Development of a non-clogging micro-hydraulic turbine of propeller type

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Abstract
This study is concerned with the development of a hollow micro-hydraulic turbine excellent in foreign matter passage performance. The runner has a circular hollow around the central (rotating) axis so that foreign matter included in water can easily flow without blocking the turbine. The laboratory experiments are conducted to investigate the turbine performance. The guide vane successfully heightens the turbine efficiency. Though the maximum efficiency decreases with increasing the hollow ratio $\varepsilon$ when $\varepsilon \geq 0.25$, it remains unchanged when $\varepsilon \leq 0.25$. The hollow of the runner effectively heightens the passage performance of the polyester fibers entrained into the turbine. When employing the guide vane, the developed micro-hydraulic turbine of $\varepsilon \geq 0.375$ is not blocked by the fibers and maintains its function.

Key words: Micro-hydraulic turbine, Foreign matter passage performance, Turbine efficiency, Guide vane

1. Introduction
In Japan, the percentage of hydraulic power generations is expected to increase steadily on the basis of a government policy promoting the development of renewable energy. As the construction of large-scale hydroelectric plants would destroy the natural environment on a large scale, expectations for the development of a small-scale hydropower, of which output is less than 100 kW, have been increasing. The small-scale hydropower distributes widely in small-scale rivers and irrigation canals. Thus, it realizes the small-scale distributed power generation. The small-scale hydropower can contribute the local production for local consumption of electric power, which is more resistant to disaster. Consequently, the development is also of great worth from the viewpoint of constructing a disaster-resistant society.

Various types of micro-hydraulic turbine have been developed [1-6]. Such hydraulic turbines are installed in small rivers and agricultural canals, and their output power is less than 1 kW. The authors [7] performed a numerical simulation of the flow through a nano-hydraulic turbine of impulse-type driven by waterfalls of extra-low head [4]. The authors [8] also conducted a numerical simulation of the flow through an open type cross-flow runner of a nano-hydraulic turbine driven by rapid and shallow stream [5].

Micro-hydraulic turbines are frequently blocked with foreign matters, such as fallen leaves, twigs and refuses, and they occasionally lose their function. A filter, equipped upstream of the micro-hydraulic turbine, can remove the foreign matters. But the equipment is a cost-up factor for the operation of the micro-hydraulic turbine. Such blockage impedes the spread of the micro-hydraulic turbine. Consequently, the development of a micro-hydraulic turbine, which is not blocked with foreign matters, can contribute the small-scale distributed power generation.

The objective of this study is to develop a micro-hydraulic turbine excellent in foreign matter passage performance. The turbine is of propeller type with a runner having a circular hollow around the central axis. In this study, such hollow micro-hydraulic turbine is designed and manufactured. The performance is investigated by using a close-loop test rig. The passage of polyester fibers entrained into the turbine is also explored. These laboratory experiments make clear the effects of the hollow diameter and the guide vane on the turbine efficiency and passage performance.
2. Hollow micro-hydraulic turbine

2.1 Comparison with existing propeller type micro-hydraulic turbine

Propeller type micro-hydraulic turbines have been widely used. The boss supporting the rotating blades as well as the generator is mounted inside a circular pipe as shown in Fig. 1. The effective cross-sectional area of the turbine is small. Thus, such micro-hydraulic turbine is frequently blocked with foreign matters, such as fallen leaves, twigs and refuses, when it is installed in small rivers and agricultural canals.

This study proposes a micro-hydraulic turbine outlined in Fig. 2. A rotational circular pipe colored red is inserted between two stationary pipes. Their axes are on a line. The inserted pipe is supported by two bearings. A runner with blades is mounted within the inserted pipe. As the runner rotates with the water flow, the inserted pipe also rotates integrally with the runner. The rotational motion of the pipe is transmitted to a generator outside of the pipe. The omission of the rotating shaft and the rearrangement of the generator markedly increase the effective cross-sectional area of the turbine. Such hollow micro-hydraulic turbine is expected to be excellent in foreign matter passage performance.

2.2 Detail of hollow micro-hydraulic turbine

Figure 3 shows the cross-section of the micro-hydraulic turbine developed in this study. A runner colored blue is embedded within the rotational pipe hatched with red. The runner and the pipe rotate integrally by the water flowing in the pipe. The diameter and length of the rotational pipe are 80 mm and 195 mm, respectively. A guide vane colored green is mounted at the end of the stationary pipe just upstream of the rotational pipe. It also has a hollow around the central axis. The diameter is the same as that of the runner.

