On the loss fof efficiency of a Francis turbine due to the cavitation phenomenon

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Abstract
Cavitation phenomenon is one of the most important phenomena that can occur in pumps and turbines. This phenomenon is undesirable and harmful in turbines and pumps, as it causes material erosion, reduction in turbo-machine efficiency, and generation of unwanted noise and vibrations. Therefore, designers and operators of turbines and pumps strive to avoid the occurrence of cavitation. The occurrence of this phenomenon in turbines and pumps can take various forms. In this paper, the occurrence of cavitation in a Francis turbine is studied, using the computational fluid dynamics software OpenFOAM. The Q criterion is also used to observe the vapor volume fraction. Validation is performed using existing experimental work. The results indicate that increasing the suction head of the Francis turbine intensifies cavitation and leads to a decrease in its efficiency. Additionally, increasing the mass flow rate of the Francis turbine up to 22 cubic meters per second reduces cavitation, but beyond this value, cavitation increases.

Keywords: Cavitation, Francis turbine, computational fluid dynamics, loss of efficiency

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Introduction

The Francis turbine is one of the types of water turbines that are used to convert the hydraulic energy of water into electrical energy. The Francis turbine has been used since the beginning of the 20th century as one of the main hydro turbines to produce electrical energy. These turbines consist of a rotating disk in a spherical shape and blades in a complex shape that turn the water's energy into mechanical energy. Then this mechanical energy is converted into electrical energy by a generator. Francis turbine is known as one of the best methods of producing clean and sustainable energy due to its efficiency and wide application. The positive features of the Francis turbine include high efficiency, adjustable speed and output power, long life and low maintenance. These turbines are used for dams and hydropower plants, especially in areas with abundant water resources. Also, Francis turbine is used to produce electric energy during peak hours and off-peak hours due to the ability to adjust the output power. Due to the increasing need for clean and sustainable energy around the world, the use of Francis turbines has been proposed as one of the effective solutions in producing clean and sustainable energy. On the other hand, new technologies in the field of designing and manufacturing Francis turbines have improved the efficiency and reduced the installation and maintenance costs of these turbines. In general, the Francis turbine is known as one of the most advanced and efficient hydro turbines, which plays an important role in producing clean and sustainable energy. Therefore, the use of these turbines in water projects and electric power plants can help improve the environment and reduce dependence on polluting energy sources [1-4]. Several researches have been carried out in the field of cavitation in Francis turbines. The geometrical specifications of the model used in this paper were selected based on the work of Zhang et al [5]. The number of blades and the dimensions and sizes have been selected based on this article. In this research, Salome software is used to create geometry as shown in "Figure 1". Using a time step equal to one propeller revolution and a rotation speed of 600 rpm to determine the time step is a common method for simulating rotating machinery. The computational grid of the turbine is also generated using Salome, including spiral casing and runner with 3,500,000 elements shown in "Figure 2". In order to reduce computational costs in the current work, other parts of the Francis turbine are omitted.

