Comparative Study on Starting Characteristics of Turbines for Wave Energy Conversion

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Abstract. Wells and impulse turbines for bi-directional airflow have been proposed as typical turbines for wave energy conversion. Each of them has some advantages and disadvantages. In recent years, the authors have proposed Wells turbine with booster and a counter-rotating impulse turbine for bi-directional airflow in order to overcome their drawbacks. In this study, the starting characteristics of four types of turbines for bi-directional airflow were compared by conducting a CFD analysis under a steady flow condition.

1. Introduction
The principle of oscillating water column (OWC) is one of the most widely used methods to capture the wave energy in the ocean. In this system, a bi-directional airflow generates in the air chamber in accordance with the sea wave motion, and this oscillating airflow then drives an air turbine. Here, as a secondary conversion device in the wave energy plant, a special type of turbines that can always rotate in a single direction are used [1]. These turbines do not require a system of non-return valves to rectify the oscillating airflow. Consequently, Wells turbine with guide vanes (Fig. 1) and an impulse turbine for bi-directional airflow (Fig. 2) have been proposed as typical turbines [2, 3], which are called “WT” and “IT”, respectively, in this study. Although Wells turbine has a high peak efficiency, it has a severe stall characteristic. While the impulse turbine has a higher efficiency in a wide range of flow coefficient, its peak efficiency is a bit lower than that of the Wells turbine though.

In order to alleviate the stall problem of the Wells turbine, the authors have proposed a Wells turbine with a booster (WT-B) (Fig. 2) [4, 5]. This system consists of a large Wells turbine and a small impulse turbine as booster and a generator. The Wells turbine would acquire energy at low flow coefficient, while the impulse turbine would do the same at high flow coefficient. Moreover, the authors have proposed a counter-rotating impulse turbine with middle vanes for bi-directional airflow as a turbine for wave energy conversion (Fig. 3) (C-IT) [6], in order to harness much energy from the ocean wave.

In this study, four types of turbines for bi-directional airflow were introduced, and their starting characteristics were compared by conducting a computational fluid dynamics (CFD) analysis under a steady flow condition.
2. Methodologies

The numerical analysis was conducted using a commercial 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 $k-\omega$ 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. The turbine rotation was modelled by the steady Arbitrary Lagrange-Eulerian (ALE) method. The casing diameter and hub-to-tip ratio of the turbines are $D=300\text{mm}$ and of $\nu=0.7$, respectively. Here, the casing diameter of the booster turbine is $150\text{mm}$. A comparison work between the experimental and computational results of WT and IT was conducted to validate the CFD work in previous studies [4-6].

**Figure 1** Cascade of Wells turbine with guide vanes (WT)

**Figure 2** Cascade of impulse turbine for bi-directional flow (IT)

**Figure 3** Principle of Wells turbine with Booster (WT-B)

**Figure 4** Cascade of counter-rotating impulse turbine (C-IT)
3. Results and Discussion

The torque characteristics of the turbines under steady flow conditions are evaluated by the torque coefficient $C_T$ against the flow coefficient $\phi (=v/u)$. The definition of $C_T$ is as follows:

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

where $A$, $Q$, $r$, $T_o$, $u$, $v$, $\rho$ and $\omega$ denote the flow passage area ($=\pi D^2(1-\varepsilon^2)/4$), flow rate generated by OWC, mean radius ($=D(1+\varepsilon)/4$), output torque, circumferential velocity ($=r \omega$) at $r$, axial flow velocity ($=Q/A$), density of air and angular velocity of rotor, respectively.

Figure 5 shows the computational and experimental results of turbine characteristics. As shown in the figure, the torque coefficients $C_T$ of IT and C-IT are higher in a wide range of flow coefficients $\phi$ than the other turbines. Especially, $C_T$ of C-IT is the highest among these four types of turbines. Thus, it can be mentioned that the C-IT has the best starting characteristics among these four types of turbines.

4. Turbine Characteristic under Sinusoidal Flow Condition

Since the airflow into the turbine is generated by the OWC, it is very important to demonstrate the turbine characteristics under the oscillating flow condition. The steady flow characteristics of the turbine are assumed to be valid for computing the performance under unsteady flow conditions, and such a quasi-steady analysis has been validated by previous studies.

The starting characteristics of the turbines are evaluated by varying the rotational speed from the rest point (i.e., $\omega = 0$). The equation of motion for a rotating system of the turbine is written by the following equation:

$$I \frac{d\omega}{dt} + T_L = T_o$$  

where $I$, $t$ and $T_L$ are the moment of inertia of the turbine rotor, time and loading torque of the generator. The flow rate in air chamber and the rotor rotational speed are assumed as follows:

$$q = Q_0 \sin(2\pi t/T)$$  

where $Q_0$ is the maximum flow rate, $t$ is the time and $T$ is the period of the wave. Here, Table 1 shows the specifications of the tested turbine rotor used in the study.

Figure 6 shows comparison of starting characteristics of the turbines for bi-directional airflow. The starting characteristics of IT and C-IT are better than WT and WT-B due to the higher torque as shown in Fig. 5. The rotational speeds of IT and C-IT are lower than WT and WT-B because the flow coefficient showing $C_T=0$ in the cases of IT and C-IT are higher than those of WT and WT-B as shown in Fig. 5. This indicates that these turbines are advantageous in terms of noise and structural strength. It can be
concluded from the above facts that the IT and C-IT have better starting characteristics among these four types of turbines.

### Table 1 Specification of turbines

| Turbine | \( I \text{ kg-m}^2 \) |
|---------|------------------------|
| WT      | 0.0193                 |
| IT      | 0.1159                 |
| WT-B    | 0.0229                 |
| C-IT    | 0.1783                 |

![Comparison of starting characteristics of the turbines for bi-directional airflow](image)

**Figure 6** Comparison of starting characteristics of the turbines for bi-directional airflow

### 5. Conclusions

In this study, four types of turbines for bi-directional airflow were introduced, and their starting characteristics were compared by conducting a computational fluid dynamics (CFD) analysis under the steady flow condition. The results obtained are concluded as follows:

1. The starting characteristics of IT and C-IT are better than the WT and WT-B.
2. The rotational speeds of IT and C-IT are lower than the WT and WT-B, and that of WT is the highest among four types of turbines.

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