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Performance comparison of turbines for bi-directional flow

Manabu Takao[1], Seisuke Fukuma[1], Shinya Okuhara[1], M M Ashraful Alam[1], Yoichi Kinoue[2]

[1]National Institute of Technology, Matsue College, Japan
[2]Saga University, Japan

E-mail: takao@matsue-ct.jp

Abstract. Bi-directional airflow is generated in the wave energy plant with oscillating water column (OWC). Turbines for bi-directional airflow have been used in such devices, and they rotates in the same direction. Some turbines for bi-directional airflow were proposed, and their performance were investigated by wind tunnel tests and CFD analyses. Typical turbines have some inherent disadvantages such as severe stall and low efficiency. Therefore, the authors proposed two unique turbines for bi-directional flow: Wells turbine with booster and counter-rotating impulse turbine. Extensive numerical works were conducted to perform a comparative study between the conventional and proposed turbines.

1. Introduction

Oscillating water column (OWC) principle is a method used to acquire the wave energy in the ocean as shown in Figure 1. As secondary conversion, the special turbines that rotate in a single direction are used in an oscillating airflow [1]. These turbines do not require a system of non-return valves. Wells turbine and impulse turbine are proposed as typical turbines, however, their efficiencies are low because they have symmetrical blades attached at zero setting angle to the center plain of rotation. In recent years, the authors have been studying on Wells turbine with a booster and counter-rotating impulse turbine to alleviate the disadvantages. In this study, four types of turbines were introduced, and their performances were compared by using computational fluid dynamics (CFD) analysis.

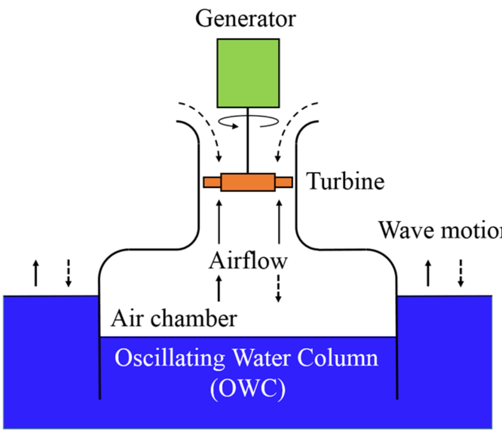


Figure 1. OWC device.

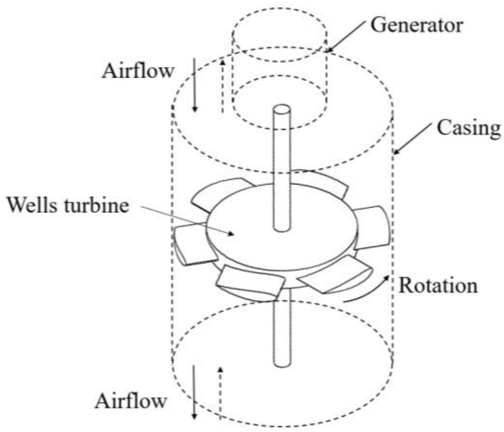


Figure 2. Wells turbine (WT).

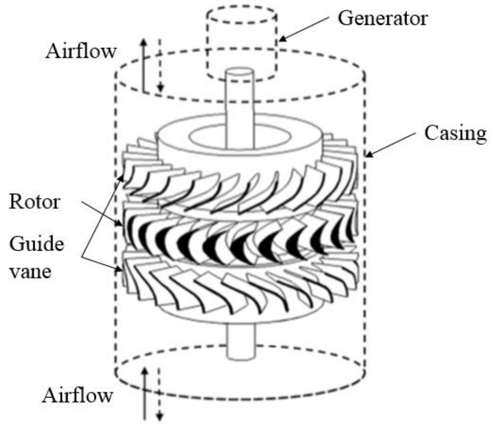


Figure 3. Impulse turbine (IT).

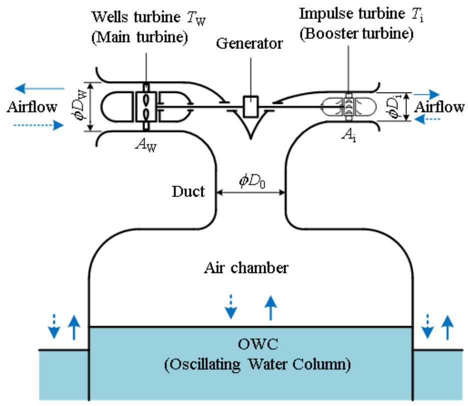


Figure 4. Wells turbine with a booster (WT-B).

