Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 1039–1045

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Study on the effects of blades outer angle on the performance of inline cross-flow turbines

Du Jiyun, Shen Zhicheng, Yang Hongxing*

Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

Abstract

Cross-flow turbine is a promising device for power supply to water monitoring sensors and meters along water supply pipes. In the previous research, an inline cross-flow turbine is proposed and the effects of blocks on turbine performance have been studied by numerical methods. Based on the results, mismatching exists between the flow inlet angle and blades outer angle, which may result in shock loss and flow separation. In this study, a numerical investigation was performed to study the effects of blades outer angle on the turbine performance. Results indicated that the matching between flow inlet angle and blades outer angle can enhance the torque output of runner first stage and significantly improve the overall turbine performance. To achieve a balance between turbine efficiency and water head reduction, the blades outer angle of the inline cross-flow turbine is suggested as 30°.

Keywords: Blades outer angle, inline cross-flow turbine, urban water supply, micro hydropower

1. Introduction

Water leakage has been a great challenge in many countries and regions around the world [1]. Taking Hong Kong for instance, due to the high water head in the water supply network and pipe deterioration, nearly 15% of the fresh water is leaked in the delivery process every year [2]. To provide timely detection and early warning of water leakage, Water Intelligent Network (WIN) which functions based on a lot of monitoring and sensing equipment is

* Corresponding author. Tel.: +852 2766 5863; fax: +852 2765 7198.
E-mail address: hong-xing.yang@polyu.edu.hk.

10.1016/j.egypro.2019.01.252

used along water mains of Hong Kong. However, most of the monitoring and sensing devices in the WIN are powered by chemical batteries which usually have limited service life and need to be replaced frequently [3]. To provide constant and reliable power for the WIN, an inline cross-flow turbine which could generate electricity using limited water head inside the water pipe was developed in the previous research [4]. In the proposed inline cross-flow turbine, two blocks which functioned as the ducted elements were designed to integrate to the pipe inner wall. Besides, a block design method was proposed and the effects of the block on turbine performance were studied by numerical methods. According to the results, mismatching existed between the flow inlet angle and blades outer angle, which might result in shock loss and flow separation. To further enhance the performance of inline cross-flow turbine, it was suggested that the blades geometries should be improved for a better matching with the proposed block design.

The blades outer angle is the inlet angle of blades at runner first stage and the outlet angle of blades at runner second stage. A suitable blades outer angle can reduce flow separation in blades passages and decrease hydraulic loss at runner inlet arc, thus total performance of the should be about 30°. An experimental and numerical study was conducted by Katayama et al. [7], four prototypes with different blades outer angles were manufactured and tested. The blades outer angles of the four prototypes are 21°, 24°, 27° and 30°, respectively. The experimental results indicated that when blades outer angle equals to 30°, the turbine has the maximum efficiency. After that, numerical study was performed to investigate the effects of blades outer angle on turbine power output. It was found that with the increase of blades outer angle, the output power ratio of the runner first stage increases while that of the runner second stage reduces. In the domain of traditional cross-flow turbine design, a blades outer angle value of 39° is widely accepted [8].

Although many researchers have suggested the optimal value of blades outer angle, situations may be different when the cross-flow turbine is used in water pipes. Therefore, in this study, the effects of blades outer angle on the performance of inline cross-flow turbine are studied using CFD simulations. Finally, the optimal blades outer angle for inline cross-flow turbine can be determined.

2. Methodology

2.1. Physical model

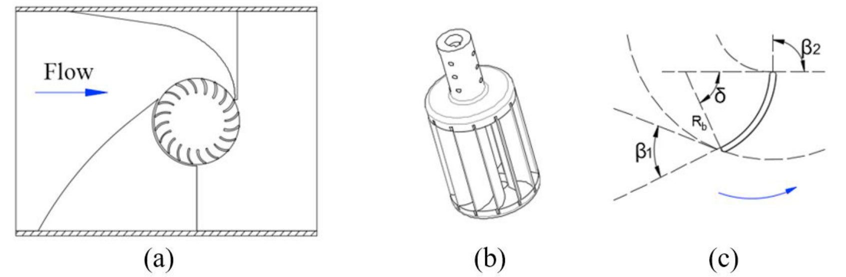

Fig. 1. Physical model of the proposed inline cross-flow turbine: (a) Block profiles; (b) Runner; (c) Blade geometries

Fig. 1 shows the physical model of the proposed inline cross-flow turbine. Two blocks are designed to surround the runner to direct water flow towards the runner and convert part of the water head into flow kinetic energy. In this study, the runner is composed of 20 blades and two discs. As indicated in Fig. 1, β_1 refers to the blades outer angle, β_2 refers to the blades inner angle while R_b refers to the blades radius.