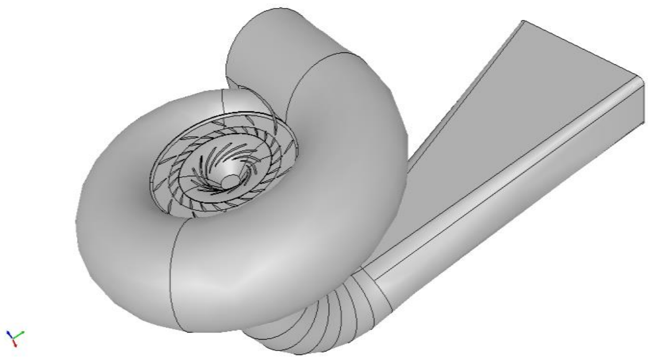
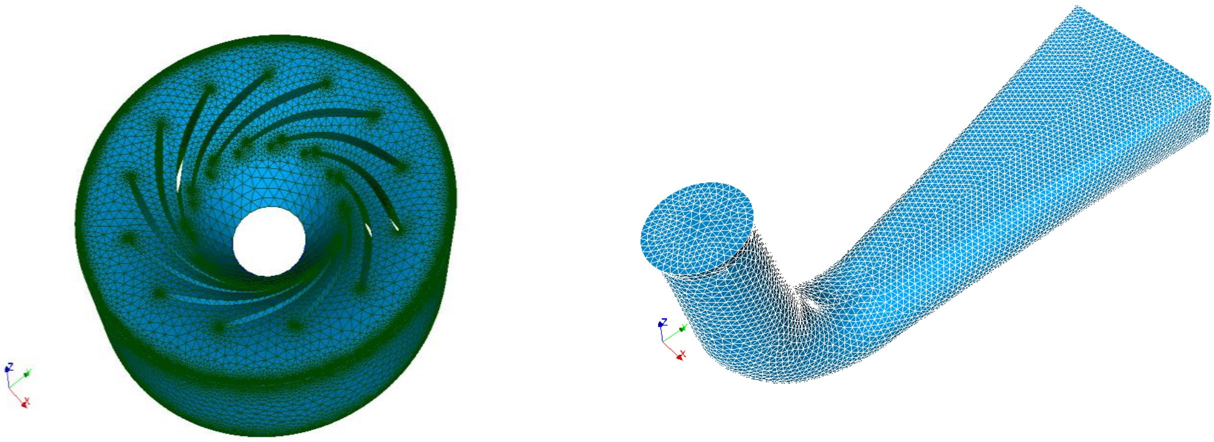


Figure (1) Modeled Francis turbine



(a) runner (b) draft tube

Figure (2) Mesh of components

Governing equations

This paper presents using OpenFOAM code to simulate the cavitating turbulent flow in the Francis turbine. The $k - \omega$ SST turbulence model for the Reynolds-averaged Navier–Stokes equations (RANS equations) is employed in OpenFOAM as written:

$$U_j \frac{\partial k}{\partial x_i} = P_k - \beta^* k\omega + \frac{\partial}{\partial x_j}\left[(\upsilon + \sigma_k \upsilon_T)\frac{\partial K}{\partial x_j}\right] \quad (1)$$

$$= \alpha S^2 - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[(\upsilon + \sigma_\omega \upsilon_T)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (2)$$

$$\nu_T = \frac{\alpha_1 K}{\max(\alpha_1 \omega . S F_2)} \quad (3)$$

The parameters appearing in these equations are:

$$P_k = \min(\tau_{ij}\frac{\partial U_i}{\partial x_j} . 10\beta^* k\omega) \quad (4)$$

$$F_1 = \tanh\{[\min(\max\left(\frac{\sqrt{k}}{\beta^* \omega y}.\frac{500}{y^2\omega}\right).\frac{4\sigma_{\omega 2}k}{CD_{\omega k}y^2})]^4\} \quad (5)$$

$$F_2 = \tanh[[\max(\frac{2\sqrt{k}}{\beta^* \omega y}.\frac{500}{y^2\omega})]^2] \quad (6)$$

$$CD_{\omega k} = \max(2\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}.10^{-10}) \quad (7)$$

$$\sigma_k = \sigma_{k_1}F_1 + \sigma_{k_2}(1 - F_1) \quad (8)$$

The constants used here are:

$\beta^* = 0.09, \beta = 0.075,\ \sigma_{k_1} = 0.85034,\ \sigma_{k_2} = 1.0, \sigma_{\omega 1} = 0.5, \sigma_{\omega 2} = 0.856$

Results and discussions

In the current work, the sample line is used to show the changes in the volume fraction of water vapor on the blade as shown in "Figure 3". The changes of water vapor volume fraction along the sampling line for different types of Francis turbine suction heads are shown in "Figure 4". From "Figure 5", it can be seen that by increasing the suction head up to 150 meters, the cavitation rate increases and causes several areas of steam to appear on the trailing edge of the Francis turbine blades. Contours of pressure changes for different types of suction heads are shown in "Figure 6". Based on this figure, it can be seen that by increasing the suction head, the pressure distribution in the throat of the pipe decreases, which is prone to increase the possibility of cavitation.

