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Research Article

Vortex breakdown in discharge cone of the Francis Turbine

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Abstract: Hydraulic turbines are usually operating at high efficiencies around 90%. It is possible to increase the efficiency by preventing flow characteristics such as failure, cavitation and vortex rope in the draft tube. In some cases, such as partial loads or overloads, pressure pulsations and vortex rope would occur in the draft tube. These undesired events would damage the components of the turbine and that also causes the efficiency to decrease. To eliminate these artifacts, it is decided to design a new component. Vortex Preventing Element, which is designed to eliminate vortex structures and pressure fluctuations, is located at the inlet of draft tube. Computational Fluid Dynamics analyses are performed for different designs having several stage numbers of vortex preventing elements. The preliminary results showed that the one stage vortex preventing element design creates more uniform flow in the draft tube and also increases the efficiency about 3%. Since more studies about the vortex preventing element are in progress, it could be said that the vortex preventing element can handle vortex phenomena in the draft tube and effects the efficiency of the Francis turbines.

Keywords: *Computational fluid dynamics, Francis turbine, Turbulence, Vortex preventing element, Vortex rope*

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Nomenclature

Abbreviations	*Descriptions*
VPE	Vortex Preventing Element
η	Efficiency
T	Torque
ω	Angular velocity
ρ	Density
g	Gravitational acceleration
Q	Discharge
H	Head

1. INTRODUCTION

Increasing energy demands of countries are enhancing the importance of renewable energy. Since renewable energy resources do not cause greenhouse gas emission and environmental pollution, they are often preferred to meet these energy demands. Due to its high potential and efficient convertibility, hydraulic energy is one of the most common type in use all over the World. Francis turbines are often favored among hydraulic turbines to use in hydroelectrically power plants. Francis turbines is generally operating with the efficiency about 90% or above as mentioned in most studies. However, it is possible to increase the value by preventing some flow phenomena such as partial loads, cavitation and vortex rope that occur in the draft tube. These undesired events would damage the components of turbine and also cause the efficiency to decrease, thereby, researches focused on diminishing some undesirable events that occur in Francis turbine components while operating.

