International Journal of Fluid Machinery and Systems
Vol. 6, No. 3, July-September 2013

DOI: http://dx.doi.org/10.5293/IJFMS.2013.6.3.152
ISSN (Online): 1882-9554

Original Paper (Invited)

A Study on Darrieus-type Hydroturbine toward Utilization of Extra-Low Head Natural Flow Streams

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Abstract

A two-dimensional Darrieus-type hydroturbine system, installed with a wear for flow streams such as small rivers and waterways, has been developed for hydropower utilization of extra-low head less than 2m. There are several problems such as flow rate change and flowing wastes to be solved for its practical use in natural flow streams. In the present study, at first, a design guideline in the case of overflow or bypass flow is shown by using simple flow model. Next, in order to avoid the unexpected obstacles flowing into the hydroturbine, an installation of waste screening system is examined. It is confirmed that the screen is effective with some amount of bypass flow rate, however the output power is remarkably deteriorated.

Keywords: low head hydropower, Darrieus turbine, bypass flow, waste screening system

1. Introduction

In recent years, fossil fuel exhaustions and greenhouse gas emissions are becoming severe global issues. The most preferable solution for them is to utilize renewable energies. Hydropower is one of the most popular renewable energies since ancient times and is able to control the output power connected to the grid widely in response to electricity demand [1]. High head hydropower generation plants, installed with large scale structures like dams, however are difficult to be newly constructed for the extensive impacts on ecological system. On the other hand, the low head hydropower, especially extra-low head less than 2m, has been almost undeveloped yet for several reasons. There are many sites of low head hydropower near urban areas and there are reused type small hydroturbine which had operated in past [2]. They are expected therefore as local energy resources as well as photovoltaic and wind power generations.

We have proposed and developed a ducted Darrieus-type hydroturbine system as an appropriate one for extra-low head hydropower [3]-[6]. The Darriues-type runner is a kind of crossflow-type turbines, which consists simply of several foils rotating around the axis perpendicular to the oncoming flow stream. Because of the unique character that the turbine can rotate regardless of the oncoming flow direction, the Darriues-type turbine has been often applied for wind power generations [7] and more recently for ocean current power [8] and tidal wave power generations [9]. The “ducted” Darrieus-type hydroturbine, which we have developed, has a two-dimensional runner installed in a duct system, in general, consisting of an inlet nozzle which accelerates the flow into turbine, a rectangular casing and a draft tube for pressure recovery from dynamic pressure downstream of runner. The most preferable runner geometry has been found from our past studies as follows: NACA0018 blades with chord length/radius of runner pitch circle ratio of 0.3 and attached as the chord tangent to the pitch circle at 1/2 chord point are supported by streamlined support arms reducing a frictional torque loss. Five-bladed runner is recommended based on excellent self-starting characteristics as well as good turbine performances. Our recent studies [4, 5] have shown that, by installing the inlet nozzle, the generated torque is increased and the

Received June 25 2012; revised January 21 2013; accepted for publication February 28 2013: Review conducted by Prof. Hyung-Hee Cho. (Paper number O13010S)
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This paper was presented at 5th International Symposium on Fluid Machinery and Fluids Engineering, October 24-27, 2012, Jeju, Korea.

draft tube and the runner casing walls could be removed without deteriorating the turbine performances. By such a simplification, the cost per unit power can be drastically reduced, which is one of the most important factors for small hydropower utilizations. The Darrieus-type hydroturbine equipped with the inlet nozzle is expected to be effective for small hydropower generations in terms of hydraulic and economic performances, although the installation of another-type channeling device is also proposed elsewhere [10] for the hydraulic performance improvement of Darrieus-type hydroturbine.

As above described, we have developed a Darrieus-type hydroturbine system, which is to be installed with a weir if utilized for flow streams such as small rivers and waterways, and its effectiveness has been demonstrated through laboratory experiments. However, there remain several problems to be solved for its practical use in such natural flow streams. One of them is a significant seasonal /occasional flow rate variation, which leads to the off-design operation. More importantly, the excessive flow rate might cause the flooding upstream of hydroturbine. Another major problem is unexpected obstacles such as dead leaves, off snapped branches and any other wastes flowing into the hydroturbine, which might cause the performance deterioration and more seriously the damage to the hydroturbine system.

