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Performance of fluidic diode for a twin unidirectional impulse turbine

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Abstract. The rectification-valve system has been invented to drive an air turbine equipped with the oscillating water column (OWC) based wave energy plant. However, this flow rectification system has widely regarded as impractical, except possibly in small devices like navigation buoys, due to the lack of durability of the valves and its complex mechanism. Moreover, as the valve size must be large for a high output, that makes the system practically infeasible. Therefore, a twin unidirectional impulse turbine topology has been suggested in previous studies to make the system valueless; the conventional unidirectional air turbines can be used. In this topology, the bidirectional airflow is rectified by the pressure difference between two unidirectional impulse turbines, and the most of airflow should get through the forward turbine. However, our previous study suggested that the mean efficiency of the twin turbine system would be lower than that of the unidirectional impulse turbine, since a portion of airflow gets through the reverse turbine whose efficiency is very low. In this study, a fluidic diode was adopted in the twin unidirectional impulse turbine system in order to reduce the air flow through the reverse turbine. The wind tunnel test and computational fluid dynamics (CFD) analysis were conducted to investigate the effect of fluidic diodes on the turbine performance. Further, the usefulness of a fluidic diode in the twin unidirectional impulse turbine topology to be discussed from the view point of mean efficiency under an unsteady flow condition.

1. Introduction

A twin unidirectional impulse turbine topology has been suggested in precious studies as an air turbine equipped with an oscillating water column based on wave energy plant [1, 2].

Figure 1 shows the principle of this topology. There are two unidirectional impulse turbines in this topology, and an oscillating airflow is rectified by them without valves. The efficiency of this topology is expected to be high because it uses a unidirectional turbine which has a high efficiency.

However, in previous study [2], the mean efficiency of this topology under an oscillating flow was shown to be much lower than it is expected because a part of airflow gets through the reverse turbine which has a very low efficiency [2].

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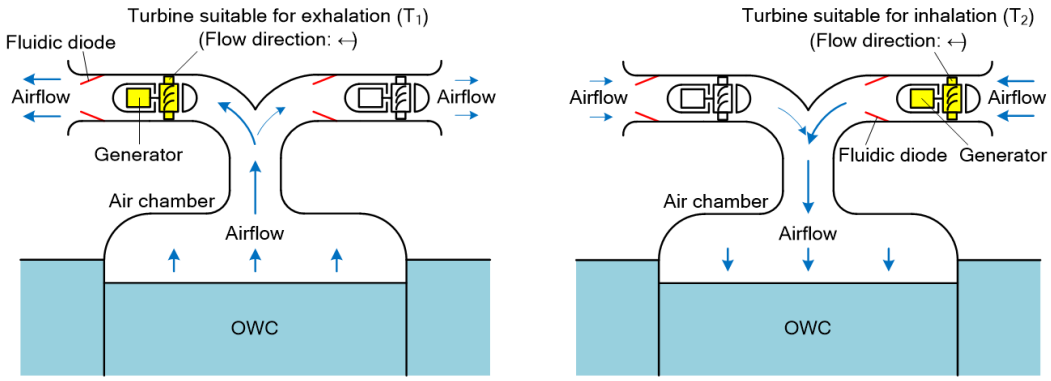
In this study, a fluidic diode [3, 4] is adopted in order to decrease the flow rate through the reverse turbine in a twin unidirectional impulse turbine topology. The objective of this study is to investigate the effect of fluidic diode on turbine performance by wind tunnel examination. Moreover, the internal flow in fluidic diode was investigated by the computational fluid dynamics (CFD) analysis.