Anup et al. [1] obtained that a swirling component occurred due to runners rotation and they investigated the vortex phenomena on draft tube's entrance in terms of different turbulence models and they revealed that when Francis turbines were operating at partial loads, swirling component of the runner outflow occurs at the outlet section of the runner. The pressure fluctuations and flow irregularities were formed at the runner outlet due to this swirling flow. The pressure fluctuations caused to a vortex rope formation take place at the inlet section of the draft tube and generates deformations on torque, axial force and radial force, consequently. The vortex rope also causes vibration, noise and wear on the mechanics of turbine. For instance, Kurokawa and Imamura [2] studied the vortex formation and preventing the vortex structures in draft tube by using j-grooves and inducer. At partial loads, it was seen that j-grooves and inducer provided a better performance for suction sides of runner blades. The swirling flow was eliminated by controlling the angular momentum of flow by using the hollows named j-grooves. The j-groove structures were also explored by Wei et al., [3] and Chen and Choi [4]. It was observed that the structures decreased the quantity of vortex structures. The jet effect of these j-grooves caused to decrease circumferential velocity component and diminishes some of vortex structure. Experimental and numerical studies were performed and it was determined that the j-groove structures partially eliminated the vortex rope formation, but there was no effect of these structures on turbine performance. Two types of pressure fluctuations, namely *synchronous* and *asynchronous* were declared by Nishi and his colleagues [5]. Due to their experimental studies, they found that draft tube elbow caused to asynchronous fluctuations to occur in a straight draft tube. In a different work, Stuparu and Susan-Resiga [6] claimed that it was inevitable that pressure pulsations caused vortex rope to occur. Numerical studies performed by them showed that the pressure pulsations were not related with the interaction between vortex rope and draft tube elbow. Muntean et al., [7] studied pressure fluctuations caused by swirling flow in a draft tube. Experimental studies, Fourier spectrum of measurements which were received from several sensors that located in draft tube and numerical studies also performed. As a consequence, it was seen that RNG k-ε and SAS k-ω models were better turbulence models to reveal vortex formation at the draft tube inlet. Susan-Resiga [8] and Zhang [9] revealed some crucial points on identifying the vortex control technique. The technique showed why the vortex phenomena occurred and the control technique affected. Finally, it was located at the entrance of draft tube and the stagnant pressure area had to be aimed at the middle of the draft tube with no decreases on efficiency. Water jet technique was used to investigate the effect on vortex rope by Foroutan and Yavuzkurt [10] with DES model. As a result, they declared that the pressure pulsations at the draft tube can partially controlled with water jet technique. Injecting air bubbles was an another technique, which was used by Dias and Riethmuller [11] to eliminate the stagnant flow at the draft tube inlet. Particle Image Velocimetry (PIV) was used to observe vortex formation. It was seen they stagnant area could partially controlled. PIV was also used by Iliescu, Ciocan and Avellan [12] to obtain cavitating vortex rope occurring due to runner blades with constant slope angle. The formation of runner blades caused to vortex rope phenomena, which affected the turbine efficiency and mechanical endurance of components. It was proven that many researchers had approached the undesirable vortex rope and pressure fluctuations events in different design methodologies. For instance, Juposhti et al., [13] investigated the rotating vortex rope mitigation using the water injection method and they calculated the required axial momentum flux of water injection for a stable swirl number. The results showed that pressure recovery of the draft tube improves and water jet with a large radius and low velocity was more effective on mitigating vortex rope. Cheng et al., [14] studied the cause of many undesirable system instabilities for hydraulic power stations. They obtained that an obvious vortex rope could be observed at a point and produces the most intensive pressure fluctuations. Due to their experimental and numerical results, they defined new parameters to evaluate the vortex strength. Besides, Yu et al., [15] investigated the evolution of the vortex rope and its association with the low-frequency pressure fluctuations under typical conditions. As a result, they stated that if there was no cavitation in the draft tube, the main reason of pressure fluctuations was vortex structures and the vortex rope behaved as a spiral vortex under partial load condition. At design condition, it behaved as a slender column and pear shaped under full load conditions. Laouari and Ghenaiet [16] studied steady and unsteady cavitation flows through a small Francis turbine and they showed that the partial-load operation gave a rise to undesired phenomena of pressure pulsations due to the vortex rope generated at the runner outlet. Moreover, the pressure fluctuations and the torque oscillation seemed to be more pronounced at partial-load and over-load operating conditions.

The scope of the study is to reveal a new component called the Vortex Preventing Element (VPE), in order to prevent these pressure fluctuations, which are commonly based on swirling flow and vortex formation in the draft tube. Since the vortex formation generally occurs as spiral shaped rope, the main idea to prevent this formation is to deform the rope by facing it to another spiral formation on the opposite direction.

2. METHOD

A new concept is revealed [17] for damping the swirling effect of runner outflow. It is considered that damping effect will prevent the low-pressure regions occurring at draft tube inlet. By preventing these low-pressure regions and stagnant regions, the flow will follow uniform streamlines and as a consequence, the performance of suction sides of the blades will increase. Three configurations are specified to determine the effect of the VPE on Francis Turbine performance:

1) *Design without the VPE,*
2) *Design with one staged the VPE,*
3) *Design with two staged the VPE.*

Models of one and two staged VPE are shown Figs. 1 and 2. The Francis turbine has five components so-called spiral case, stay vanes, guide vanes, runner and draft tube.

The VPE is mounted between the runner outlet and draft tube inlet (Figs. 3 and 4). This new component may generate a resistance to swirling flow that occurs at runner outlet. Since the swirling flow causes performance decreases on suction side of Francis turbine blades, it is thought that VPE brings additional increments on turbine performance and efficiency. For this concept, a spiral structure having opposite helical direction with respect to swirling flow is considered. To see the effects of the helical path on the turbine performance one and two stages VPE are used. The height and width of the vortex preventing elements remain constant, while the number of helice and helicel path’s form may change.