Figure 4 shows an example of the runner having four blades. A circular hollow is provided around the rotating (central) axis so that foreign matters included in water could pass through the runner. The ratio for the hollow diameter \( D_2 \) to the pipe diameter \( D_1 \) (=80 mm) is defined as the hollow ratio \( \varepsilon = \frac{D_2}{D_1} \). The runner is the flat blade cascade as depicted in Fig. 5. Table 1 lists the specifications. The axial length \( B \) and the blade thickness \( t \) are 32 mm and 5 mm, respectively. The blade inlet angle \( \alpha_1 \) and outlet angle \( \alpha_2 \) are 70 deg. The runners with the hollow diameter of 0, 20 mm, 30 mm and 40 mm are used in this study.

An example of the guide vane is shown in Fig. 6. The cascade has eight cambered blades. The specifications are
The blade inlet angle $\alpha_1$ and outlet angle $\alpha_2$ are 0 deg and 53 deg, respectively.

A cut model of the developed micro-hydraulic turbine is presented in Fig. 7. The runner rotates with the outer circular pipe around the pipe axis. The rotational motion is transmitted to a generator or a torque meter through a belt.

Table 1 Specifications of runner

<table>
<thead>
<tr>
<th>Hollow diameter $D_2$ mm</th>
<th>0</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter $D_1$ mm</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial length $B$ mm</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade thickness $t$ mm</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade inlet angle $\alpha_1$ deg</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade outlet angle $\alpha_2$ deg</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of blades</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Specifications of guide vane

<table>
<thead>
<tr>
<th>Hollow diameter $D_2$ mm</th>
<th>0</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter $D_1$ mm</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade thickness $B$ mm</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum blade thickness $t$ mm</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade inlet angle $\alpha_1$ deg</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade outlet angle $\alpha_2$ deg</td>
<td>53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of blades</td>
<td>8</td>
<td></td>
<td></td>
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</table>

3. Experimental

3.1 Experimental setup

To investigate the turbine performance, a laboratory experiment is conducted by using a closed-loop test rig shown in Fig. 8. Water in the tank is circulated by a pump. The pipes upstream and downstream of the turbine are made of transparent acrylic resin so that the behavior of the foreign matter or polyester fibers entrained into the loop can be observed. The pressures at two points just upstream and downstream of the turbine are measured. The water flow rate is also measured by a flowmeter of propeller type mounted in a bypass pipe upstream of the turbine. To detect the turbine output, the torque is measured by a torque meter driven by the turbine. The rotational speed of the turbine is controlled by a powder brake connected with the torque meter.

The runner and the guide vane are produced in a short period of time by a 3D printer. The design parameters are the hollow diameter, the blade geometry and the number of blades. Thus, the effect of the parameters on the turbine efficiency $\eta$ and the passage ratio $\zeta$ can be effectively explored.
3.2 Entrainment and passage of polyester fibers

Polyester fibers are entrained into the turbine to simulate the entrainment of foreign matters such as fallen leaves and refuses involved in the water flow in small rivers and agricultural canals. Spherically-shaped fibers with diameter $D_f$ of 30 mm, 50 mm and 70 mm are entrained into the water flow from the water tank. Figure 9 presents the fibers. After the experiment, the turbine is disjointed to observe the fibers attaching to the guide vane and the runner.

The water passing through the turbine returns to the tank. Thus, the fibers flowing with the water can be caught at the entrance of the tank by a net. The passage ratio of the fiber $\zeta$ is defined as

$$\zeta = m_1/m_0 \ldots (1)$$

where $m_1$ is the mass of the fibers caught at the tank entrance and $m_0$ is the mass of the fibers entrained into the water flow upstream of the turbine.

3.3 Experimental conditions and turbine efficiency

Table 3 summarizes the experimental conditions. The water flow rate $Q$ is 0.01 $m^3/s$. The cases of the hollow ratio $\varepsilon$ of 0, 0.25, 0.375 and 0.5 are studied. The spherically-shaped polyester fibers with diameter $D_f/D_1$ of 0.375, 0.625 and 0.875 are released into the water flow.

The efficiency of the hydraulic turbine $\eta$ is defined as

$$\eta = T\omega / [Q(P_1-P_2)] \ldots (2)$$

where $T$ is the torque, $\omega$ is the angular velocity of the turbine, $Q$ is the water flow rate, $P_1$ and $P_2$ are the pressures at the positions 320 mm upstream and 183 mm downstream of the rotational pipe respectively.

