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Original Paper

Performance characteristic investigation and stay vane effect on N_s100 inline francis turbine

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Abstract: This study presents the performance characteristics of a small Francis turbine with an inline casing and is a continuation of a previous study. A new runner design has been implemented using the previous facility. The specific speed of the new runner has been modified from N_s 80 to N_s 100 m-kW-min^{-1}. This turbine can be installed in a city water supply system. To dissipate excess pressures in the water line system an inline-turbine can be used instead of an inline-pressure reducing valve. Thus, some of the energy can be recovered by utilizing the pressure difference. For best applicability and minimal space consumption, the turbine is designed with an inline casing instead of a common spiral casing. As a characteristic of inline casing, the flow accesses to the runner are in the radial direction, showing low efficiency. The installation of vanes improves the internal flow and positively affects the output power. In contrast to the previous study, the new runner reduces the effect of the stay vanes by maintaining a higher efficiency.

Keywords: Francis turbine, Inline casing, Stay and guide vanes, Performance, Internal flow

1. Introduction

Francis turbines have been widely used globally because of their wide range of heads and flow rate applications. In addition, they also provide a good efficiency of approximately 90%. In most applications, the turbine is used for high heads and flow rates. However, in this study, the Francis turbine has been applied in a much smaller scale: it is designed for city water supply system. In general, a pressure-relief valve is normally used in the system because jet flow with high pressure will be formed when water is directly supplied to the public. However, a large amount of energy is wasted; therefore, a new type of Francis turbine with an inline casing is suggested in such situations to recycle the energy and decrease the pressure instead of using a pressure reducing valve.

In general, a spiral casing is preferred in a Francis turbine to supply water from the penstock to the vanes and through its unique shape of continual cross sectional area reduction, it maintains a near uniform velocity of water around the vanes. However, owing to the simplicity of the water supply piping system, an inline flow passage is required. **Figure 1** shows the schematic view of the inline Francis turbine. The leakage and clearance parts are included in this study because the previous study showed that the leakage affects the performance considerably; especially, for small-scale turbines, the leakage can decrease the efficiency up to 3% at the normal operation.

2. Pump-turbine model and Numerical methods

This study is a continuation of the previous study conducted by the same authors **[1]-[3]**. However, there are some differences in the design specifications. The new runner has been designed with a lower head of 16m and flow rate of 0.028m^3/s. **Table 1** shows the similarities and differences in the design specifications. The same inline casing and piping dimensions have been used in the new design. The runner inlet diameter is the same but the exit diameter has been increased. The meridional shape of the new runner has been modified as illustrated in **Figure 2**. Some modifications have been made to the previous fluid domain, especially to the areas that connect to the new runner. These parts include the guide vane, leakage, and draft tube cone.

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The width B_g of the guide vane was modified from 15.5 to 18.8 mm. The draft tube cone was modified at the connection of the runner because the diameter changed from 100 to 112 mm. Furthermore, the leakage part was changed because the meridional shape of the new runner is different from that in the previous study. **Figure 3** illustrates these modifications.

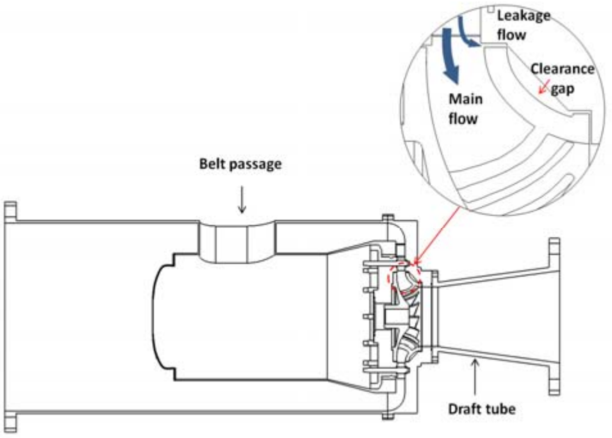

Figure 1: Schematic view of the inline Francis turbine

Table 1 Design specifications of Inline Francis Turbine

Parameters	N_s 80	N_s 100
Effective head H	20 m	16 m
Flow rate Q	0.020 m^3/s	0.028 m^3/s
Rotational speed n	1800 min^{-1}	1800 min^{-1}
Runner inlet diameter D_1	0.150 m	0.150 m
Runner outlet diameter D_e	0.100 m	0.112 m
Runner blade number Z_1	13	13
Guide vane number Z_2	12	12