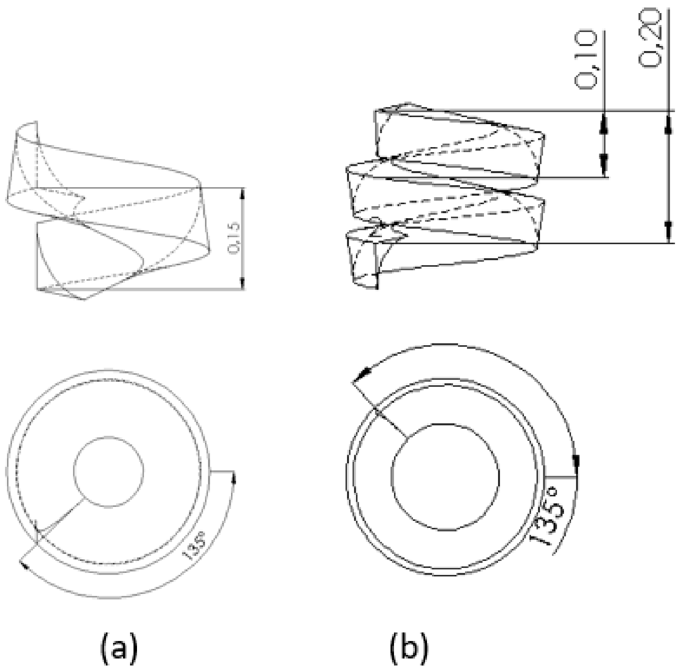

Figure 1. Dimensions of one and two staged VPE.

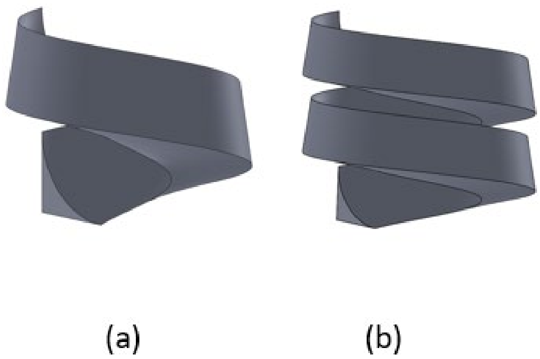

Figure 2. 3D models of one and two -staged VPE.

Since Computational Fluid Dynamics (CFD) is one of the most common tools of performance analysis in terms of low CPU and low time costs, a CFD study is performed for three cases outlined above.

Table 1. Mesh details.

No	Element	Mesh Number (in millions)
1	Spiral Case	2.5
2	Stay Vanes	2
3	Guide Vanes	4.4
4	Runner	8.5
5	VPE	1
6	Draft Tube	1.5

Realizable k-ε is used as turbulence model for its robustness. Mass-flow inlet and pressure outlet is specified at spiral case inlet and draft tube outlet respectively. ANSYS Mesher is used to generate mesh structures of components. Computational domains are given in Figs. 3 and 4.

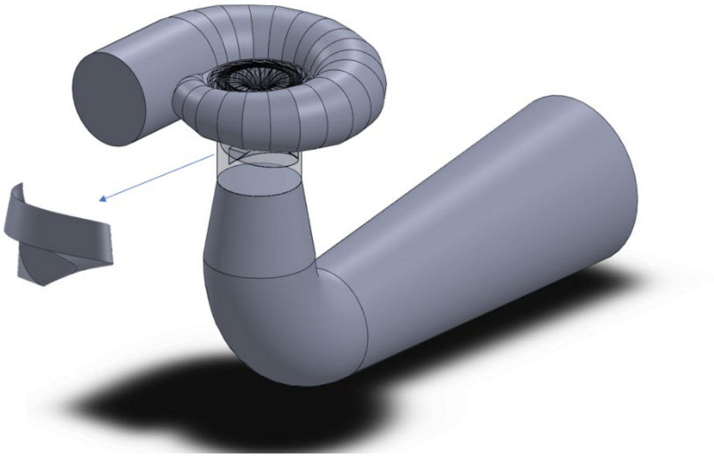

Figure 3. Numerical fluid domain of the Francis turbine having a VPE with one stage.

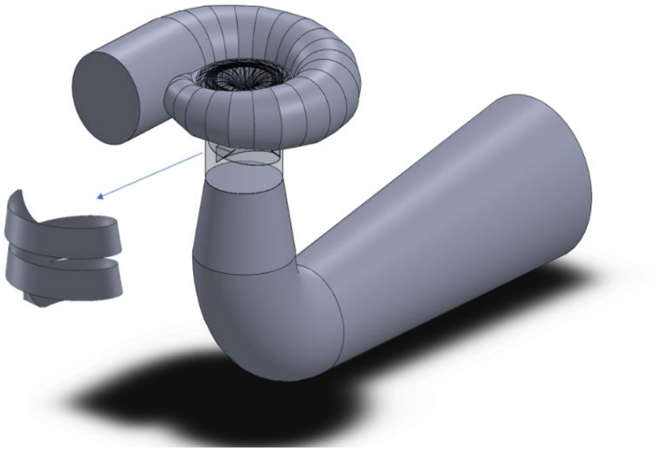

Figure 4. Numerical fluid domain of the Francis turbine having a VPE with two stages.