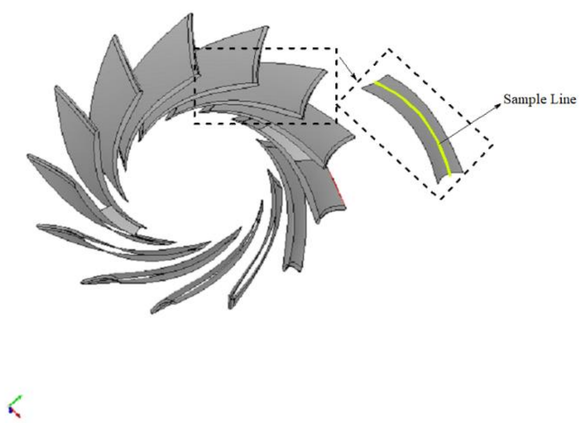


Figure (3) Sampling line for extraction of water vapor volume fraction changes

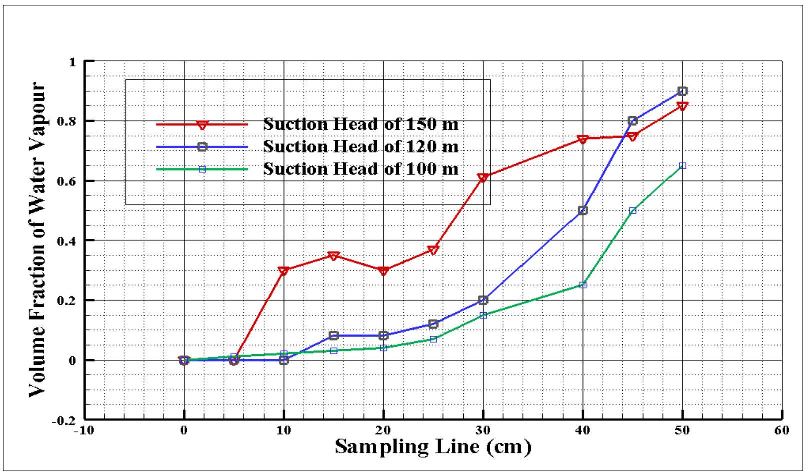


Figure (4) Changes of water vapor volume fraction along the sampling line for different types of Francis turbine head suction

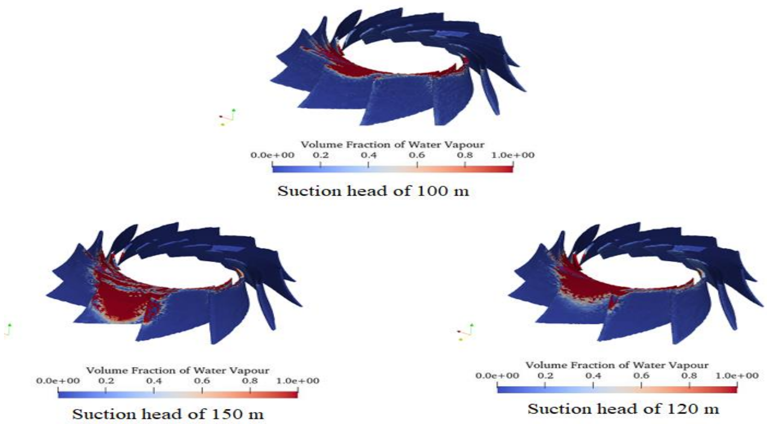


Figure (5) Contours of water vapor volume fraction changes for different suction heads