In the present study, we firstly propose an overflow system for the problem mentioned above, which enables us to avoid the flooding of upstream channel by lowering the weir. The effects of overflow on turbine performances are investigated experimentally by changing the height of the weir. We also investigated the effects of bypass flow, instead of overflow, on turbine performances. The bypass flow is available by the bypass opening on the weir to adjust the flow rate into the hydroturbine installed in the main flow passage. In both cases of overflow and bypass flow, as it is very important to predict the flow rate into the turbine before the design/selection of turbine, the prediction methods based on one-dimensional flow model are developed. And also, in order to avoid the unexpected obstacles flowing into the turbine, the installation of screen upstream of hydroturbine, which leads the obstacles to the bypass flow, is tentatively examined. The effectiveness of this screening system is discussed along with the turbine performance deterioration with this system.

2. Experimental apparatus

Figure 1 shows the schematic view of our test waterway and Darrieus-type hydroturbine. The test waterway with a downstream width of W_d=1,200mm is divided into up- and downstream channels by a weir with the maximum height of H_{w0}=1,000mm, at which the test hydroturbine is installed. Water in the upstream channel enters the runner section through the inlet nozzle with the width of S_{in}=400mm (S_{in}/D=0.8), where D denotes the diameter of the runner pitch circle (D=500mm). The water is collected downstream of the hydroturbine, and is fed back to the upstream channel by a circulating pump.

The test runner has five NACA0018 blades with a chord length of l=75mm and a blade span of B=300mm, which are placed in parallel with the runner pitch circle. A coreless type electric-generator with 48 poles (Sky-denshi Co., SKY-HR350) is used under the same rotational speed of the generator and the runner. Experiments are performed with various electric loads to control the runner rotating speed under constant flow rate conditions.

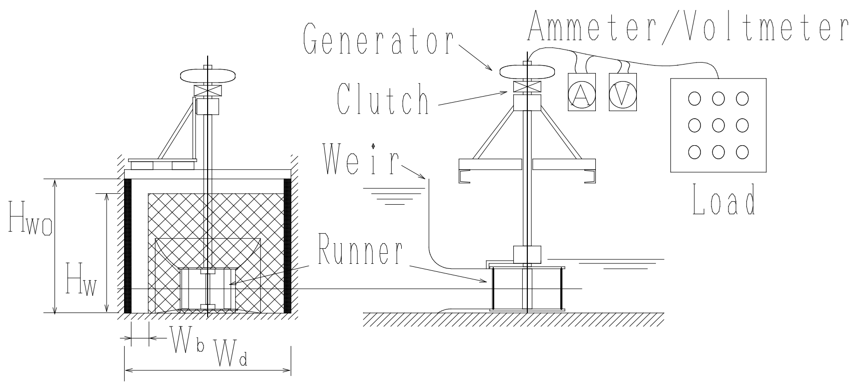


Fig. 1 Schematic view of test water way

In the present study, in order to investigate the effects of overflow and bypass flow on turbine performances, both of which are considered to overcome the unfavorable excessive flow rate, the following adjustments of the weir are carried out, which are also shown in Fig. 1. To realize the overflow above the weir, the height of the weir denoted by H_w is lowered from the maximum height of H_{w0}. On the other hand, to realize the bypass flow, the bypass opening with the width of W_b is employed with H_w=H_{w0}. To evaluate the turbine performances, we measure the total flow rate of Q with the orifice flow meter installed downstream of the circulating pump, the flow rate in the inlet nozzle Q_n with the propeller type velocimetry (Kenek Co. Ltd., MODEL: VR-301) installed inside the nozzle, and the head difference H between up- and downstream channels with the differential pressure transducer (Kyowa Electric Instruments Co. Ltd., PD-200GA). Then, the normalized turbine performances such as head coefficient C_h, power coefficient C_p and turbine efficiency η can be evaluated by,

$$C_h = \frac{H}{V_n^2/2g}, \quad C_p = \frac{P}{\rho V_n^3 B S_{in}/2} \quad \eta = \frac{P}{\rho g Q_n H} = \frac{C_p}{C_h} \tag{1}$$

where Z denotes the number of blades (Z=5), ρ the fluid density, g the acceleration of gravity, P the generated power and V_n the average velocity at the nozzle exit section.