(a) Exhalation (b) Inhalation

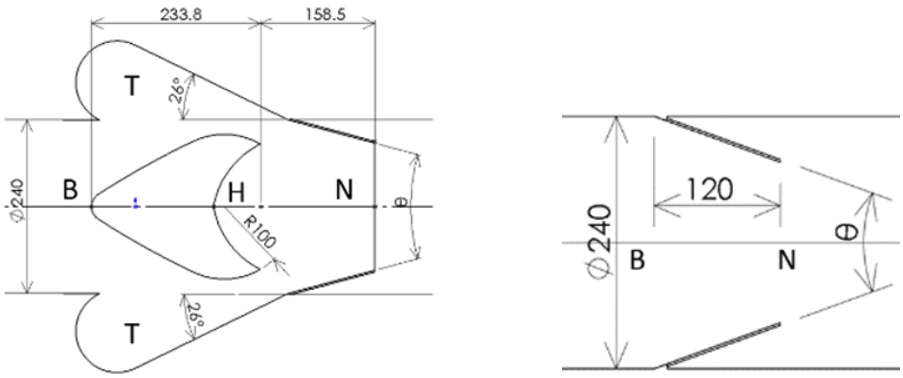
Figure 1. Principle of twin-impulse turbine for wave energy conversion.

2. Twin unidirectional impulse turbine topology and fluidic diode

In a twin unidirectional impulse turbine topology, two unidirectional impulse turbines coupled with an electric generator are installed as shown in Figure 1. In this study, when air flow gets through a turbine or fluidic diode, the flow direction that indicates smaller flow resistance is described as “forward flow”, and the flow direction that indicates larger flow resistance is described as “reverse flow”. Here, indices “f” and “r” stand for “forward flow” and “reverse flow”, respectively. A turbine in forward flow and in reverse flow are described as “forward turbine” and “reverse turbine”, respectively.

The principle of a twin unidirectional impulse turbine topology is as follows. An oscillating air flow is produced in an air chamber. Then, it is rectified into a forward turbine that has the high efficiency by a reverse turbine. Consequently, electricity is produced at high efficiency. However, the average efficiency in this topology is considerably low than that of a unidirectional impulse turbine, because a part of the air flow gets through the reverse turbine that resulting in a very low efficiency of energy conversion [2]. As a way to get rid of this problem, it was suggested to rectify the oscillating air flow by installing fluidic diode downstream from a forward turbine [4].

Fluidic diode indicates a different pressure differences between the front and back against forward and reverse flow directions. Figure 2 shows the fluidic diodes adopted in this study. Figure 2(a) shows a special type fluidic diode (unique type) which is designed by referring a fluidic diode suggested in refs. [4, 5]. The flow passage is composed of a bluff body (B) that has a hollow (H) rear, a toroidal region (T) and a conical nozzle region (N). In this study, a CFD analysis for unique type diode was carried out by changing the taper angle θ of the conical nozzle region (N). Figure 2(b) shows a fluidic diode which has a shape of a conical nozzle (nozzle type). The projection length is 120 mm and the larger diameter is 240 mm. A wind tunnel test was carried out for both unique and nozzle type diodes by varying their taper angle θ.



(a) Unique type (b) Nozzle type

Figure 2. Tested fluidic diodes.

3. Experimental and computational methods

In this study, the rectification property of the fluidic diode in a steady flow was examined by a wind tunnel test. Tested fluidic diodes were examined by varying their taper angle θ. In the wind tunnel test, a suction test apparatus was composed of a centrifugal fan, a fluidic diode and a tube of which the internal diameter was 240 mm as shown in Figure 3. The fan can generate a steady flow in the fluidic diode. The flow rate Q was measured by a pitot tube (OKANO WORKS, LK-0). The pressure in the settling chamber was measured by a pressure detector (OKANO WORKS, POP202) in order to examine the pressure differences Δp_f and Δp_r between the front and back of the fluidic diode in both the forward and reverse flows. The performance of the fluidic diode was evaluated by the pressure ratio R_D. The definition of this parameter is as follows:

$$R_D = \Delta p_r / \Delta p_f \tag{1}$$

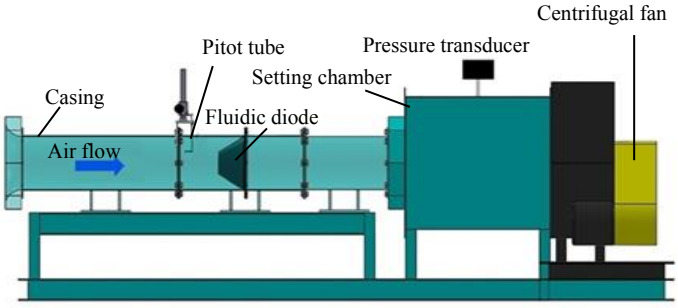
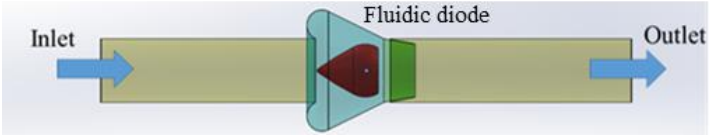
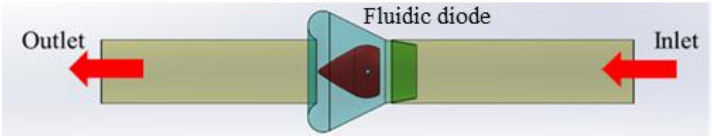


Figure 3. Test apparatus.

As a CFD tool, SCRYU/Tetra of Software Cradle Co., Ltd. was used. The governing equation was the Reynolds averaged Navier-Stokes equations, and a standard k-ε model was used as a turbulence model. The working fluid was incompressible air at 20°C. The computational region was a flow passage composed of tube and fluidic diode, and the computational region of unique type diode was consisted of approximately 1,000,000 mesh elements. As a boundary condition, the tube inner wall and diode walls were set to the no-slip boundary condition, and an inflow condition with a constant flow rate was set at the inlet. The outlet was opened to the atmosphere.



(a) Forward flow



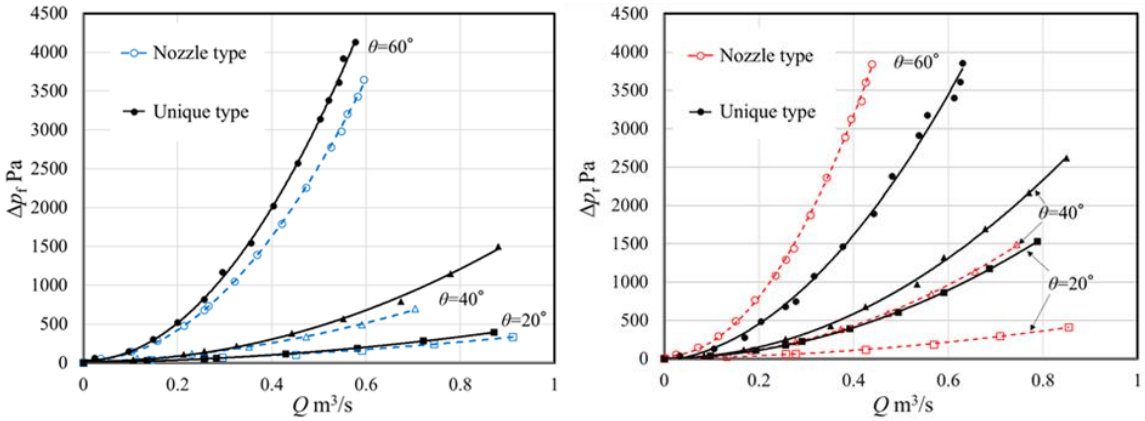
(b) Reverse flow

Figure 4. Schematics of the computational domain.

4. Results and discussion

Figure 5 shows Δp-Q characteristics that obtained from wind tunnel tests of unique and nozzle type diodes. As seen from Figure 5(a), the pressure difference Δp_F in forward flow shows an approximately similar curve regardless of the type of fluid diode at each taper angle θ. In addition, in the case of θ=20°, the pressure difference Δp_F in both cases is almost the same. Therefore, the effect of a bluff body and a toroidal region in forward flow is not so significant. On the other hand, Figure 5(b) shows Δp-Q characteristic curves in reverse flow. The pressure difference Δp_R in reverse flow of unique type diode is larger than that of nozzle type diode at θ=20° and 40°. However, when θ=60°, Δp_R of nozzle type diode is larger than that of unique type.