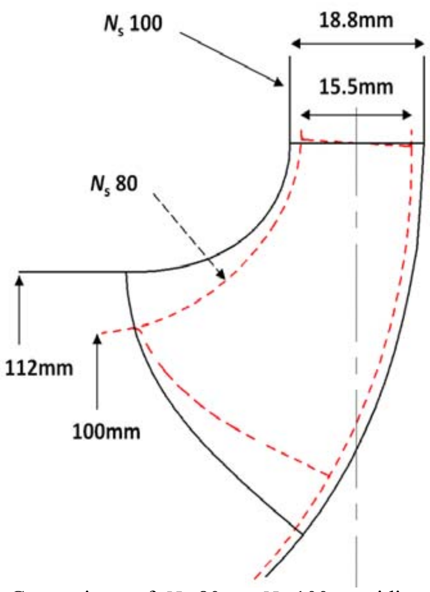

Figure 2: Comparison of N_s 80 to N_s 100 meridional shape

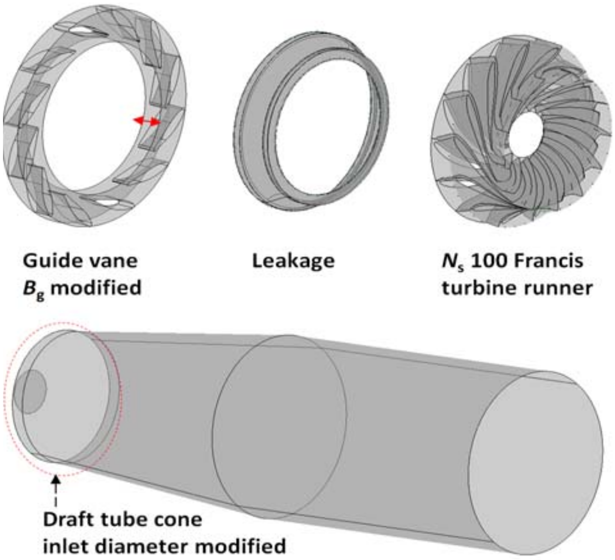

Figure 3: Separate isometric views of the modified regions for the fluid domain

The performance investigation and internal flow analysis of the turbine were conducted using computational fluid dynamics (CFD). The CFD analysis is very useful in predicting the hydraulic machinery performance at various operating conditions **[4]-[7]**. Therefore, the same procedure was followed from the previous studies **[2-3]**. A turbulence dependence test was conducted in the previous study, and similarly a shear stress transport (SST) model has been applied to this analysis. The model is well known to estimate both separation and vortex occurring on the wall of a complicated blade shape. This study employs a commercial CFD code ANSYS CFX to conduct CFD analysis **[8]**. The operating condition maintains the head at 16 m and the flow rate range varies according to the guide vane openings, as shown in **Table 2**. **Table 3** summarizes the boundary conditions.

Table 2 Operating conditions for performance evaluation

Case	Guide vane opening [%]	Flow rate [m^3/s]
1	55	0.015
2	62	0.017
3	70	0.021
4	83	0.025
5	90	0.027
6	100	0.030

Table 3 Numerical methods and boundary conditions

Calculation type	Unsteady state
Turbulence model	SST
Mesh type	-Hexahedral -Tetrahedral(Stay vane & leakage)
Total mesh number	Nodes: 8.3×10^6 Elements: 12.0×10^6
Wall	No slip
Inlet	Total pressure
Outlet	Static pressure

Additionally, shape and location of the stay vane with respect to guide vane was investigated. **Table 4** and **Figure 4** present the description of the four cases. Furthermore, the circumferential velocity and pressure were investigated at the locations of blue and red circles marked in the figure. The red circles represent the study of the stay vane outlet and the inlet distribution of the guide vane, whereas the blue circles represent the study of the outlet distribution of the guide vane. The initial design is commonly used with a spiral casing.