In addition to the above experiments, we propose the installation of screen upstream of hydroturbine together with the bypass opening, which is aiming at avoiding the unexpected wastes flowing into the turbine. Figure 2 shows the picture of screen installed in the upstream channel. The screen consists of vertically aligned horizontal cylindrical bars attached in the frame (width*height =1.5m*0.8m), which is placed with the inclined angle of θ to the flow stream direction. As waste models, combinations of plastic bags and weights are used, as shown in Fig. 3. By only using the plastic bag, floating wastes like dead leaves are simulated, while the combination of plastic bag and weight is a model for long and narrow wastes like off snapped branches, which flows beneath the water surface.

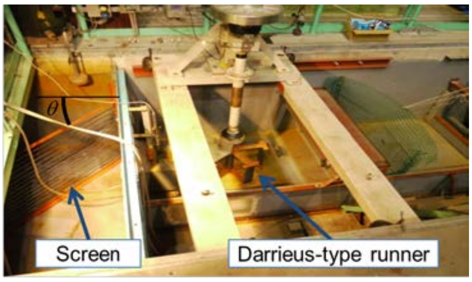
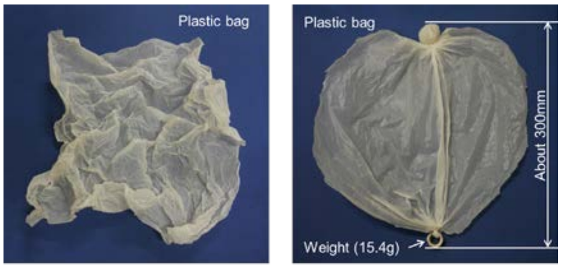


Fig. 2 Screen installed in upstream channel



(a) Floating waste (b) Waste under water

Fig. 3 Pictures of waste models

In the experiment, the performance of this system is evaluated by the probability of wastes passing through the bypass flow channel, X, which is defined by the number of wastes passing through the bypass passage divided by the total number of wastes introduced into the upstream flow channel.

3. Results and discussions

3.1 Effects of overflow on turbine performances

Figure 4 shows comparisons of turbine performances with two different weir heights of H_w/H_{w0}=0.75 and 0.56 with overflow under the constant total flow rate of Q=200L/s. The results without overflow are also shown for the constant flow rates of Q_n=Q=120 and 140 L/s with H_w/H_{w0}=1.0. The head coefficient per one blade C_h/Z, the power coefficient per one blade C_p/Z, and the turbine efficiency η at various flow rate ratios Q_n/Q are plotted against the speed ratio defined by the blade peripheral speed over the average velocity at the inlet nozzle section as U/V_n.

From these figures, we can find that the turbine performances take quantitatively similar values for the all cases, meaning that the turbine performances can be summarized by the flow rate into the hydroturbine whatever the overflow rate is. The head coefficient C_h increases with the increase of U/V_n, whereas the power coefficient C_p takes the maximum value at U/V_n=3.0, resulting in the maximum efficiency at U/V_n=2.7. And also, though Q_n/Q takes smaller values with the lower weir, as Q_n/Q decreases with the increase of U/V_n, the increase of U/V_n leads the increase of head as well as the rise of water level in the upstream channel, resulting in the increase of flow rate of overflow above the weir.

