it is further reduced at low flow rates, like in high specific speed, mixed flow pumps. On the contrary, the Francis pumping head keeps increasing at reducing flow rate, as in lower specific speed pumps. However, this deficiency of Deriaz at part load conditions is due to the non optimum angular position of its rotor blades, and can be alleviated in the entire range thanks to the capability to regulate these blades as well, which is not applied here.

The pattern of the corresponding hydraulic efficiency curves of the two machines are quite more similar (Fig. 4b,d). In turbine operation (Fig. 4b) the maximum attainable efficiency of Deriaz turbine is higher (~89% compared to ~83% of Francis). However, Francis turbine exhibits maximum efficiency at higher discharge rates (~85%), where it can become more efficient than Deriaz (Fig. 4b). On the other hand, Deriaz is much more efficient at the design point of pump operation (Fig. 4d), whereas this advantageous performance is eliminated at off design conditions (Fig. 4d). It must be noted here that the geometry of of both machines is obtained by one-dimensional hydraulic analysis, and it is not numerically optimized. For this reason, the attained efficiencies, especially in pumping mode, are not quite high for that size and type of hydraulic turbomachines.

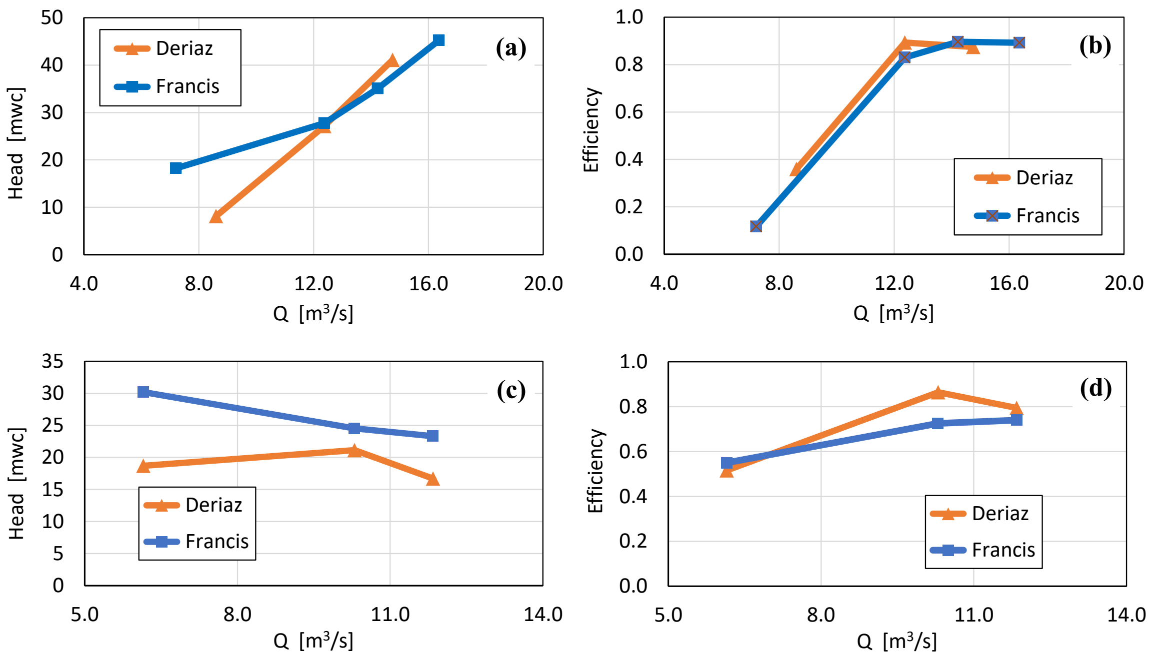

Fig. 4. Characteristic operation curves of head and efficiency for turbine mode (a,b), and for pump mode (c,d).

3.2 Fish-friendly behaviour

Regarding the environmental performance of the two machines, the following Figure 5 shows the iso-surfaces that enclose the regions of their flow volumes, where the static pressure is below the threshold value, set here at minus 10000 Pa (gauge). In both operation modes the low pressure region is formed on the same side of the rotor, at the exit for the turbine and at the inlet for the pump (Fig. 5). The so-formed volume looks larger in Deriaz than in Francis turbine mode (Fig. 5a,b), whereas the opposite is valid in pump operation (Fig. c,5d). The corresponding quantitative results in Table 2 show that the percentage differences are even higher in turbine mode, and smaller in pump mode, because of the larger volume of Francis rotor. On the other hand, the results in Table 1 indicate that the fraction of particle trajectories entering these volumes is rather analogous to the volumes themselves, than to the volume percentages.