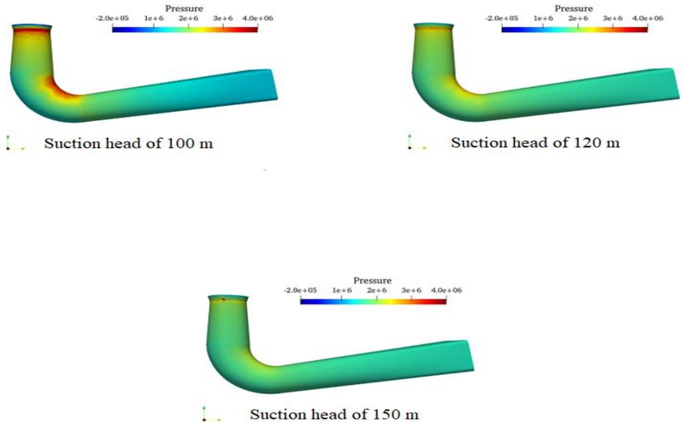


Figure (6) Pressure distribution in draft tube for different suction heads

In the following, the effect of flow rate on the occurrence of cavitation phenomenon has been investigated. With the gradual increase of the flow rate up to 22 m^3/s at a pressure equivalent to constant head, the rate of growth of water vapor bubbles in the blades and tube draft decreases, but this decrease in bubble growth stops after the flow rate of 22 m^3/s and it starts to increase. The changes of water vapor volume fraction along the sampling line for various flow rates in the Francis turbine are shown in "Figure 7" and the contours of water vapor volume fraction changes for various flow rates are shown in "Figure 8". In the following, the pressure distribution in the draft tube, has been investigated. "Figure 9" shows the pressure distribution in the draft tube. From this figure, it can be seen that with the increase in flow rate, the pressure increases significantly, which consequently causes a decrease in cavitation. But as it is clear from this figure, at a flow rate of 22 cubic meters per second, the pressure distribution decreases, this means an increase in the possibility of cavitation phenomenon, and the Francis turbine should be optimized in its operating conditions.

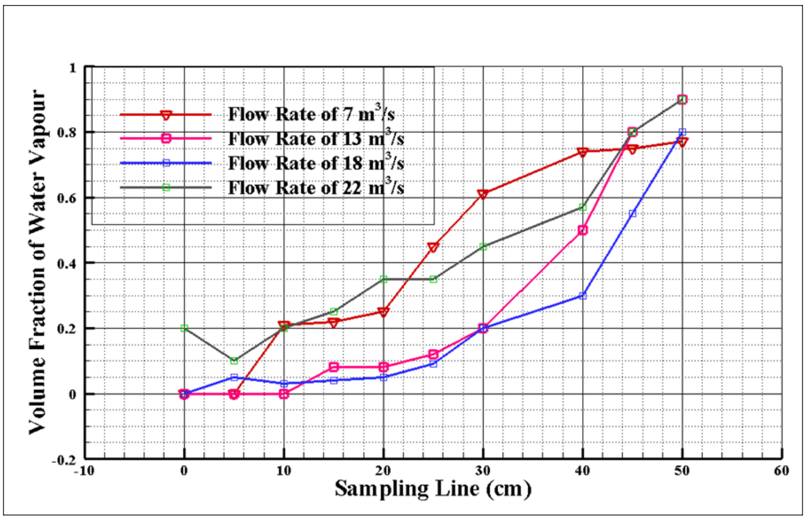


Figure (7) Changes of water vapor volume fraction along the sampling line for various flow rates in the Francis turbine

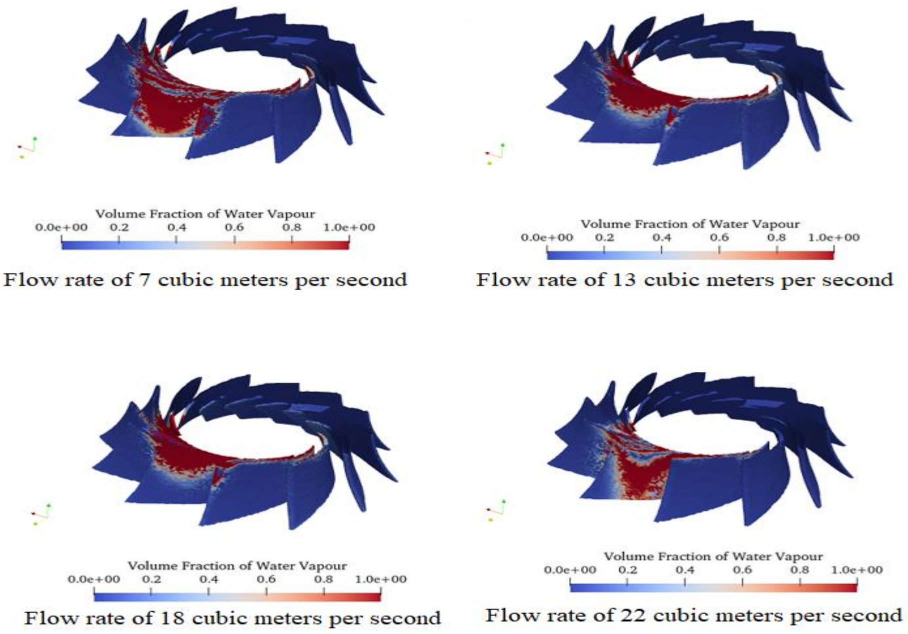


Figure (8) Contours of water vapor volume fraction changes for various flow rates