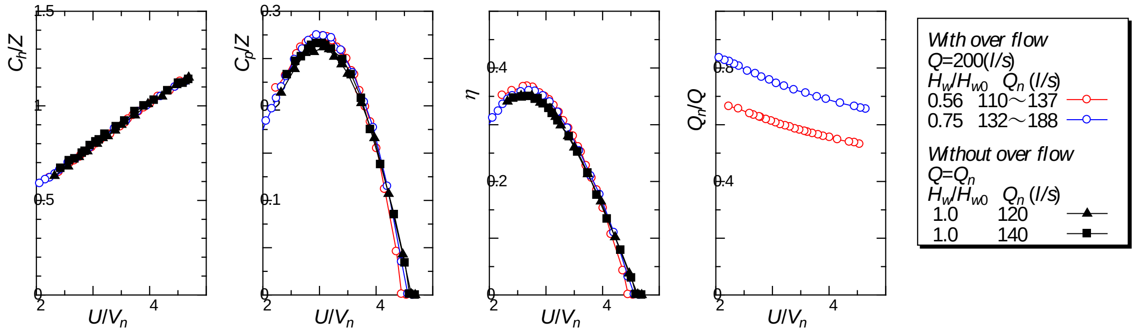


Fig. 4 Turbine performances with overflow above the weir

The above results clearly indicate that the turbine performances with the overflow can be estimated from those without the overflow, provided the flow rate Q_n into the runner. When this kind of hydroturbine is being applied for flow streams with large flow variations, one should consider the excessive flow, and an appropriate weir design is necessary for avoiding the flooding of upstream channel. At the present stage, it is very useful if one can predict the value of Q_n against total flow rate of Q and the given hydroturbine performances, which will be proposed below based on the formula on the discharge flow rate over the sharp edged weir.

According to the Japanese Industrial Standard (JIS), the discharge flow rate over the weir can be estimated by

$$Q_{weir} = KW_d(h_u - H_w)^{2/3}, \quad K = 107.1 + \frac{0.177}{h_u - H_w} + 14.2\frac{h_u - H_w}{H_w} \tag{2}$$

where h_u=H+h_d and h_d denote the heights of water level in the upstream and downstream channels, respectively. Figure 5 shows the comparisons of the flow rate ratio of the hydroturbine Q_n (=Q-Q_{weir} in the prediction) to the total flow rate Q between the experiments and the above predictions, plotted against the velocity ratio of hydroturbine. The figure clearly suggests the availability of the above prediction.

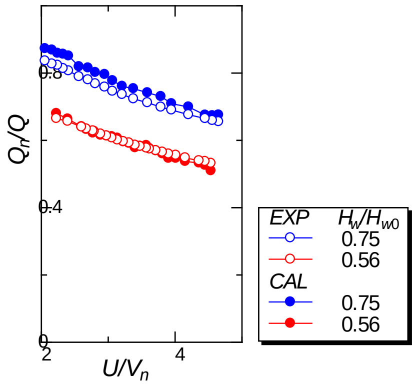


Fig. 5 Comparisons of flow rate ratio Q_n/Q between experiments and proposed predictions in overflow cases.

Considering the design criteria, the upstream level of water surface h_u must be restricted by maximum value h_{umax} which corresponds to the depth of the upstream channel. The maximum flow rate in the channel during the seasonal/occasional flow rate variations may be given at the design stage, from which we can estimate the maximum flow rate of overflow $Q_{weirmax}$ by Q-Q_{nd} (Q_{nd} is the rated flow rate of the hydroturbine). Finally, the weir can be designed with the appropriate height H_w, which will be determined from the following equation.

$$\left(107.1+\frac{0.177}{h_{u\max}-H_w}+14.2\frac{h_{u\max}-H_w}{H_w}\right)(h_{u\max}-H_w)^{2/3}=\frac{Q_{weir\max}}{W_d} \tag{3}$$

3.2 Effects of bypass flow on turbine performances

Figure 6 shows comparisons of turbine performances with the different bypass opening geometries under the flow rate of the hydroturbine Q_n= roughly 100L/s. The bypass openings are set at the both sides of the runner, and the total width of bypass openings is expressed by W_b in this case, which is changed from 0.0 to 0.22W_d. All performance curves have the same tendency with and without the bypass flow, whereas the value of C_h slightly decreases and C_p increases with the increase of W_b/W_d, i.e. the increase of bypass flow rate. As a result, η is increased.