Table 4 Stay vane investigation cases

Case	Stay vane description
A	Initial design
B	Location changed (inline with guide vane)
C	Shape modified (inline with guide vane)
D	No stay vane

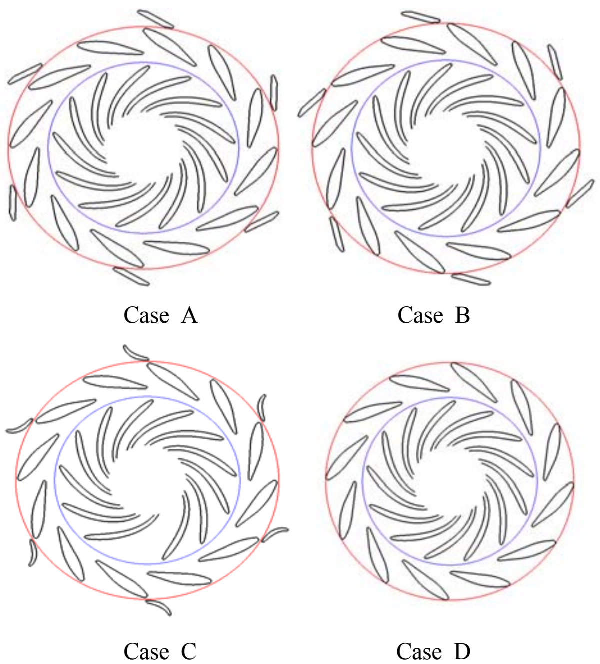

Figure 4: Stay vane investigation cases

3. Results and Discussion

3.1 Characteristics of performance curves

Figure 5 presents the performance curves of the N_s 100 turbine with the characteristics of efficiency, power and head with respect to the flow rate.

The results showed that this turbine performed sufficiently well because it achieved a maximum efficiency of 89.58% at a flow rate of 0.025 m^3/s. The head was maintained at 16 m and the power output was 3.4 kW. The leakage losses were also considered in the efficiency calculation. **Figure 6** shows the comparison of the leakage losses for the N_s 100, previous, and new turbines considering leakage loss. The new turbine improved in efficiency from its predecessor by 0.71%; however, the overall leakage at the best efficiency point increased from 1.80% to 2.37%, which is quite high yet. Therefore, the new turbine outperformed its predecessor. The higher leakage loss could have been due to change in shape of the leakage section. Moreover, the flow rate and head are different for the two turbines, and could have affected the high leakage.

The pressure distribution and streamlines in **Figure 7** show that the internal flow in the leakage is quite different for the two turbines. The recirculation flow inside the leakage part further affected the difference in loss among the two turbines.

The runner blade showed relatively smooth streamlines and a smooth pressure distribution along the flow passage as observed in **Figure 8**. Therefore, the efficiency of the runner was relatively high. However, near the leading edge pressure side there were small recirculation flows that could not be completely removed. This is also because the length of the runner blade is relatively longer for low specific speeds.

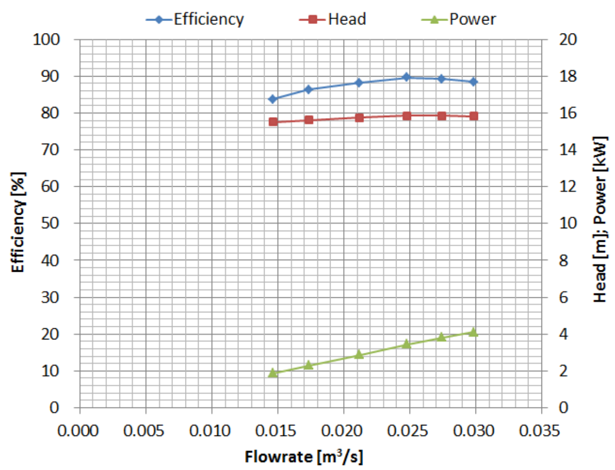

Figure 5: Performance characteristic curves of the N_s 100 inline Francis turbine according to guide vane opening

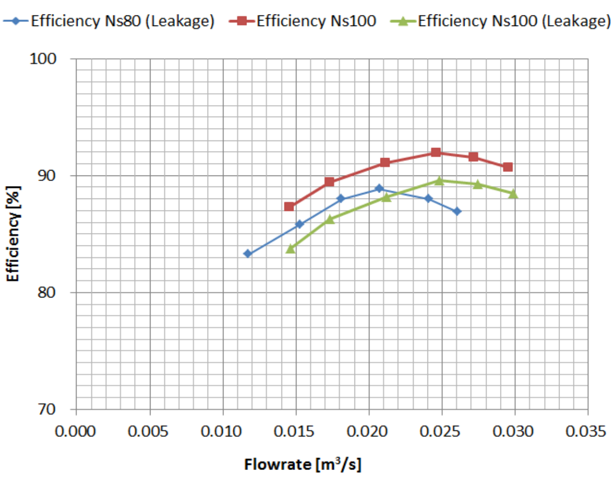

Figure 6: Efficiency comparison of the N_s 80 and N_s 100 inline Francis turbine with leakage effect for N_s 100