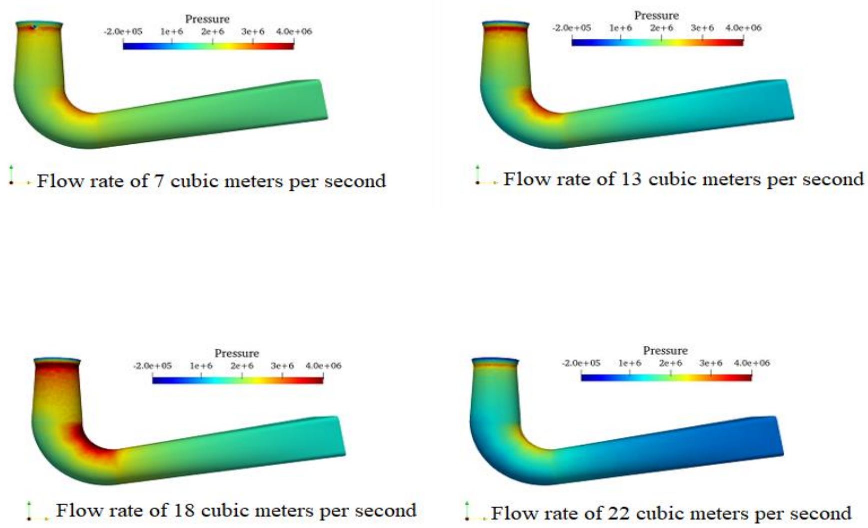


Figure (9) Pressure distribution in draft tube for different flow rates

Concluding remarks

In this paper, the effect of parameters such as suction head and flow rate on the volume fraction of water vapor in cavitation-prone areas was evaluated. The results show that with the increase in the suction head of the Francis turbine, cavitation intensifies and causes a decrease in the efficiency of the Francis turbine. It was also observed that by increasing the flow rate of the Francis turbine, cavitation decreases up to 22 cubic meters per second, but after this value, cavitation increases, which can cause the loss of efficiency in the Francis turbine.

References

[1] Breeze, P. (2018). Chapter 4 - Hydropower Turbines. Hydropower. P. Breeze, Academic Press: 35-46.

[2] Drtina, P. and M. Sallaberger (1999). Hydraulic turbines—basic principles and state-of-the-art computational fluid dynamics applications. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 213(1): 85-102.

[3] Escaler, X., E. Egusquiza, M. Farhat, F. Avellan and M. Coussirat (2006). Detection of cavitation in hydraulic turbines. Mechanical Systems and Signal Processing 20(4): 983-1007.

[4] Kumar, P. and R. P. Saini (2010). Study of cavitation in hydro turbines—A review. Renewable and Sustainable Energy Reviews 14(1): 374-383.

[5] Zhang, H., & Zhang, L. (2012). Numerical simulation of cavitating turbulent flow in a high head Francis turbine at part load operation with OpenFOAM. Procedia Engineering, 31, 156-165.

[6] Foias, C. (1997). What do the Navier-Stokes equations tell us about turbulence. Contemporary Mathematics, 208, 151-180.

[7] Hellsten, A., Laine, S., Hellsten, A., & Laine, S. (1997). Extension of the k-omega-SST turbulence model for flows over rough surfaces. In 22nd atmospheric flight mechanics conference (p. 3577).

[8] Dhakal, T. P., & Walters, D. K. (2009, January). Curvature and rotation sensitive variants of the K-Omega SST turbulence model. In Fluids Engineering Division Summer Meeting (Vol. 43727, pp. 2221-2229).