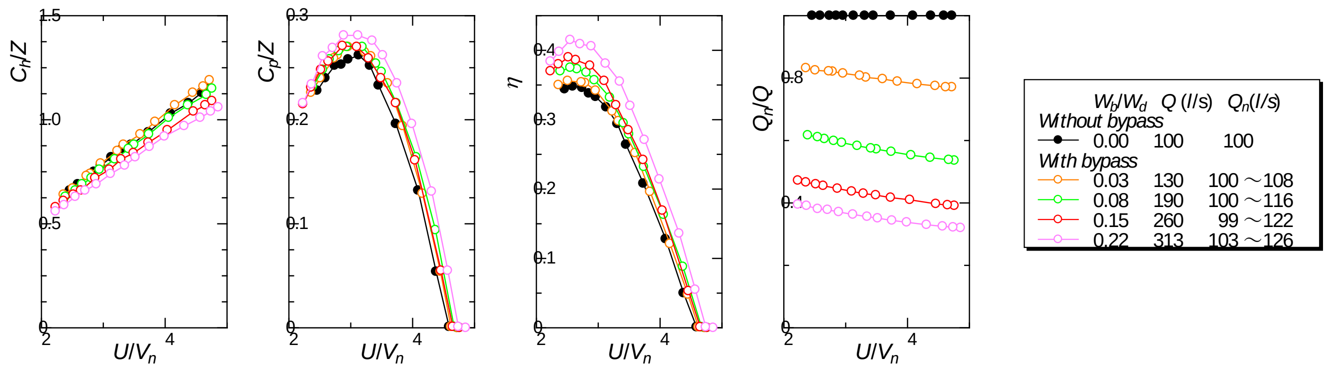


Fig. 6 Turbine performances with bypass flows

To understand the reason why the head coefficient C_h is decreased with the increase of W_b/W_d, the horizontal distributions of through-flow velocity component are measured at the section by 1D downstream of the center of the runner. Figure 7 shows the results of flow measurements at the turbine operating point of U/V_n=2.5 for the various bypass opening conditions. Since the hydroturbine is a resistance component for the incoming flow, the flow is going outward from the runner, which resulting in a slower velocity region downstream of the runner ($-1<2Y/D<1$). This can be found regardless of W_b/W_d. However, we can see that the flow outside of the runner increases with the increase of W_b/W_d, which is simply because of the increase of the bypass flow rate. Apparently the momentum exchange through the entrainments between the bypass flow and the wake of the runner occurs downstream, probably resulting in the slight head decrease with the increase of W_b/W_d.

To examine the validity of the above hypothesis, we consider the momentum balance downstream of the weir by a simple model shown in Fig. 8. At the section 1, the flow discharges from both the runner and the bypass opening with the different velocities of V_n and V_b respectively. The height of the water surface is assumed to be h_0 which is different from h_d at the section 2 far downstream of runner. At the section 2, the flow mixing between the runner discharging flow and the bypass flow is completed and the velocity becomes uniform there with V_d. From the momentum equation along with the continuity equation in the control volume shown in Fig. 8, we can numerically calculate h_0 and the total pressure increase H_{12} along the streamline from the runner exit to downstream section.