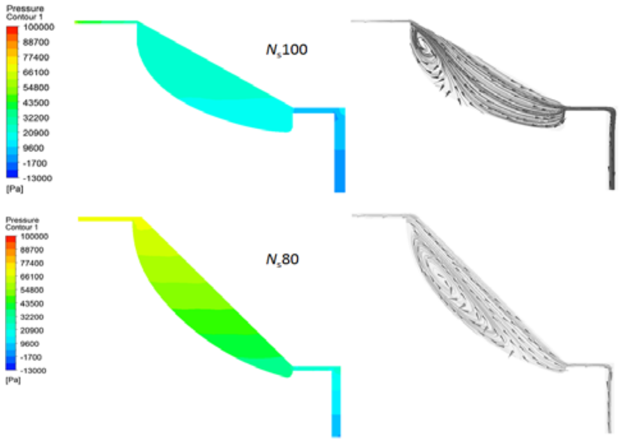

Figure 7: Comparison of pressure and streamline distribution on leakage for N_s 80 and N_s 100

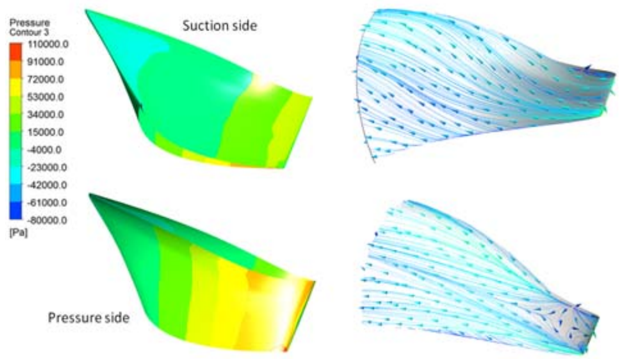

Figure 8: Pressure and streamline distribution on runner at best efficiency point on pressure and suction sides

3.2 Investigation of stay vane effect

Several cases of stay vanes were more thoroughly investigated. The initial case was compared with a curved shape. Further, the location of the stay vane was changed to make it inline to the guide vane and study its effect on the efficiency and flow pattern at the inlet passage.

The pressure distributions of the four cases were compared at the red and blue locations shown in **Figure 4**. The pressure distribution at the stay vane exit (guide vane inlet; (red location)), shown in **Figure 9**, was reduced to one quarter of the rotation to show clear visibility and easily distinguish the pressure fluctuations with maxima and minima to compare the differences between each case. A similar location was selected for the velocity distribution shown in **Figure 11**. However, the pressure distribution at the guide vane outlet (blue location) is presented for the full rotation because the fluctuations with the minima and maxima were easily visible, as shown in **Figures 10 and 12**. The results of the pressure and velocity distributions showed that Cases B and C do not positively affect the efficiency and flow distribution at the passage of the stay and guide vanes. This is because when the stay and guide vanes are inline to each other, there exists a small gap between them. The flow between this gap could experience sudden changes and has a high possibility for recirculation. This phenomenon changes the velocity and pressure considerably, as seen in **Figure 11**: the velocity fluctuates between 1 to 7 m/s. Such sudden changes negatively influence the structural components and cause large vibrations. In Case A, the stay vane overlapped the guide vane, thus providing a smoother blend of flow, which reduced the fluctuation. Furthermore, Cases A and D show similar results of pressure and velocity fluctuations. Therefore, it can be conjectured that the stay vanes for the new turbine do not considerably affect the efficiency and their removal could contribute to a more economical design of the system.

Figures 13 - 16 display that the flow distributions for Cases B and C show distorted flow patterns at the contact points of the stay and guide vanes. Comparatively, Cases A and D show good flow patterns; thus the efficiency is positively affected in these cases. Although the trends are similar for all the cases, the maxima and minima show that Cases B and C have large peaks in pressure, which negatively affects the structural vibrations and efficiency and increases the occurrences of recirculation flows.