Figure 6 and Table 1, 2 show a comparison of pressure ratio R_D. The R_D of unique type diode is 3.60, and it is higher than that of nozzle type diode whose R_D is 1.08. Therefore, a larger rectification effect can be expected from the unique type diode. However, the R_D of nozzle type is increased as θ increases, while it decreases in the unique type diode. In the case of θ=60°, the R_D of unique type is 0.83, and it is lower than that of nozzle type whose R_D is 1.90 at this angle. As a result, the rectification effect of the unique type diode become larger than that of the nozzle type when taper angle θ is small. On the other hand, the rectification effect of nozzle type diode become larger at a larger taper angle θ.



(a) Forward flow (b) Reverse flow

Figure 5. Δp-Q characteristics.

Figure 7 show a comparison between the simulation and experimental results. As shown in figure, the predicted pressure difference across the fluidic diode has a good agreement with the experimental data.

Figure 8 and 9 shows velocity vectors and pressure distributions, respectively, around the unique type diode in both the forward and reverse flows. In Figures 8 and 9, in a forward flow, the air flows from left to right, while it flows from right to left in a reverse flow. As shown in Figure 8(a) and 9(a), in a forward flow, the airflow gently collides against the bluff body, and then, it smoothly flows through the toroidal and hollow parts because of the vortex in those parts, and it finally flows through the conical nozzle region.

Table 1. Experimental results (nozzle type).

θ °	20	40	60
Δp_f Pa	58.8	127.5	681.6
Δp_r Pa	63.7	196.1	1294.5
R_D	1.08	1.54	1.90

Table 2. Experimental results (unique type).

θ °	20	40	60
Δp_f Pa	49.0	151.9	813.4
Δp_r Pa	176.4	254.8	676.2
R_D	3.60	1.68	0.83

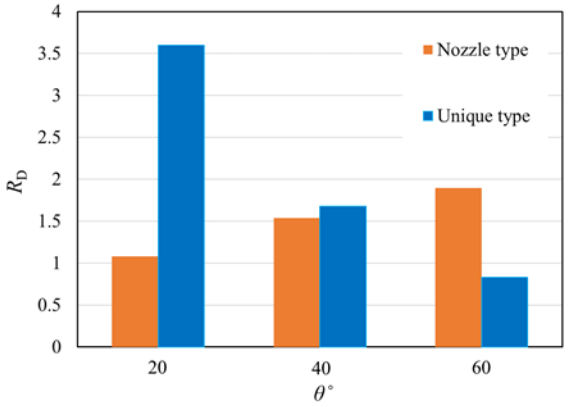


Figure 6. Comparison of R_D.