2.2. Numerical setup

In this research, the computational fluid dynamics (CFD) method which has been proved effective in hydro turbine design and performance prediction [6,7] was adopted to study the effects of blades outer angle on the turbine performance. The 3D models of different turbines were built in SolidWorks 2014 then imported in ANSYS ICEM 14.5 for grids generation using unstructured tetrahedral grids. Fig. 2 shows the final meshing and the total grids number is about 3.8 million.

The CFD simulations were performed in Ansys CFX 14.5 using *SST k-w* model. The flow velocity is considered as the inlet boundary condition of the inlet face while the outlet boundary condition is set as pressure outlet with the pressure equal to atmospheric pressure. Besides, the boundary condition of turbine wall and blades is set as non-slip smooth wall. The maximum residual is set to 10^{-5}.

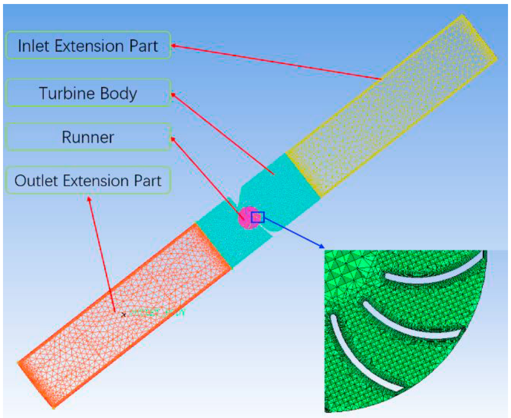

Fig. 2. Meshing of the inline cross-flow turbine

2.3. Data analysis

In the simulation, the torque of blades and the water head difference from the inlet to the outlet were recorded at the inlet velocity of 1.5m/s, which is the average flow velocity inside the water mains in Hong Kong. To analyze the results, the tip speed ratio (TSR) is introduced. The TSR means the ratio of the circumferential velocity of the turbine to the mean turbine runner inlet velocity and it can be calculated using Eq.1. Different TSR values can be obtained by varying the angular velocity ω. As this method has been validated in our previous research, the meshing independence test and further experimental validation are not present in this paper.

$$TSR = \frac{r\omega}{V} \tag{1}$$

where r is the impeller radius (m) while V is the mean turbine runner inlet velocity (m/s).

3. Results and discussion

3.1. The mismatching between flow inlet angle and blades outer angle

Fig. 3 indicates the research results about flow inlet angle along the runner inlet arc from the precious research. It can be observed that the flow inlet angle reduces when runner inlet arc angle increases from 0° to 50° and fluctuates from 26° to 32° in the runner inlet arc angle range from 50° to 105°. To achieve a good matching between the flow inlet angle and blades outer angle, the optimal value of blades outer angle may occur in the range from 26° to 32°. In this research, computations were performed when β_1 equals to 26°, 28°, 30° and 32° to study the effects of blades outer angle on the performance of inline cross-flow turbine. The values of runner main geometrical parameters are listed in Table 1.

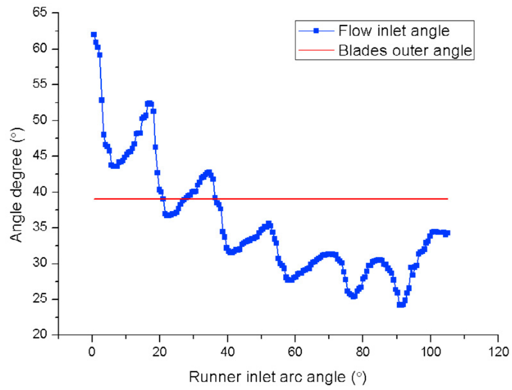

Fig. 3. Flow inlet angle along the runner inlet arc

Table 1. The main runner geometrical parameters.

Blades outer angle β_1	Blades inner angle β_2	Blades radius R_b	Blades number N_b
26°	90°	14.9mm	20
28°	90°	15.2mm	20
30°	90°	15.5mm	20
32°	90°	15.8mm	20