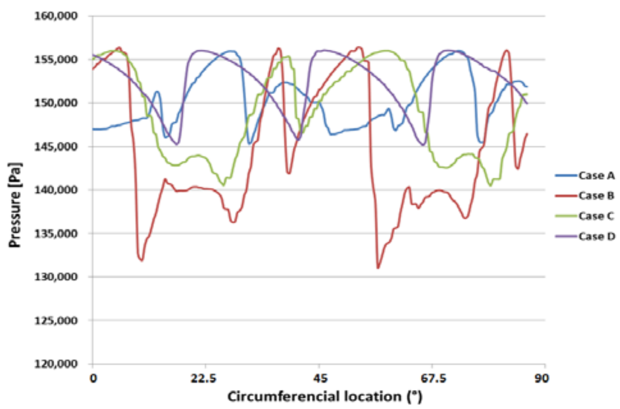

Figure 9: Pressure distribution on guide vane inlet

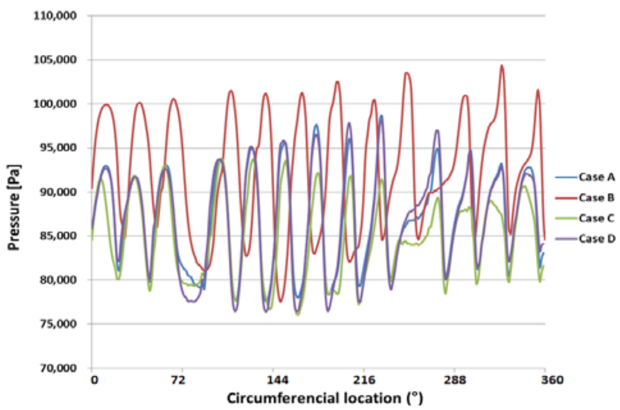

Figure 10: Pressure distribution on guide vane outlet

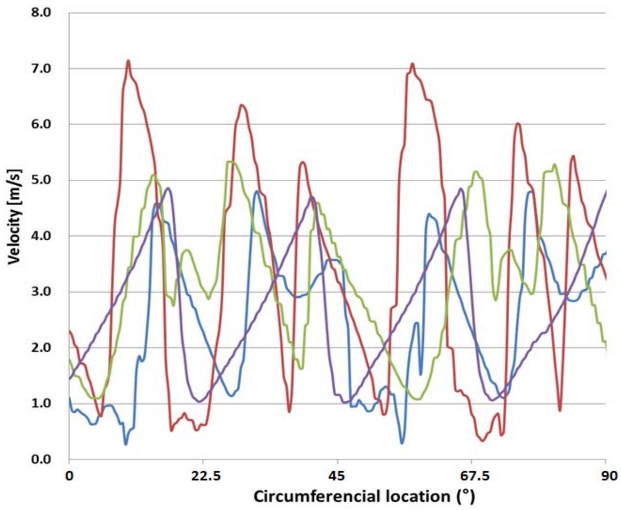

Figure 11: Velocity distribution on guide vane inlet

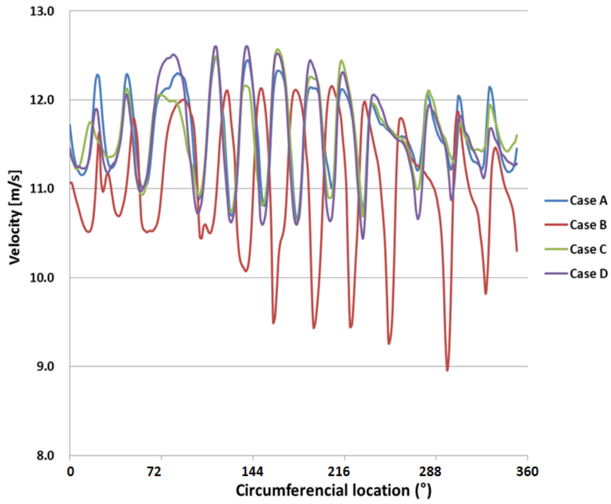

Figure 12: Velocity distribution on guide vane outlet

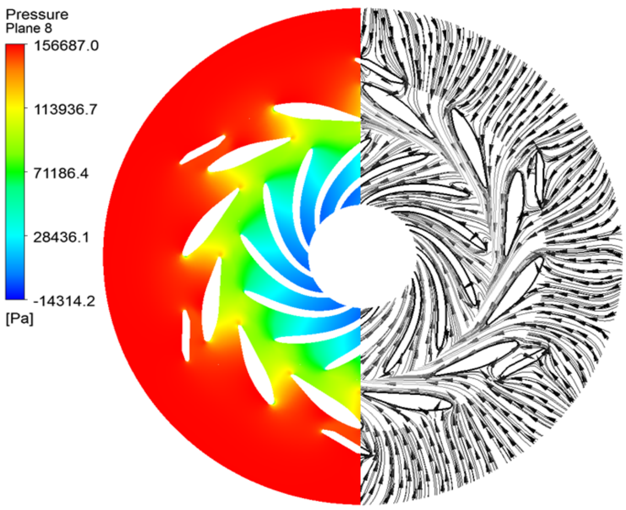

Figure 13: Pressure and velocity distribution at best efficiency point (Case A)