All components are meshed separately and then combined and solved in ANSYS CFX by using some approaches. Mesh details are given in Table 1.

Table 2. Boundary conditions for the simulations.

Boundary Condition Type	Location
Mass Flow Inlet	Spiral Case Inlet
Static Pressure Outlet	Draft Tube Outlet
Multiple Reference Frame	GV-Runner Interface & Runner-Draft Tube Interface
Generel Grid Interface	Other Stationary Element Interfaces

As a consequence of scaling process, a discharge flow rate is extracted from equations and this value is determined as inlet boundary condition. Since the opening of draft tube is interferes with water channel, it is assumed that pressure equals to atmospheric pressure 1 atm, thereby, the outlet boundary condition is specified for the model. The mesh independency is applied for the study and it is seen that after 20 millions elements, study becomes mesh independent. Thus, hexahedral and tetrahedral elements are used and inflation layers are generated for runner and guide vanes. MRF and GGI approaches are used in CFX to define rotation. Mesh structures of components are given in Fig. 5.

Each of the Francis turbine components is individually meshed. The reason is the complex geometries in stay vanes, guide vanes and runner blades so that that will increase skewness value in a single mesh structure. In addition, skewness value and aspect ratio value controls are applied in the created mesh structure. The $y+$ value for the model is also found to be 116, and this value varies between 50 and 130 in similar studies. In our case, this value is found to be appropriate.