The high shear stress regions in the machines are plotted in Figure 6. Here the threshold value is 600 Pa, and it can be observed that for turbine operation (Fig. 6a,b) the high shear volume in Francis turbine is much larger than that in Deriaz (the black cylindrical surface shown in Deriaz is the shroud boundary layer, with very small width). The high shear regions are smaller in pump operation (restricted mainly to the shroud layer), and comparable among the two machines (Fig. 6c,d). The corresponding numerical data in Table 2 confirm that in turbine operation the high shear volume and the particle trajectories passing through it are much higher in Francis turbine. Concerning the pump operation, these values are too low for both machines, and for this reason the data in Table 2 are obtained and given for a lower shear threshold of 115 Pa, in order to facilitate their comparison, and show that they are similar for both machines.

Considering that a reversible machine used for pure pumped storage will operate for similar periods as pump and as hydroturbine, its mean environmental performance can be assessed by averaging the fish impact indicators in both operation modes, or in a complete storage-production cycle. These results are also presented in Table 2, showing that the two machines have comparable behavior regarding both barotrauma and shear forces indicators.

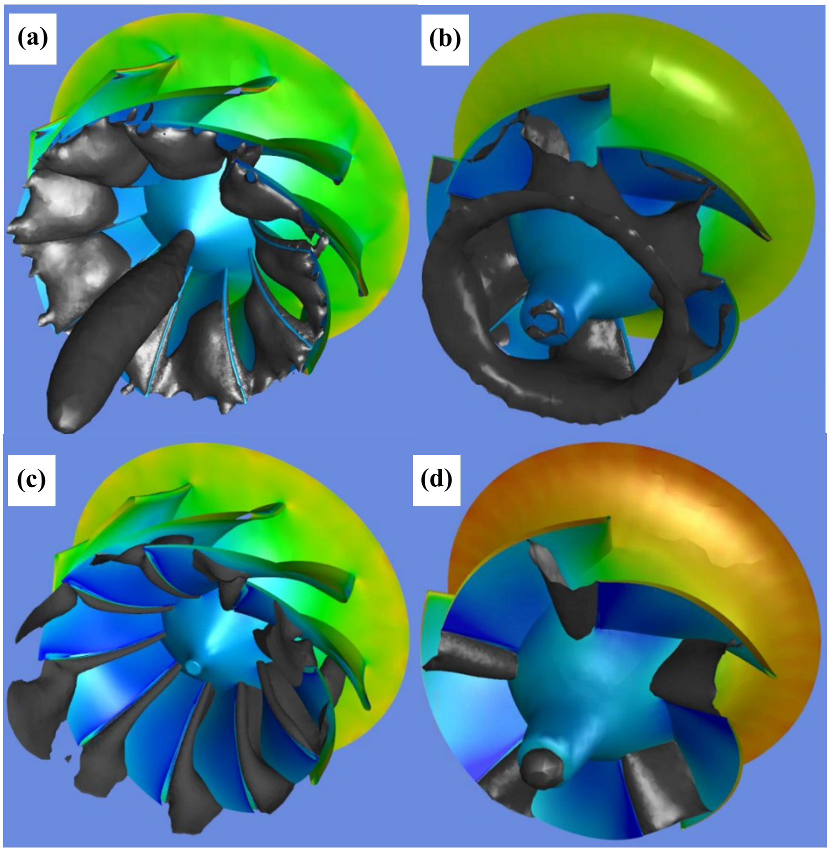

Fig. 5. Low pressure volumes in turbine (up) and in pump (down) operation, for Francis (left) and Deriaz (right).

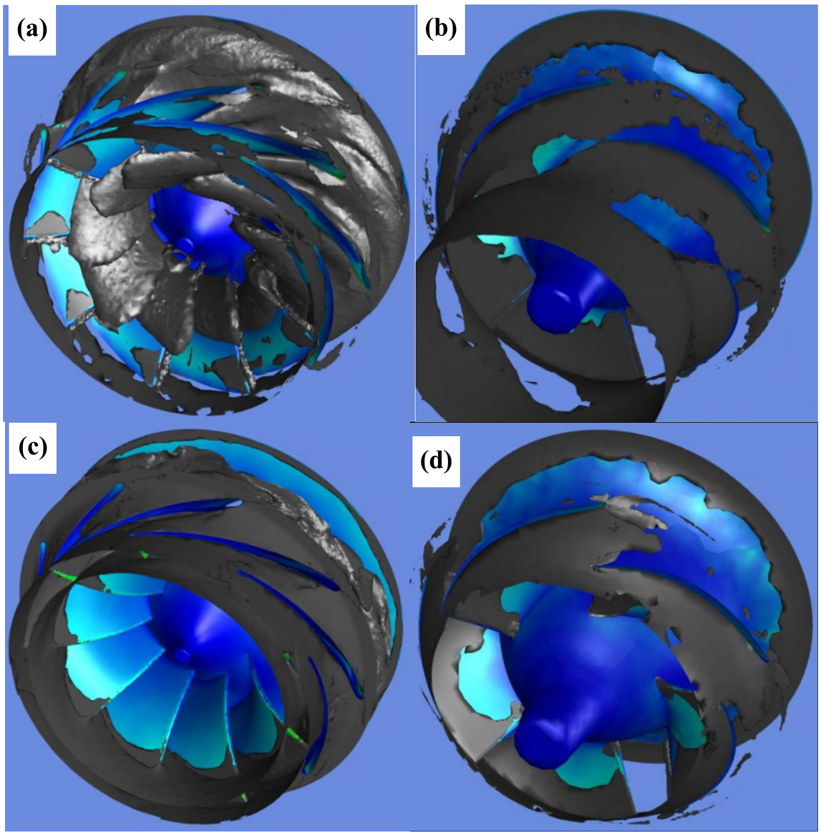

Fig. 5. High shear volumes in turbine (up) and in pump (down) operation, for Francis (left) and for Deriaz (right).