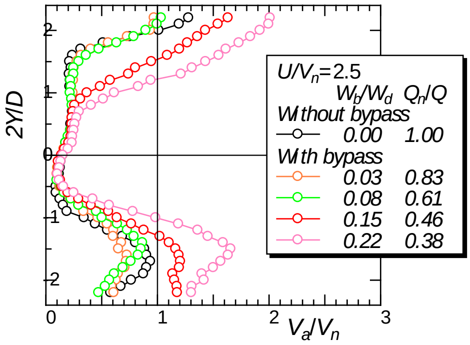


Fig. 7 Horizontal distributions of thru-flow velocity component at 1-D downstream of the center of runner

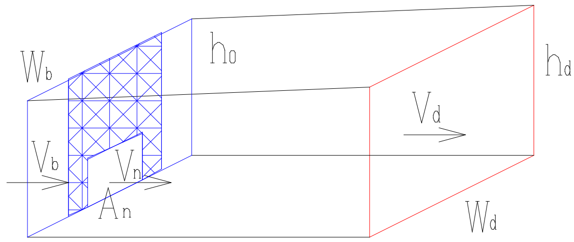


Fig. 8 A simple one-dimensional streamtube model.

Assuming that the consumed head at the runner is h_u-h_0, we can re-estimate the head coefficient C_h' as follows.

$$C_h' = \frac{h_u - h_0}{V_n^2/2g} = \frac{H - H_{12}}{V_n^2/2g} = C_h - \frac{H_{12}}{V_n^2/2g} \tag{4}$$

Figure 9 shows the re-estimated head coefficient C_h' from the measured head coefficient C_h for various bypass opening widths of W_b/W_d. We can see good agreements between them, indicating the validity of our hypothesis.

Besides the decrease of the head coefficient with bypass flow, remarkable increase of power coefficient is found in Fig. 6, which contributes the efficiency improvement. One reasonable explanation is that the bypass flow works as a kind of barrier to prevent the main flow, in the downstream path of Darrieus blade rotating, running away from the runner. Actually, from Fig. 7, we can recognize the slightly increase of the through-flow velocity downstream of the runner ($-1<2Y/D<1$) with the increase of the bypass flow, which increases the effective input power. In addition, as the bypass opening is increased, the momentum change between the bypass flow and through-flow inside the runner seems to become intensive as shown in Fig. 7, and some amount of power might be added to the runner input power in the downstream path of Darrieus blade rotating by this momentum exchange. This might also be a reason why an advantageous increase of power coefficient with bypass flow is obtained.

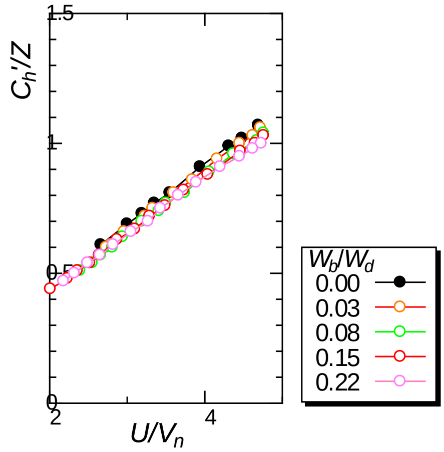


Fig. 9 Modified head coefficient with bypass flow by 1-D streamtube model

Although the turbine efficiency improvement due to reasons considered above is found with bypass flow, we should note that the bypass flow rate always exists in contrast with the overflow studied in the previous sub-section and it increases simply with the width of bypass opening. In this case, we utilize only $\rho g Q_n H$ out of the total water power of $\rho g Q H$ as an input power. If we define the total turbine efficiency η_r against the total water power, which yields to be $\eta_r=(Q_n/Q)\ \eta$, it can be easily found that the total turbine efficiency η_r is deteriorated with even small bypass opening. However, the concept of bypass flow still remains useful if we take account of waste removal, which will be described later in the following sub-section. Then, the optimization is necessary at the design stage of the weir and the hydroturbine, but for which the prediction method of main flow rate Q_n is required against the total flow rate of Q and the given hydroturbine performances.