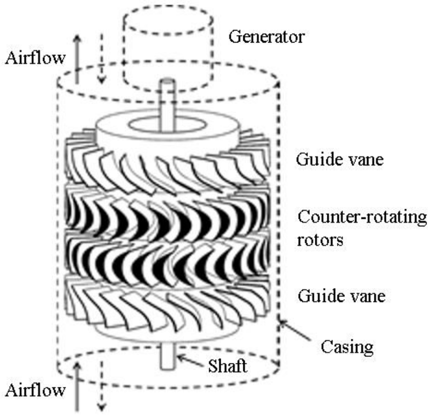


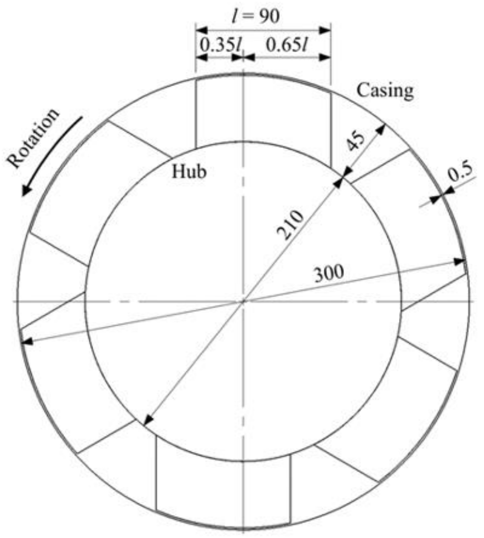
Figure 5. Counter-rotating impulse turbine (C-IT).

2. Turbines for bi-directional flow

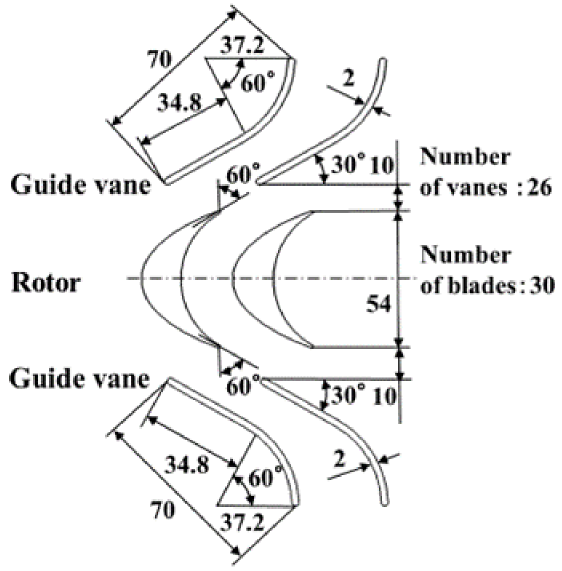
A brief introduction of four type of turbines introduced in this study is given below.

Wells turbine (WT) was invented by A. A. Wells of The Queen's University Belfast in 1976 (Figure 2) [2]. This turbine has some symmetrical blades attached at zero setting angle. For the purpose of torque increase and decrease of pressure difference, two row of guide vanes were attached at the front of and back of the rotor. This turbine had been used extensively in wave energy conversion (WEC) project because of its simple structure and miniaturization of generator. However, there are problems of its strength and noise because of its high rotational speed. Moreover, this turbine has stall problem when the flow rate increases.

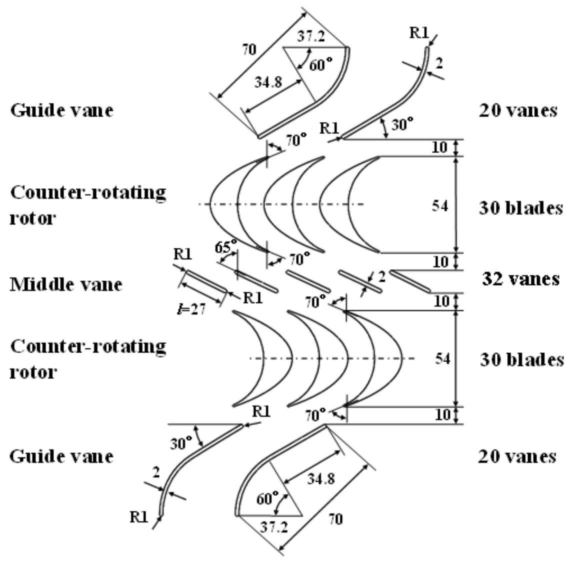
In the year of 1999, the authors invented an impulse turbine (IT) for the alternating airflow, it can be a suitable candidate to develop a high performance self-rectifying air turbine for wave energy conversion (Figure 3) [3]. This turbine is consisted of a rotor that blade profile is of circular and elliptical arcs, and two row of guide vanes that blade profile is of linear and circular arcs. The results of performance testing of the impulse turbine at both starting and running conditions reported that the impulse turbine possesses high efficiency in a wide range of flow rates. However, the peak efficiency of impulse turbine is very close to the Wells turbine.



