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Development of a propeller-type hollow micro-hydraulic turbine with excellent performance in passing foreign matter

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A B S T R A C T

This study develops a micro-hydraulic turbine with excellent performance in the passage of foreign matter included in the water flow. The runner has four blades, with a circular hollow around the rotating axis to pass foreign matter through the runner. The ratio of the hollow diameter D_2 to the runner outer diameter D_1, D_2/D_1, is defined as the hollow ratio ε. Laboratory experiments are conducted by introducing polyester fibers into the water flow as foreign matter. The turbine efficiency η decreases with increasing ε under the fiber-free condition. For the runner having no hollow ($\varepsilon = 0$), η decreases drastically with increasing the mass of the introduced fibers. This is due to the blockage of the runner by the fibers. But η for the runners provided with the hollow decreases less. This demonstrates that the hollow makes the fibers pass successfully through the runner. Additional experiments are conducted using the runner with $\varepsilon = 0.25$. The blade leading edges near the central axis are rounded with radius R. When $R/D_1 = 0.1875$, the decrease in η due to the fibers is extremely small. The rounded leading edges successfully prevent the runner from catching the fibers, demonstrating that they effectively heighten the passage performance of foreign matter through the runner.

1. Introduction

Hydropower is a promising renewable energy resource that enables consistent power generation without being affected by the weather. In Japan, the percentage of energy generated by hydropower facilities is expected to increase steadily following government policy changes that promote renewable power generation. Distributed power generation can help to stabilize the power supply in the event of natural disaster. These considerations lead us to expect increasing use of small-scale distributed power generation that employs micro-hydraulic turbines harnessing energy without interrupting the normal flow of rivers and irrigation canals. Individual devices typically yield a power output of less than 100 kW. Several types of micro-hydraulic turbine have been studied. Savonius [1–3], cross-flow [4–6], propeller [7–9], and impulse [10] micro-hydraulic turbines have been tested experimentally. Performance tests for pump-reversing water turbines have also been conducted [11–13]. A micro-hydraulic turbine with an open cross-flow runner driven by rapid- and shallow-streams frequently observed in agricultural canals has also been studied [14]. The authors have performed numerical simulations of the flow through cross-flow [15,16], impulse [17], and rapid- and shallow-stream [18] micro-hydraulic turbines. These studies find that the efficiency of the micro-hydraulic turbines, predicted from the simulated flow, agrees nicely with the corresponding experiments. The authors have demonstrated the effectiveness of numerical simulation for the design of micro-hydraulic turbines.

The performance of micro-hydraulic turbines operating in small rivers and irrigation canals is affected drastically by foreign matter included in the water flow, such as fallen leaves, twigs, and refuse. Foreign matter adheres to the runners and deteriorates performance. The rotation of the micro-hydraulic turbine can be stopped completely when the runner is blocked with foreign matter. A filter installed upstream of a micro-hydraulic turbine can solve this problem by removing foreign matter before it reaches the runner. Such equipment increases operation costs, however. Downtime from stoppages and the increase of the operation costs for cleaning filters raise the per-kW price of a micro-hydraulic turbine's power output. The development of a micro-hydraulic turbine whose performance is not deteriorated by foreign matter has not yet been reported. Archimedes screw-shaped micro-hydraulic turbines have

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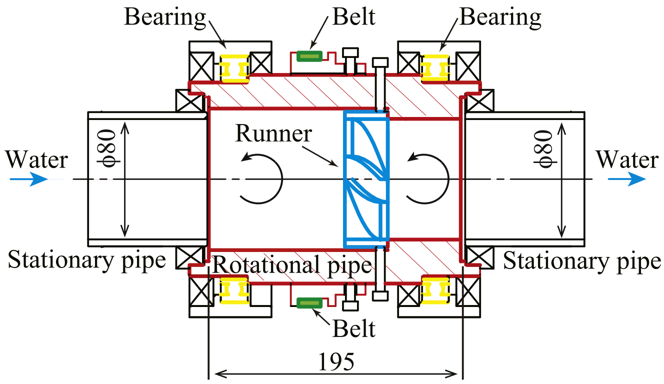

Fig. 1. Cross-section of micro-hydraulic turbine.

been shown to operate without stoppages from foreign matter [19]. Yet the Archimedes screw's ability to pass foreign matter through has not been investigated, so the superiority of Archimedes screw turbines for long-term installation in small streams is unclear.