Assuming that the head consumed by the runner $H=C_h(V_n^2/2g)$ is equal to the head loss for the bypass flow represented by $\zeta(V_n^2/2g)$, where ζ and V_n denote the loss coefficient and area-averaged bypass flow velocity defined by $Q_b/W_b h_d$ (Q_b: bypass flow rate), respectively, we obtain;

$$\zeta \frac{V_b^2}{2g} = C_h \frac{V_n^2}{2g} \tag{5}$$

The continuity equation yields

$$Q = Q_n + Q_b = S_{in} B V_n + W_b H_d V_b \tag{6}$$

From Eqs. (5) and (6), the main flow rate Q_n is predicted as

$$\frac{Q_n}{Q} = \frac{1}{1 + \dfrac{S_{in} B}{W_b h_d} \sqrt{\dfrac{C_h}{\zeta}}} \tag{7}$$

The value of loss coefficient of bypass flow ζ might be estimated by the momentum equation downstream of the weir, but we herein use the experimental values which are measured under the conditions with only the bypass flow by closing the inlet of nozzle.

Figure 10 shows comparisons of the flow rate ratio of Q_n/Q between the experiments and the predictions. We can see fair agreements between them. Then, by using this prediction method together with the head modification done by Eq. (4), we can estimate the available power with the bypass flow configuration, which may be useful for the preliminary assessment at the design or the planning stage.

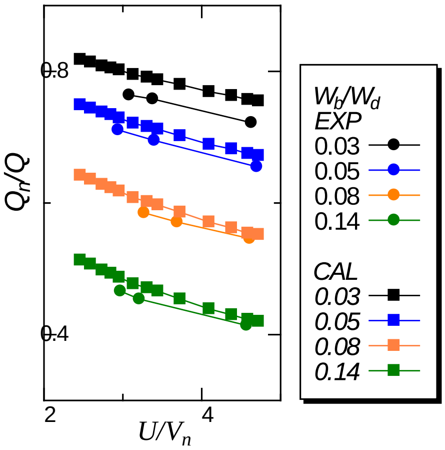


Fig. 10 Comparisons of the flow rate ratio with bypass flow between experiments and predictions

3.3. Removal of flowing wastes

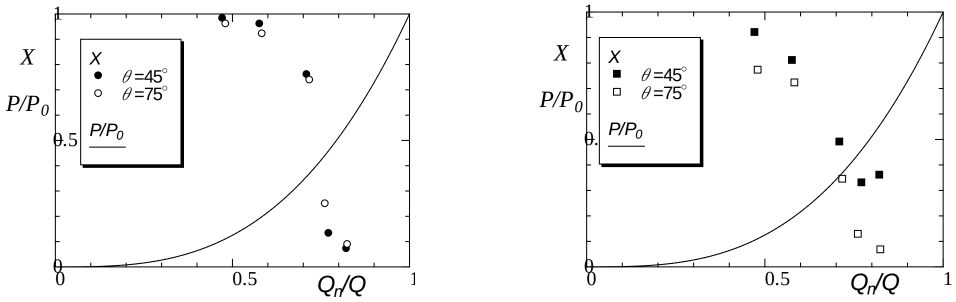
Finally, the conceptual waste removal system using a screen is experimentally examined for two kinds of model wastes, the floating one and the flowing one beneath the water.

Figure 11 shows the removal rates of wastes X for (a) floating waste and (b) waste flowing beneath the water surface, plotted against the flow rate ratio of Q_n/Q at the constant turbine speed ratio of U/V_n=3.0. Two inclined angles of screen, θ=45° and 75° are examined here. The flow rate ratio is adjusted by changing the width of bypass opening. The change of the available power P with bypass flow increasing is also shown as a solid line of the ratio of P to the power P_0 without the bypass flow.

It can be seen from Fig. 11 that, for the both wastes, small bypass flows up to 20% of total flow rates (Q_n/Q>0.8) have almost no effect on wastes removal. One of the reasons for this is that the width of bypass opening is so narrow that some of wastes can be easily stuck on the screen. By further decreasing the flow rate ratio Q_n/Q with the increase of bypass opening, some amount of wastes starts to flow away through the bypass opening. This is more remarkable for the floating waste. The effect of screen angle θ is not observed for the floating waste, because the nozzle of the hydroturbine may be placed at the bottom of the channel; it seems that the floating wastes with light weight hardly flow along the main flow into the hydroturbine. On the other hand, for the waste beneath the water surface, the inclined angle of θ=45° is more effective. Finally, by reducing the flow rate ratio up to Q_n/Q<0.5, most of wastes could be led to the bypass flow opening, then we can manage safe turbine operation with this waste removal system, However, even with Q_n/Q=0.7, the available power is significantly reduced to P/P_0=0.35, since the power is proportional to the cube of incoming velocity into the runner.