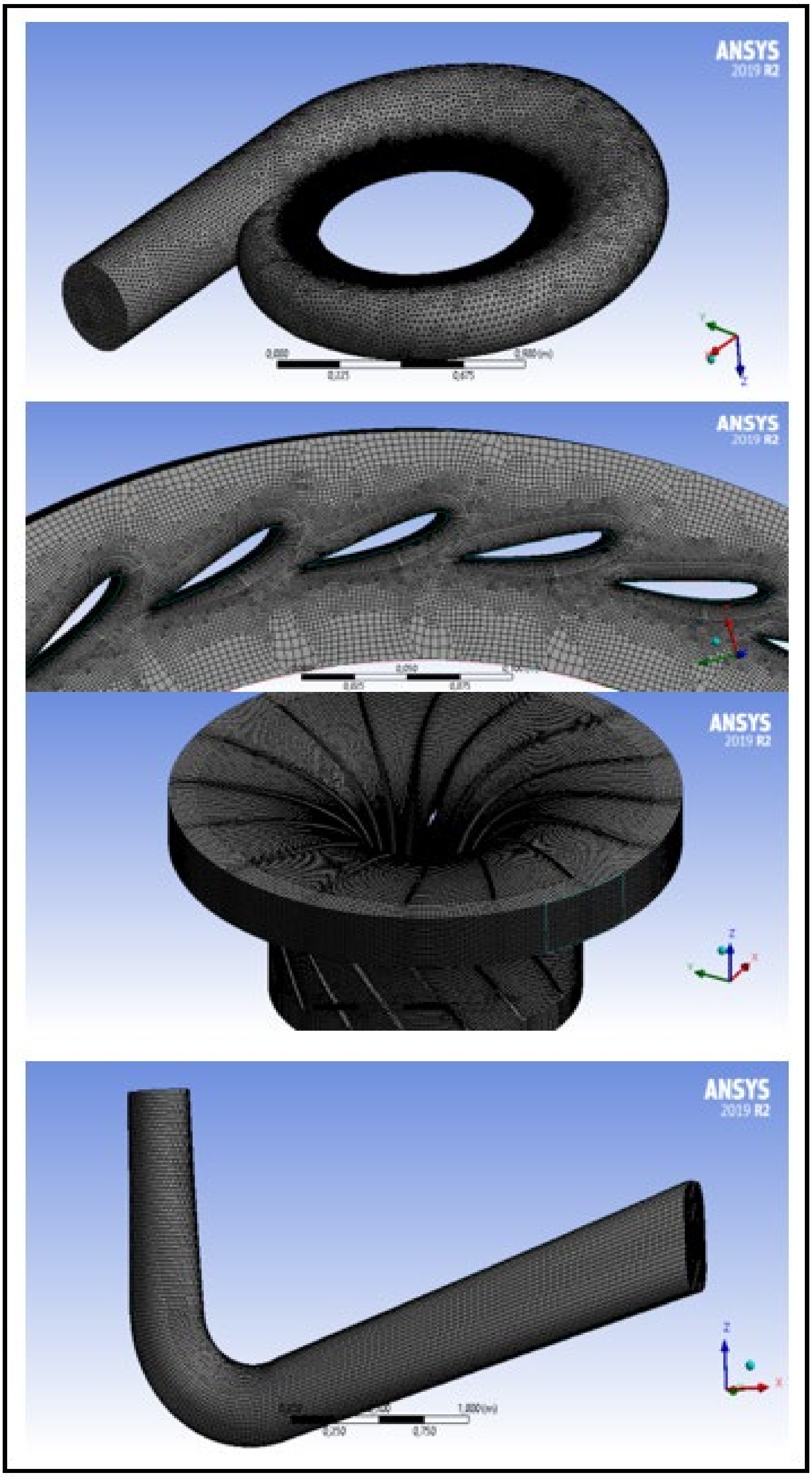

Figure 5. Mesh structures.

3. RESULTS AND DISCUSSION

Three different CFD analyses are performed for three different cases and compared with each other in terms of pressure distributions, streamlines and velocity vectors. By examining the pressure distribution of draft tube of one-stage VPE on Fig. 6 it is seen that the pressure fluctuations are partially eliminated. The uniform flow start to form earlier than the standard turbine. Besides, it is seen that high pressure regions that occurred at inlet section of draft tube do no longer exist.