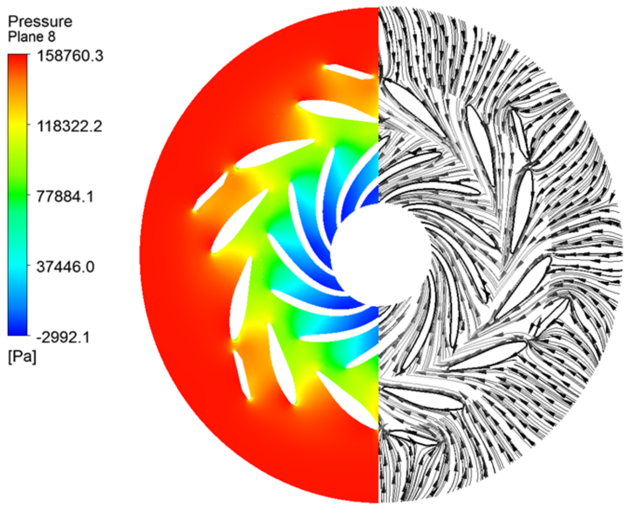

Figure 14: Pressure and velocity distribution at best efficiency point for Case B

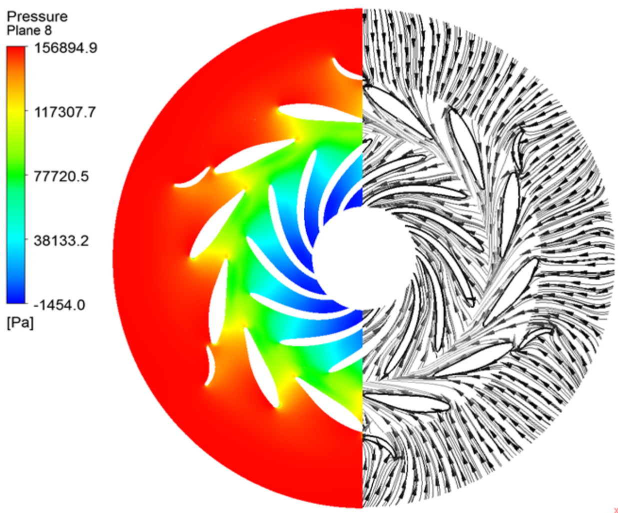

Figure 15: Pressure and velocity distribution at best efficiency point for Case C

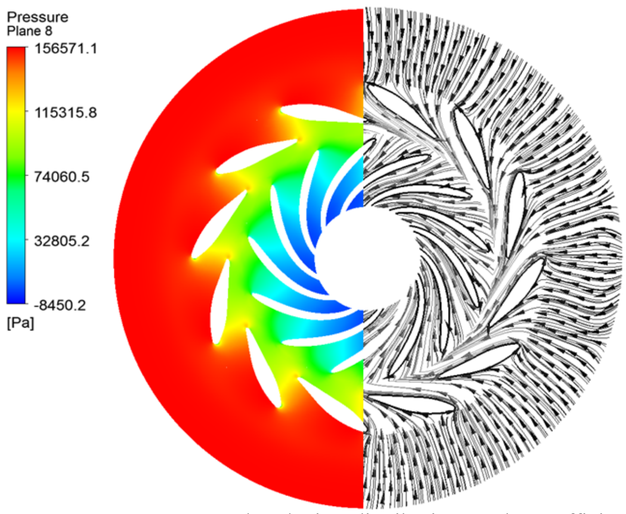

Figure 16: Pressure and velocity distribution at best efficiency point for Case D

4. Conclusion

In this study, the performance of a new inline Francis turbine was investigated and compared with the results of the previous study. Although, both turbines showed relatively similar efficiencies, the new turbine outperformed its predecessor, and the effect of the stay vanes was reduced. In the previous study, the effect of stay vanes showed considerable increase in the efficiency up to 5%. However, the stay vanes for the new turbine slightly affected the efficiency and, thus removing them could be more economical to the overall system. Another interesting discovery was the effect of leakage on the efficiency. Future studies could investigate the shape of the leakage to reduce the losses and improve the efficiency. The leakage part in the previous study was narrower and longer than that in the present study, and the internal flow results of the two differ considerably. However, there are limitations to the leakage because of the change in meridional shape.

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