The present study develops an entirely novel micro-hydraulic turbine that passes foreign matter excellently. The turbine employs a runner with four blades embedded in a pipe. The runner is provided with a circular hollow around the central axis that allows foreign matter to pass freely. The unique hollow is made possible because the innovative design has no rotating shaft. The authors successfully constructed the prototype runners using 3D printing technology and tested both their efficiency and ability to pass foreign matter. Polyester fibers were introduced into the water flow to simulate foreign matter. The experiments illustrate the effects of a hollow diameter and inform refinements to the shape of the blade leading edge of the runner.

2. Design and experimental method

2.1. Propeller-type hollow micro-hydraulic turbine

Fig. 1 shows a cross-section of the micro-hydraulic turbine. A freely rotating pipe (hatched with red in the diagram) is inserted between two stationary pipes, with their axes co-linear. The inserted pipe is supported by two bearings. A runner (shown in blue in the diagram) is embedded within the rotating pipe. When water flows through the pipe, the runner and the pipe rotate together. The inner diameter of the stationary and rotating pipes is 80 mm, and the axial length of the rotating pipe is 195 mm. The gap between the stationary and rotating pipes is 1 mm, and no seals are used at the gap.

Fig. 2 shows a photograph of the runner. It has four blades with a circular hollow around the rotating axis. The hollow allows foreign matter included in the water to pass through the runner. The ratio of the hollow diameter D_2 [m] to the runner outer diameter D_1 [m], D_2/D_1, is defined as the hollow ratio ε. The minimum value of D_2 is set at 20 mm so that foreign matter passes successfully through the runner without deteriorating the turbine efficiency. This study investigates the effect of D_2 on the runner performance at $D_2 = 20$, 30, and 40 mm. Thus, it employs the runners with $\varepsilon = 0.25$, 0.375, and 0.5. The ε value for the runner shown in Fig. 2 is 0.375.

2.2. Experimental setup and efficiency of micro-hydraulic turbine

To investigate the performance of the micro-hydraulic turbine, laboratory experiments were conducted using the closed-loop test rig shown in Fig. 3. Water in the tank is circulated by a pump and drives the micro-hydraulic turbine. The pipes upstream and downstream of the micro-hydraulic turbine are made of transparent acrylic resin so that the behavior of foreign matter introduced into the loop can be observed. The pressures are measured at two points, 320 mm upstream and 183 mm downstream of the micro-hydraulic turbine. The water flow rate is measured by a propeller-type flowmeter mounted in a bypass pipe upstream of the micro-hydraulic turbine. The rotating pipe of the micro-hydraulic turbine is connected to a torque meter by a belt to measure the produced torque. The rotational speed of the micro-hydraulic turbine, which is also measured by the torque meter, is controlled by a powder brake connected to the torque meter.

The efficiency of the micro-hydraulic turbine, η, is defined as

$$\eta = \frac{T\omega}{Q(P_1 - P_2)} \quad (1)$$

where T [Nm] is the torque, ω [rad/s] is the angular velocity, Q [m^3/s] is the water flow rate, and P_1 [Pa] and P_2 [Pa] are the pressures upstream and downstream of the micro-hydraulic turbine, respectively.

2.3. Foreign matter and passage performance

Spherically shaped polyester fibers, shown in Fig. 4, were used to simulate foreign matter. The authors chose this material

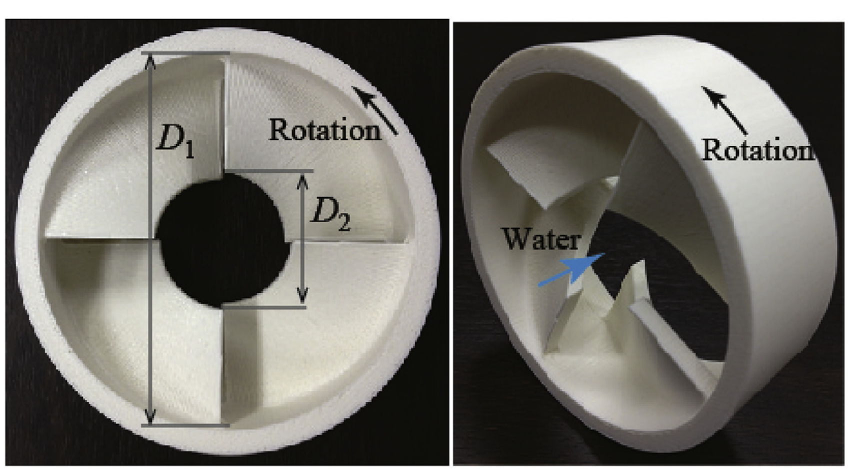

Fig. 2. Runner with circular hollow around the central axis ($\varepsilon = 0.375$).