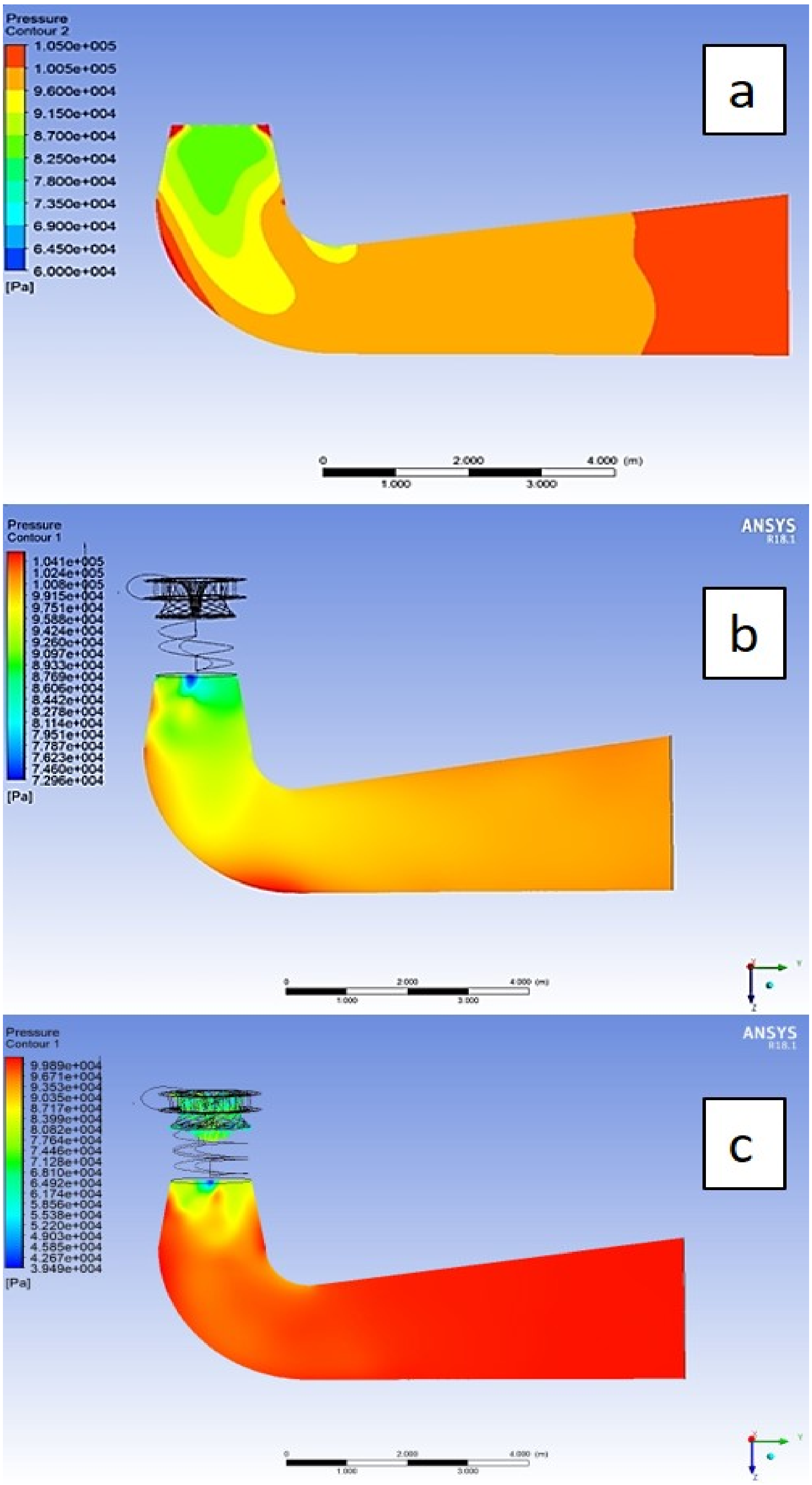

Figure 6. The pressure distributions of a draft tube for a) standard turbine, b) included one stage VPE, c) included two stage VPE.

The pressure distribution of draft tube for two-stage VPE design is given in Fig. 6. It is seen that the low-pressure region is diminished in comparison of the designs VPE with one spiral and without VPE. On the other hand, it is seen in Fig. 6 that the flow pressure, which is heading towards the draft tube outlet cannot reach to atmospheric pressure. This effect may decrease the turbine efficiency and create high water stream in the outlet water channel.

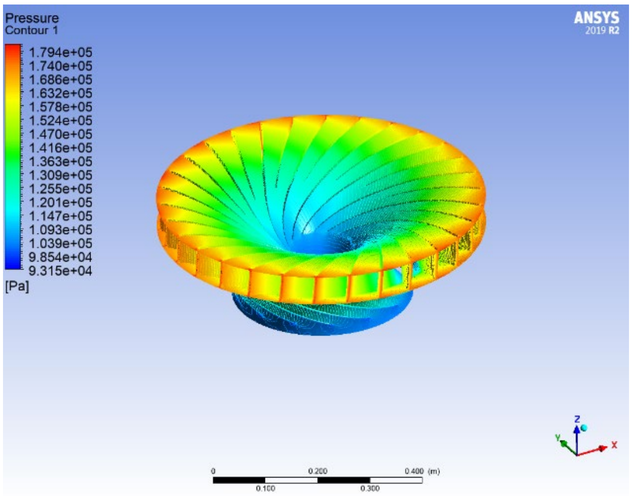

Figure 7. The pressure distribution of runner.

The pressure distribution of runner is given in Fig. 7. It is seen that the runner pressure distribution cruises normally through the draft tube but at the outlet section the pressure is decreased below the atmospheric pressure. In standard Francis turbine runner, outflow follows the swirling streamlines caused by rotational velocity. By considering the runner outlet section in Figs. 8(a,b), it can be seen that the same vector patterns are occurred. It is also obvious that VPE is regulating the outflow in the axial direction. That would provide the flow to pressurize the stagnant regions and to annihilate the undesired flow fluctuations.