(a) Wells turbine (D_W=300mm)



(b) Impulse turbine (D_i=300mm)



(c) Counter-rotating impulse turbine with middle vanes (C-IT-M)

Figure 6. Turbine configuration.

In order to alleviate the stall problem of Wells turbine, authors proposed a WEC system of Wells turbine with a booster (WT-B) (Figure 4) [4]. This system consists of a large Wells turbine, a small impulse turbine and a generator. The impulse turbine designed for alternating airflows is used as the booster turbine. The Wells turbine would acquire energy at low flow rates, while the impulse turbine would do the same at high flow rates.

M. E. McCormick of the United States Naval Academy proposed the counter-rotating impulse turbine (C-IT) for wave energy conversion in 1978 (Figure 5) [5]. This turbine has some inherent disadvantages of complicated construction and noise pollution. Moreover, in a model test, Richards et al. reported that the average efficiency of this turbine is of about 30%. However, a demonstration experiment using by "Kaimei" was reported that the power output of this turbine is higher than the one of Wells turbine in the ripple.

In this paper, the cascade geometry of each turbines has been adopted the most suitable one. The diameter ratio of WT-B is of 0.5. The computational data of C-IT was used, and it has middle vanes between two rotors (C-IT-M).

3. CFD analysis

Figure 6(a) shows a detailed about the configuration of Wells turbine. The specification are as follows: casing diameter, DW=300mm; blade profile, NACA0020; chord length, 90mm; number of blades, 6; solidity at mean radius, 0.67; hub-to-tip ratio, □=0.7.

As shown in Figure 6(b), the details of the impulse turbine rotor are as follows: casing diameter, Di=300mm; ratio of blade thickness, 0.3; chord length, 54mm; rotor inlet and outlet angle, □=60˚; hub-to-tip ratio, □=0.7. The adopted turbine rotor and guide vanes were reported as the most promising one in previous studies. In this study, the size impulse turbine is half of the Wells turbine in the WT-B system.

Figure 6(c) shows the specification of C-IT. The specification of rotor is as follows: casing diameter, 300mm; chord length, 54mm; ratio of blade thickness, 0.3; rotor inlet and outlet angle of rotor blade, 70˚; number of blades, 30; solidity at mean radius, 2.02. The details of guide vanes are as follows: chord length, 70mm; blade thickness, 2mm; number of vanes, 20; solidity at mean radius, 1.75; setting angle of guide vane, 30˚. In addition, the specification of middle vanes are as follows; chord length, 27mm; blade thickness, 2mm; number of vanes, 32; setting angle of guide vane, 65˚; middle vanes solidity, 1.08.

The numerical analysis was conducted using a CFD software of SCRYU/Tetra that is developed by Cradle Co., Ltd. The Reynolds-averaged Navier-Stokes (RANS) equations were used as governing equations, and the SST k-□ model was employed as turbulence model. As boundary conditions, the inflow condition was set at the inlet, the outlet was open to the atmosphere, and the no-slip condition was set on the solid boundaries. Turbine rotation was modelled by the steady Arbitrary Lagrange-Eulerian (ALE) method.

4. Evaluation formula

The turbine performance under steady flow conditions was evaluated by the torque coefficient C_T, input coefficient C_A, efficiency η, and flow coefficient ϕ. The definition of these parameters are as follows:

$$C_T = T_o / \{\rho(v^2 + u^2)Ar/2\} \tag{1}$$

$$C_A = \Delta pQ / \{\rho(v^2+u^2)Av/2\} = \Delta p / \{\rho(v^2+u^2)/2\} \tag{2}$$