Then, to realize the hydroturbine system with this kind of waste removal device in natural flow streams, preliminary investigations of flow rate variations and possible waste types and sizes at the planned sites of turbine installation are necessary. After that, the optimized design of hydroturbine and weir could be achieved.

Here, bypass flow opening type is tentatively examined for removal of some wastes. As one of other effective methods, overflow type, as discussed in Sec. 3.1, might be considered, which will be examined as future work.



(a) Floating waste (b) Flowing beneath the water surface

Fig. 11 Removal rate of wastes plotted against the flow rate ratio with bypass flow

4. Conclusions

For the practical use of Darrieus-type hydroturbine installed with a weir into real natural flow stream sites, the effects of overflow and bypass flow on the turbine performances have been firstly investigated. The screening device of flowing wastes used with bypass flow is tentatively examined. Main conclusions are listed as follows.

1) Even with the overflow above the weir, the turbine performances can be expressed by the head coefficient, the power coefficient, and the efficiency based on the flow rate into the runner. The flow rate of overflow is found to be estimated by a generally used formula for weirs, from which we can calculate the flow rate into the runner.
2) Given the possible maximum flow rate of the channel, the appropriate height of weir with overflow can be determined by the proposed prediction method, which is useful for the design and selection of weir and hydroturbine.
3) With the bypass opening on the weir, the head coefficient, the power coefficient, and the efficiency are slightly deviated from those without bypass flow. The main reason for this seems to be due to the momentum exchange between the bypass flow and the runner flow downstream of the weir
4) The prediction method of bypass flow rate is also proposed and is found to be useful for the design of the weir.
5) The screening device of flowing wastes used with bypass flow is found to be effective with some amount of bypass flow rate, however the output power, which is proportional to the cube of turbine flow rate, is remarkably deteriorated.

Nomenclature

B	Span length of Darrieus blade [m]	Q_b	Bypass flow rate [L/s]
C_h	Head coefficient	Q_n	Main flow rate [L/s]
C_h’	Head coefficient	Q_{nd}	Rated flow rate of the hydroturbine [L/s]
C_p	Power coefficient	Q_{weir}	Overflow rate [L/s]
D	Diameter of runner pitch circle [m]	$Q_{weirmax}$	Maximum overflow rate [L/s]
g	Acceleration of gravity [m/s^2]	S_{in}	Inlet nozzle width [m]
H	Total head between up- and downstream [m]	U	Peripheral speed on runner pitch circle [m/s]
H_{12}	The head between Sectin1 to Section2 [m]	V_b	Average velocity of bypass flow [m/s]
H_d	Downstream total pressure [m]	V_d	Average velocity of downstream [m/s]
H_u	Upstream total pressure [m]	V_n	Average velocity of inlet nozzle [m/s]
H_w	The height of the weir [m]	W_b	Bypass opening width [m]
H_{w0}	Maximum height of the weir [m]	W_d	Downstream channel width [m]
h_0	Water level of Sectin1 [m]	X	The removal rates of wastes
h_d	Downstream water level [m]	Z	Number of Darrieus blades
h_u	Upstream water level [m]	θ	Screen angle [°]
h_{umax}	Depth of the upstream channel [m]	ρ	Fluid density [kg/m^3]
K	Flow coefficient	η	Turbine efficiency based on the velocity at the inlet nozzle
L	Chord length [m]	η_r	Turbine efficiency
P	Generated power with bypass flow [W]	ζ	Loss coefficient of bypass opening
P_0	Generated power without bypass flow [W]		
Q	Total flow rate [L/s]		

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