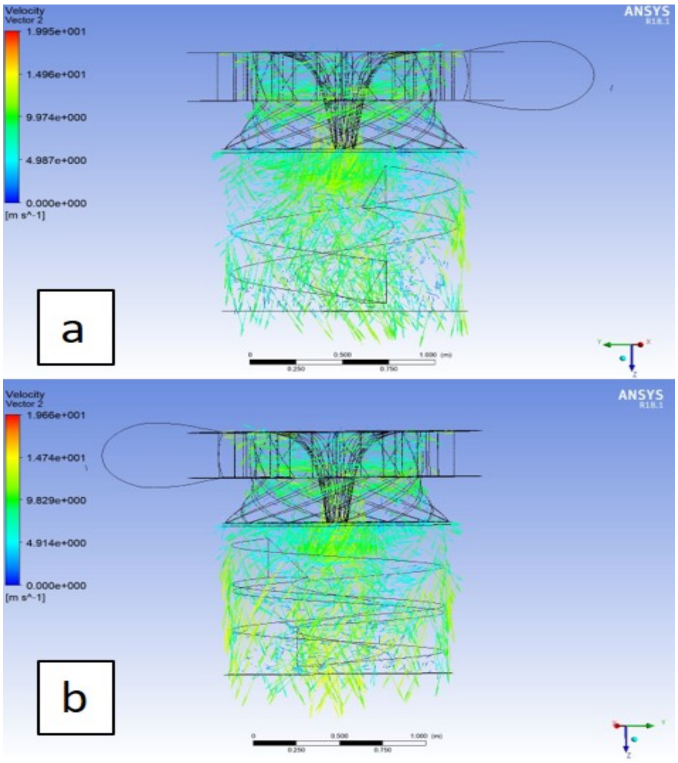

Figure 8. The velocity vectors of turbine runner for a) one stage VPE, b) two staged VPE.

As seen in Figs. 8(a,b), the resistance of the two stage VPE may block the flow more than one stage VPE and causes to decrease velocity field. Meanwhile, as the velocity decreases, the flow vectors become more stable and tend to the center of the draft tube inlet, easing the low pressure region. When comparing the efficiencies of these three designs, the most efficient one obtained is the one staged-VPE design (Table 3).

The efficiencies of the turbines are determined from the Eq. 1.

$$\eta_{turbine} = \frac{P_{shaft}}{P_{hydraulic}} = \frac{T\ \omega}{\rho\ g\ Q\ H} \tag{1}$$

The efficiency of standard Francis turbine is obtained as 90%. One stage VPE design has an efficiency of 93%. Our final design having two stage VPE has an efficiency of 89%. Since the stage number of VPE increases, it is seen that the efficiency starts to decrease. The reason of decrease on efficiency is considered as the low pressure levels at the end of the draft tube. As water flows through the draft tube, the head is recovered normally. However, in two stage VPE design, head is not recovered back entirely, on the one hand, this problem does not exist in one stage VPE design. This means that one stage is the most suitable design for Francis turbines.

Table 3. Efficiency values of turbines.

Case	Efficiency
Standard Turbine	90%
Design with 1-Stage VPE	93%
Design with 2-Stage VPE	89%

4. CONCLUSION

In the present study, the effects of the Vortex Preventing Element (VPE) relating to prevent vortex formation in the draft tube of the Francis turbine are examined. For this aim, the VPE is designed to diminish vortex formation that caused by swirling flow and stagnant regions in the draft tube. The principle of this element is to resist the outgoing flow from runner by spiral forms and regulate the flow before to draft tube. According to three different designs, namely standard Francis turbine, Francis turbine with one stage VPE and Francis turbine with two staged VPE are considered. These three designs are analyzed with computational fluid dynamics method by using a k-ε turbulent model due to its robustness and compared with each other in terms of efficiency and flow characteristics.

The concluding items are as follows:

i. Vortex Preventing Element guides the swirling flow in the draft tube and regulates the flow.
ii. One stage VPE causes to diminish the pressure fluctuations partially in the center of draft tube entrance and consequently increases the turbine efficiency.
iii. One stage VPE design increases the efficiency of the turbine about 3%.
iv. Two stage VPE design has more regulated effects on the vortex flow in the draft tube. But the pressure at the draft tube outlet is not equal to the atmospheric pressure and this may cause the undesirable efficiency decrease. In addition, since the flow is faster than the standard Francis turbine without the VPE, there may be some discharge problems in the outlet water channel.

As future works, more optimization analyses are required to clear out some problem outlined. Therefore, transient analyses of various designs with VPE are performed nowadays. By considering the possible effects of VPE height and guide vanes angle on performance and vortex phenomena as well as the number of VPE stages and interaction effects, it has been observed that more optimization work is required to be done.

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