<table>
<thead>
<tr>
<th>Table 3 Experimental conditions</th>
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<tbody>
<tr>
<td>Flow rate $Q$ $m^3/s$</td>
</tr>
<tr>
<td>Rotational speed $N$ rpm</td>
</tr>
<tr>
<td>Hollow ratio $\varepsilon$</td>
</tr>
<tr>
<td>Diameter of spherically-shaped polyester fiber $D_f/D_1$</td>
</tr>
</tbody>
</table>

4. Results and discussions

4.1 Turbine efficiency

The relation between the turbine efficiency $\eta$ and the rotational speed $N$ is investigated without entraining the polyester fibers. The effect of the hollow ratio $\varepsilon$ is shown in Fig. 10. The result for the runner without the hollow ($\varepsilon=0$) is shown in Fig. 10 (a). The maximum efficiency $\eta_{max}$ is 0.174 when the guide vane is employed. But it is 0.1 when the guide vane is not employed. One can confirm the effect of the guide vane. Figure 10 (b) shows the result for $\varepsilon=0.25$. The guide vane demonstrates the effect even for the runner having the hollow around the central axis. The result for the higher hollow ratio ($\varepsilon=0.375$) is shown in Fig. 10 (c). Though the efficiency lowers markedly, the effect of the guide vane is confirmed. When the hollow ratio is further increased ($\varepsilon=0.5$), the efficiency decreases more as found from Fig.
10 (d). This is because the blade area of the runner reduces, and accordingly the energy of the water is less converted. It should be noted that the maximum efficiency $\eta_m$ is 0.086 when the guide vane is employed. The rotational speed also decreases with increasing $\varepsilon$.

Figure 11 rearranges the relation between $\eta$ and $N$ by using the parameter $\varepsilon$. Figure 11 (a) shows the result when the guide vane is employed. The efficiency of the runner of $\varepsilon=0.25$ is almost the same as that of the runner of $\varepsilon=0$. The hollow less affects the efficiency. But $\eta$ decreases with increasing $\varepsilon$. The efficiency for the runner of $\varepsilon=0.5$ is rather low. The maximum efficiency $\eta_m$ is about 49% for the runner of $\varepsilon=0$. The result when the guide vane is not employed is shown in Fig. 11 (b). The effect of $\varepsilon$ on $\eta$ is almost the same as that when the guide vane is used.

![Fig. 10 Relation between rotational speed $N$ and turbine efficiency $\eta$](image)

![Fig. 11 Effect of hollow ratio $\varepsilon$ on turbine efficiency $\eta$](image)

The maximum efficiency $\eta_m$ and the rotational speed $N_m$ are shown in Fig. 12. When $\varepsilon \leq 0.25$, $\eta_m$ remains almost unchanged. The hollow scarcely affects the turbine efficiency. But $\eta_m$ lessens with increasing $\varepsilon$ when $\varepsilon>0.25$. The rotational speed $N_m$ decreases monotonously with increasing $\varepsilon$. Such changes in $\eta_m$ and $N_m$ due to $\varepsilon$ are not affected by the guide vane.
4.2 Passage of polyester fibers and turbine operating condition

The passage ratio $\zeta$ changes as the function of the hollow ratio $\varepsilon$ as shown in Fig. 13. When employing the guide vane, the passage ratio for the runner of $\varepsilon=0$ is extremely low, $\zeta=0.14$. It is still low, $\zeta=0.15$, for the runner of $\varepsilon=0.25$. But the passage ratio becomes markedly higher, $\zeta=0.9$, at $\varepsilon \geq 0.375$. When the guide vane is not employed, the passage ratio for the runner of $\varepsilon=0$ is low, $\zeta=0.3$. But $\zeta$ is remarkably higher at $\varepsilon \geq 0.25$, and $\zeta=1$ at $\varepsilon \geq 0.375$. These demonstrate that the hydraulic turbine is excellent in foreign matter passage performance. It is found that the guide vane lowers the foreign matter passage performance.

The micro-hydraulic turbine breaks down due to the entrained polyester fibers depending on the experimental condition. The change in the operation is also indicated in Fig. 13. When employing the guide vane, the turbine breaks down at $\varepsilon \leq 0.25$. This is because the passage ratio is very low ($\zeta=0.14$), and therefore the turbine is blocked by the fibers as explained later. But the turbine maintains its function at $\varepsilon \geq 0.375$. This is because the turbine is not blocked. When the guide vane is not employed, the turbine breaks down at $\varepsilon=0$. But it maintains its function at $\varepsilon \geq 0.25$. It is found that the operation of the micro-hydraulic turbine is not affected by the entrained polyester fibers when $\zeta \geq 0.9$.