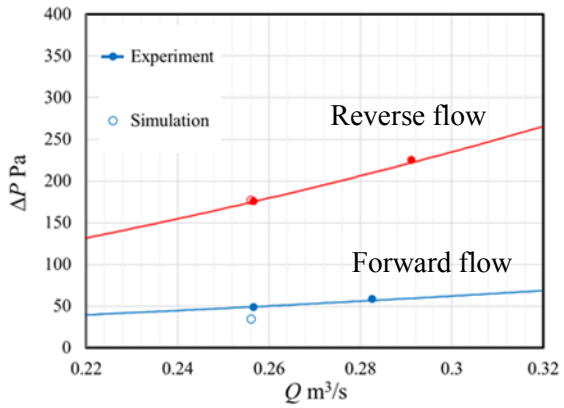
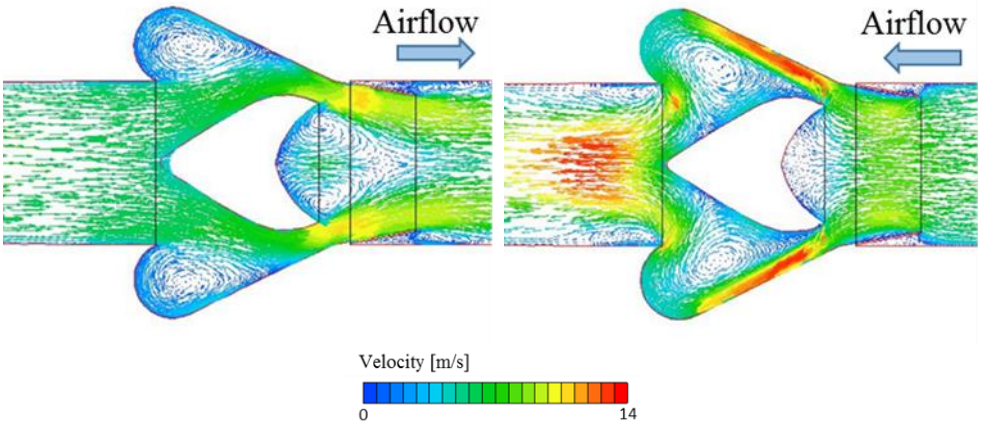
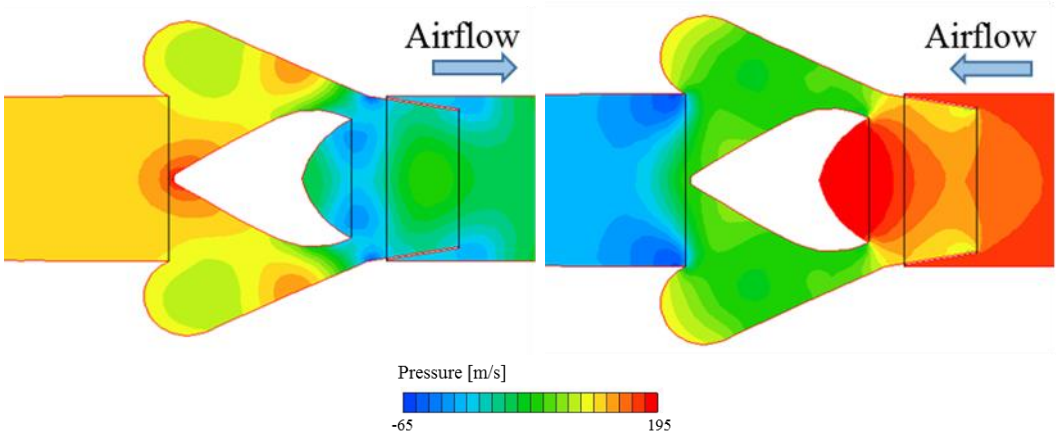


Figure 7. Comparison of simulation and experimental results (unique type, θ=20°).



(a) Forward flow (b) Reverse flow

Figure 8. Velocity vectors in fluid diode (unique type, θ=20°).



(a) Forward flow (b) Reverse flow

Figure 9. Pressure distributions (unique type, θ=20°).

On the other hand, as shown in Figure 8(b) and 9(b), the airflow first collides at the conical nozzle region, and the accelerated airflow then collides with the hollow. Finally, the airflow collides against the toroidal region, and it flows along the bluff body. There are two large velocity collisions in reveres flow, while there is no such a large velocity collision in forward flow. The larger velocity collisions are considered to be the main cause of the improved rectification performance of the tested fluidic diode.

5. Conclusions

In this study, the effect of fluidic diode on flow rectification was investigated by wind tunnel tests. Moreover, the internal flow of fluidic diodes was investigated by the computational fluid dynamics (CFD) analysis. As a result, when taper angle θ of the conical nozzle region (N) is small, the rectification effect of unique type diode become larger than that of the nozzle type diode. On the other hand, when taper angle θ of the conical nozzle region (N) is large in a nozzle type diode, the rectification effect become large.

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