3.2. Turbine performance

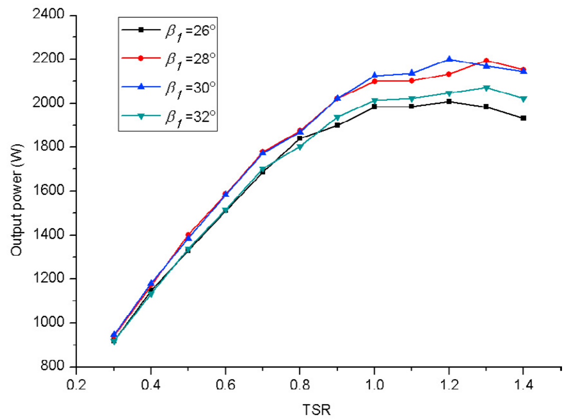

Fig. 4. The influence of blades outer angle on turbine output power

All the simulations were conducted under the flow velocity of 1.5m/s at different TSRs. Fig. 4 indicates the influence of β_1 on turbine output power. It could be observed that the output power of turbines with β_1 equals to 28° and 30° are better than the other models. The maximum turbine output power, 2200W, occurs when β_1=30° at TSR equals to 1.2. It can also be noticed that when the TSR is lower (less than 0.8), the power deviation between each model is smaller. When the TSR is higher, the variation becomes more obvious. As can be seen in Fig. 5 is the effects of β_1 on water head reduction. With the increase of blades outer angle, water head reduction through the turbine decreases. When the blades outer angle is 26°, the water head reduction is higher than the other three models. The main reason for this phenomenon is that in the model with β_1 equals to 26°, mismatching between flow attack angle and blades outer angle is severe, resulting in more hydraulic loss than other models. The effects of blades outer angle on turbine efficiency is shown in Fig. 6. When β_1 increases from 26° to 30°, the maximum turbine efficiency increases significantly from 45.9% to 49.6%, keeping increase β_1 from 30° to 32°, the turbine efficiency decreases slightly from 49.6% to 48.5%. Therefore, the turbine obtains its best efficiency when β_1=30°, where the TSR is 0.8. The variation of turbine output power and efficiency with the change of blades outer angle proves that a good matching between flow attack angle and blades outer angle can significantly improve the turbine performance. To obtain a better turbine efficiency, the blades outer angle of the inline cross-flow turbine is suggested as 30°.

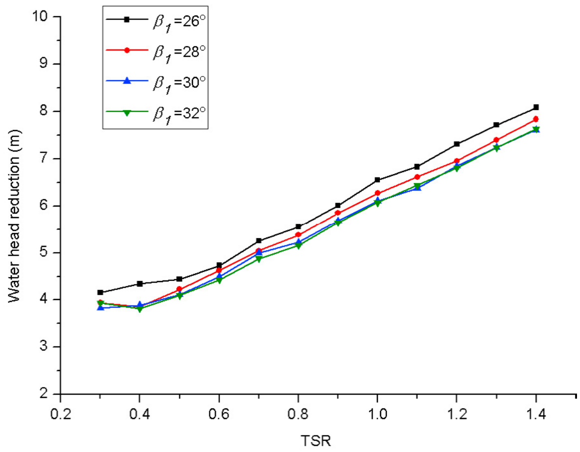

Fig. 5. The influence of blades outer angle on water head reduction

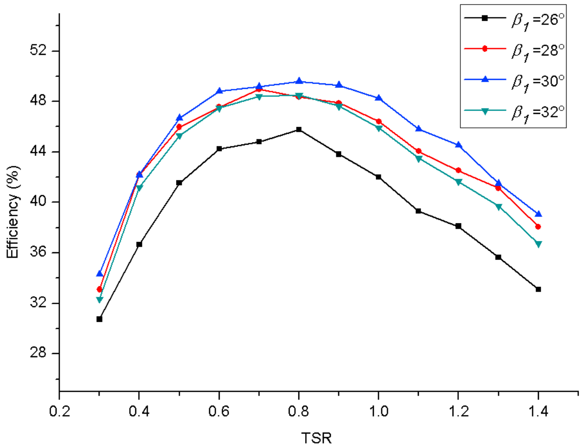

Fig. 6. The influence of blades outer angle on turbine efficiency

3.3. Torque output of each blade and runner stage

The influence of blades outer angle on torque output of each blade is shown in Fig. 7. It can be observed that at runner first stage, the output torque of each blade increases gradually with the increase of runner inlet arc angle due to the function of conversion block, while the blade torque at second runner stage increases first then decreases. When blades outer angle is 30°, the blade output torque at first runner stage is improved comparing to other models, which means the flow attack angle matches well with the blades outer angle. For the other three models, the performance of the first runner stage is similar.

To study the influence of blades outer angle on the performance of each runner stage, the percentage of total torque output at each runner stage is recorded and shown in Fig. 8. It can be observed that for all the four studied cases, each runner stage can generate nearly 50% of the total output torque, but slight difference exists between different models due to the different blades outer angles. It can be seen that the highest torque output of the first runner stage occurs when blades outer angle equals to 30°, this is mainly because that a good matching between the flow attack angle and the blades outer angle is achieved in this case, leading to less hydraulic loss and better performance at the first runner stage.