However, the third performance indicator, the probability of fish strike on the rotating blades, exhibits more pronounced differences. The results in the the last row of Table 2 show a clear superiority of Deriaz machine, that achieves quite lower strike probabilities in both turbine and pump operation mode. This is the mainly due to the smaller number of blades of this machine, that makes it more friendly than the corresponding Francis machine to the passing fish fauna, considering moreover, that such strikes are usually fatal.

The average strike probability during a storage cycle in Deriaz is almost half than in Francis machine (Table 2), and, according to Eq. (2), this analogy should be retained regardless the size (length) of the passing fish. The same is expected to apply for other off-design operation conditions of the machines. In the usual cases of part load operation, the barotrauma and shear conditions become milder due to the reduced flow velocities, but for the same reason, the strike probability increases, making the advantage of Deriaz turbine more important.

Table 2. Computed fish injury/mortality indicators of Deriaz and Francis machines.

	Turbine mode		Pump mode		Average	
Indicator	**Deriaz**	**Francis**	**Deriaz**	**Francis**	**Deriaz**	**Francis**
Low pressure volume (m^3)	0.345	0.225	1.374	3.123	0.860	1.674
Low pressure volume (%)	12.7	5.0	50.6	70.0	31.6	37.5
High shear volume (m^3)	0.034	0.680	1.327	1.361	0.680	1.02
High shear volume (%)	1.2	15.2	48.8	30.5	25.0	22.9
Total numner of streamlines	17436	22724	21368	29494	19402	26109
Streamlines in low pressure (%)	9.4	5.7	36.5	53.9	22.9	29.8
Streamlines in high shear (%)	0.5	12.9	52.9	35.5	26.7	24.2
Blade strike probability (%)	**30.7**	**49.8**	**29.8**	**76.7**	**30.3**	**63.3**

4. Conclusions

In this work, numerical modelling of the flow and performance characteristics of two reversible pump-turbines of different type, Francis, and Deriaz, is carried out for the same operation conditions, in order to compare their energy efficiency and possible impact on passing fish fauna.

The results showed that the two machines can attain high and comparable hydraulic efficiencies in both pump and turbine operation mode. Similar are also their indicator values for barotrauma and shear stress injure probabilities of passing fish. However, the Deriaz turbine exhibits about half probability of fish collision with the blades leading edge. This provides a clear advantage to this machine type for being used in sites where fish protection is important. Moreover, the double regulation feature of Deriaz, which is not used in the present work, can make it more competitive for pumped storage applications also in terms of overall energy efficiency.

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The Authors

I. Kassanos graduated in Mechanical Engineering from the National Technical University of Athens. Greece. and has and MSc in Energy Conversion and Management from the University of Nottingham. He works with a UK hydroturbines manufacturer and he is completing his Ph.D. in numerical design of reaction hydroturbines at the Laboratory of Hydraulic Turbomachines. NTUA. He is experienced in CFD simulation. performance prediction. fluid structure interaction and design optimization of reaction turbines and their components. as well as in field measurements and Laboratory testing of hydraulic turbines.

V. Alexopoulos studied Electrical & Electronic Engineering and graduated as a Control Engineer from the University of East London. U.K. He works for more than 16 years in pumps and electric motor industry expertized in manufacturing. He participated in the EU-National research project "Manufacturing. connection & improvement of an electric motor suitable for dry or submerge operation of Sewage Pumps". He also researched in the field of Merchant Ships roll stabilization systems. by designing a fin controller using pole assignment and robust control techniques. He is experienced in Finite Element methods and in electric motors. generators and pumps testing techniques.

I.S. Anagnostopoulos graduated in Mechanical Engineering from the NTUA. Greece. and received his Ph.D. in Computational Fluid Mechanics. He worked for several years as post-doctoral researcher in the NTUA and as R&T consultant in the private sector where he has been involved in feasibility studies for various industrial innovations. He has participated in more than 40 research projects. and has more than 120 scientific publications in international journals and conferences. Also. he has developed advanced computer codes for the simulation of various fluid flow mechanisms in industrial applications. as well as for modelling and optimisation of the design and operation of hydroelectric and hybrid energy systems with pumped storage. He is Director of the Laboratory of Hydraulic Turbomachines. School of Mechanical Engineering. NTUA. and his current research activities include the numerical and experimental flow analysis and hydrodynamic design in pumps and hydroturbines.