$$\eta = T_o\omega / (\Delta pQ) = C_T/(C_A\phi) \tag{3}$$

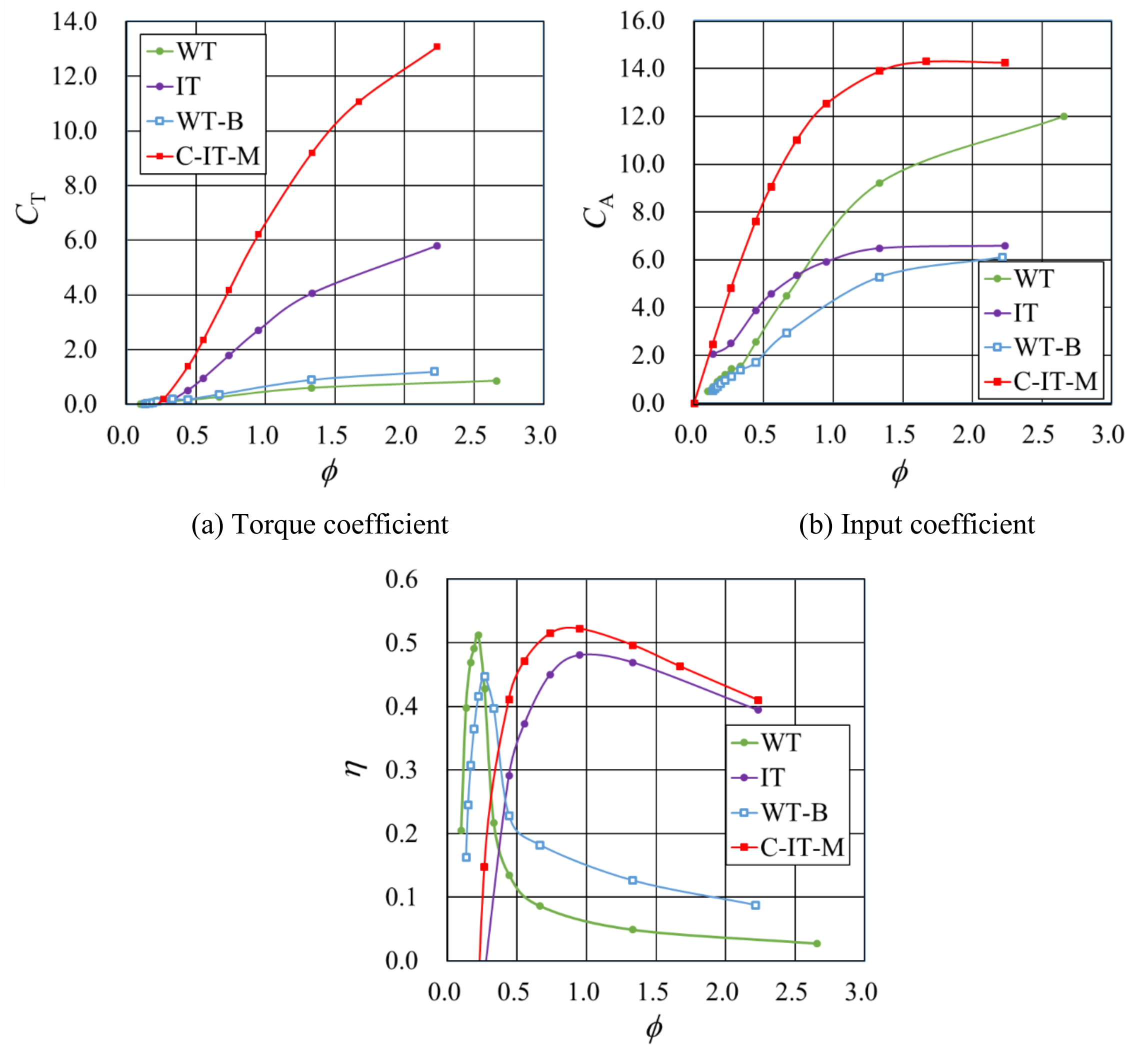
$$\phi = v/u \tag{4}$$

where A, q, T, u and ω denote the flow passage area $\{=\pi D^2(1-v^2)/4\}$, flow rate through the turbine, the turbine output torque, circumferential velocity at mean radius and the turbine angular velocity, respectively.

5. Results and discussion

A comparison work between the experimental and computational results of single turbine was conducted to validate the CFD work in previous studies as in [4], [5].

Figure 7 shows the computational results of turbine characteristics. As shown in Figure 7(a), the torque coefficients C_T of IT and C-IT-M are higher in a wide range of flow coefficients ϕ than the other turbines. In particular, C_T of C-IT-M is the highest among these four type of turbines. Thus, it can be mentioned that the C-IT-M has the best starting characteristics among these four types of turbines. Moreover, the input coefficient C_A of C-IT-M is also the highest among them. Figure 7(c) shows the computational efficiency, and the peak efficiency of WT-B is lower than one of WT. In a high flow coefficient, the efficiency of WT-B shows a twice value of WT's efficiency. Thus, it can be mentioned that the small IT acts as the booster turbine. As the rotation speed of WT is highest among these four type of turbines, the peak efficiency of WT is low in a range of low flow coefficient.



(a) Torque coefficient (b) Input coefficient

(c) Efficiency

Figure 7. Computational results of turbine characteristics.

6. Conclusion

In this study, four type of turbines was introduced, and their performance were compared by using CFD analysis. The results are summarized as follows:

1. The C-IT-M has the best starting characteristics among four types of turbines.
2. In the WT-B system, the small IT is expected and it acts as the booster turbine.
3. Rotation speed of WT is highest among four type of turbines.

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