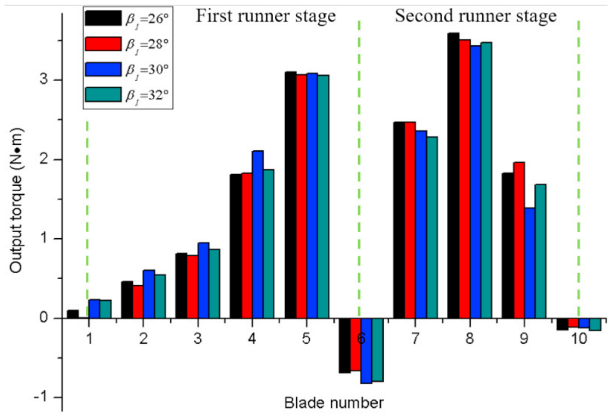

Fig. 7. The influence of blades outer angle on torque output of each blade

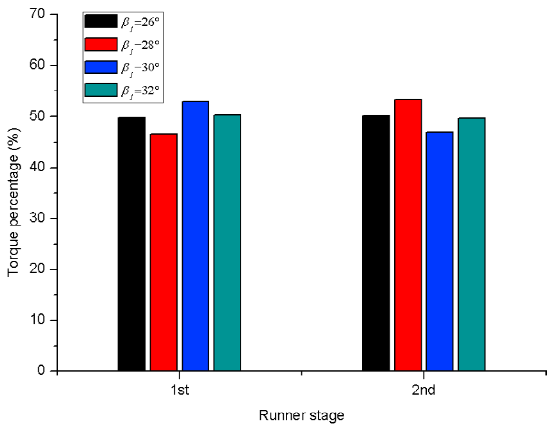

Fig. 8. The influence of blades outer angle on torque of each runner stage

Conclusion

This research presents the numerical study on the effects of blades outer angle on the performance of inline cross-flow turbine. As referred from the present study, the followed conclusions can be obtained:

(1) A good matching between flow inlet angle and blades outer angle can enhance significantly improve the turbine performance. Specially, the maximum turbine efficiency increased significantly from 45.9% to 49.6% when adjusting the outer blade angle from 26° to 30°.

(2) A suitable blades outer angle can enhance the torque output of runner first stage.

(3) To achieve a balance between turbine efficiency and water head reduction, the blades outer angle of the inline cross-flow turbine is suggested as 30°.

Acknowledgements

The authors would appreciate the financial supports provided by the Innovation and Technology Fund of Hong Kong Special Administrative Region Government (Grant No.: ITS/032/13) and the help from the Water Supplies Department of the Hong Kong SAR Government.

References

[1] Du, J., Shen, Z., & Yang, H. (2018). Effects of different block designs on the performance of inline cross-flow turbines in urban water mains. Applied Energy, 228, 97-107.
[2] Du, J., Shen, Z., & Yang, H. (2018). Performance enhancement of an inline cross-flow hydro turbine for power supply to water leakage monitoring system. Energy Procedia, 145, 363-367.
[3] Du, J., Shen, Z., & Yang, H. (2018). Numerical study on the impact of runner inlet arc angle on the performance of inline cross-flow turbine used in urban water mains. Energy, 158, 228-237.
[4] Du, J., Yang, H., Shen, Z., & Guo, X. (2018). Development of an inline vertical cross-flow turbine for hydropower harvesting in urban water supply pipes. Renewable Energy, 127, 386-397.
[5] Adhikari, R. (2016). Design improvement of crossflow hydro turbine (Doctoral dissertation, University of Calgary).
[6] Mockmore, C. A., & Merryfield, F. (1949). The Banki water turbine.
[7] Katayama, Y., Iio, S., Veerapun, S., & Uchiyama, T. (2015). Investigation of blade angle of an open cross-flow runner. International Journal of Turbo & Jet-Engines, 32(1), 65-72.
[8] Sammartano, V., Aricò, C., Carravetta, A., Fecarotta, O., & Tucciarelli, T. (2013). Banki-Michell optimal design by computational fluid dynamics testing and hydrodynamic analysis. Energies, 6(5), 2362-2385.
[9] Du, J., Yang, H., Shen, Z., & Chen, J. (2017). Micro hydro power generation from water supply system in high rise buildings using pump as turbines. Energy, 137, 431-440.
[10] Du, J., Yang, H., & Shen, Z. (2018). Study on the impact of blades wrap angle on the performance of pumps as turbines used in water supply system of high-rise buildings. International Journal of Low-Carbon Technologies, 13(1), 102-108.