4.3 Adhesion of polyester fibers to guide vane and runner

Figure 14 shows the photograph when the runner of $\varepsilon=0$ is used in conjunction with the corresponding guide vane. The passage ratio $\zeta$ is 0.14. Though some fibers are attached to the runner, the blockage is not observed. The guide vane is nearly blocked. Such blockage causes the breakdown of the turbine.

When the guide vane is not employed for the runner of $\varepsilon=0$, the runner is blocked by the fibers as found from Fig. 15, where $\zeta=0.3$. This is because the runner has less space around the rotational (central) axis, and therefore the fibers cannot easily pass through the runner. The turbine breaks down due to the blockage.

Figure 16 shows the photograph when the guide vane is used for the runner of $\varepsilon=0.25$. The passage ratio $\zeta=0.15$ is almost the same as that for the runner of $\varepsilon=0$. The runner is not blocked, though some fibers are attached to it. The hollow around the central axis demonstrates the effect. But the guide vane is blocked, and it induces the breakdown of the turbine.
Fig. 14 Guide vane and runner of $\varepsilon=0$

Fig. 15 Runner of $\varepsilon=0$ in the case of non-use of guide vane

Fig. 16 Guide vane and runner of $\varepsilon=0.25$

Fig. 17 Runner of $\varepsilon=0.25$ in the case of non-use of guide vane

Fig. 18 Guide vane and runner of $\varepsilon=0.5$
When the guide vane is not used for the runner of \( \varepsilon=0.25 \), the runner is not blocked by the fibers as found from Fig. 17. The turbine maintains its function.

Figure 18 shows the photograph when the guide vane is used with the runner of \( \varepsilon=0.5 \). The fibers are attached to the leading edge of the guide vane. But the blockage is not induced. It should be noted that the fibers are not attached to the runner. The hollow makes the fibers pass through the runner. The turbine maintains its function. When the guide vane is not employed for the runner of \( \varepsilon=0.5 \), no fibers are attached to the runner, though the depiction of the photograph is omitted.

5. Conclusions

A micro-hydraulic turbine with a hollow runner is designed and manufactured. The efficiency of such hollow micro-hydraulic turbine is investigated with the use of a closed-loop test ring. Polyester fibers are entrained into the turbine so as to simulate the entrainment of foreign matters included in water flow when the turbine is installed in small rivers and agricultural canals. The passage ratio of the fibers is also examined. The results are summarized as follows:

1. The guide vane successfully heightens the efficiency \( \eta \) irrespective of the hollow ratio \( \varepsilon \).
2. The maximum efficiency \( \eta_m \) decreases with increasing the hollow ratio \( \varepsilon \) at \( \varepsilon>0.25 \). But it remains unchanged at \( \varepsilon \leq 0.25 \). The rotational speed for \( \eta_m \) lowers with increasing \( \varepsilon \).
3. The hollow around the rotational (central) axis of the turbine effectively heightens the passage ratio \( \zeta \).
4. The turbine maintains its function when \( \zeta \geq 0.9 \).
5. When employing the guide vane, \( \zeta \geq 0.9 \) is achieved at \( \varepsilon \geq 0.375 \). When the guide vane is not employed, \( \zeta \geq 0.95 \) is attained at \( \varepsilon \geq 0.25 \).

Nomenclatures

- \( B \): axial length of runner and guide vane
- \( D_1 \): diameter of runner and guide vane
- \( D_2 \): diameter of hollow
- \( D_f \): diameter of spherically-shaped polyester fiber
- \( m_0 \): mass of polyester fiber released into turbine
- \( m_1 \): mass of polyester fiber captured at tank inlet
- \( N \): rotational speed
- \( N_m \): rotational speed when \( \eta_m \) appears
- \( P_1 \): pressure at turbine inlet
- \( P_2 \): pressure at turbine outlet
- \( Q \): flow rate
- \( t \): blade thickness
- \( T \): torque
- \( \alpha_1 \): blade inlet angle
- \( \alpha_2 \): blade outlet angle
- \( \varepsilon \): hollow ratio = \( D_2 / D_1 \)
- \( \zeta \): passage ratio of polyester fiber = \( m_1 / m_0 \)
- \( \eta \): turbine efficiency
- \( \eta_m \): maximum value of \( \eta \)
- \( \omega \): angular velocity

References


