Simplified Structure of Ducted Darrieus-Type Hydro Turbine with Narrow Intake for Extra-low Head Hydropower Utilization *

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Abstract
A ducted Darrieus-type hydro turbine has been proposed for extra-low head hydropower utilization of total head less than 2m, where development is almost not done in the commercial base. Though the efficiency of Darrieus-type turbine, which is cross flow type, is not so high as conventional type, the Darrieus-type has a cost-advantage due to the simple structure. By installing a narrow intake at upstream of the runner, the efficiency becomes higher than normal intake that a width of which is the same as one of runner section. In the case of normal intake, the casing clearance between the runner pitch circle and the side-wall at the runner section becomes the influential factor which deteriorates the efficiency. On the other hand, in the case of narrow intake, it is possible to keep efficiency high, based on the fact that the distorting flow to the clearance is prevented. In the present paper, the effects of narrow intake and draft tube on turbine performance are experimentally examined and the design guideline of simplified structure for ducted Darrieus-type turbine with narrow intake is proposed.

Key words: Hydro Turbine, Low Head Hydropower, Ducted Darrieus-Type, Casing Clearance, Simplified Structure

1. Introduction
While greenhouse gas emissions problems have become serious, effective utilization of renewable energy is desired. Now a day, solar and wind powers have been developed in various places in the world although these energies might not become main substitute of fossil fuel. Hydropower has been utilized in ancient time and is well-known as having the highest cost advantages, which is expressed as a ratio of cost for its construction and maintenance to generated power, however known as the environmental destroyer for dam construction. As the result, hydropower stations for large power > 100kw has been already developed or stopped planning for construction, especially in Japan. Hydropower generation \( L \) is extracted as an expression of \( L = \eta \rho g Q H \), where \( \eta \) is the efficiency of hydro turbine, \( \rho \) the water density, \( g \) the acceleration of gravity, \( Q \) the flow rate and \( H \) the head. Micro-hydropower is generally called for \( L < 100 \)kW and often nano- and pico-hydropower for \( L < 10 \)kW, and \(< 1 \) kW. The current development is oriented to "run of the river type", not "dam type" for micro-power.

In micro-hydropower range, high head sites are in country-area with a defect that the generated power has to be transmitted to the consuming place with loss and the appropriate places are not so many. On the other hand, low head sites are in open field near urban area.
of consuming much electricity and lots of appropriate places are found for power generation. For developing micro hydropower, low head sites should be therefore focused and on account of low head the increase of generating power depends on taking lots of flow rate into the turbine.

Key factors to develop the micro-hydropower are "the cost-advantage" and "environmental friendly". To satisfy both factors the turbine system has to be a simple structure for run of the river type with high efficiency, reliable and easy operation, maintenance in ease and long life because of the cost exponentially increasing with the decrease of power for conventional type turbine system. Authors have proposed a ducted Darrieus-type turbine system for utilizing extra-low head hydropower (1)-(3), and development of the other type of hydro turbine is not done almost under such kind of conditions. Two-dimensional type of Darrieus turbine brings about a simple structure and the possibility of self-starting. Under the restriction of low head, the radius \( R \) of rotating pitch circle in the case of vertical axis or the blade span length \( B \) in the case of horizontal axis is changeable for available flow rate. This is an advantage of cross-flow type. It was shown in author’s previous reports (4)-(6) that the adoption of draft tube and narrow intake is effective to make the efficiency higher. In order to utilize the ducted Darrieus-type turbine for low head hydro turbine, it is necessary to improve the cost-advantage as high as possible. In the present paper, influence of clearance between the runner pitch circle and the side-wall of duct casing on the turbine efficiency under the case with narrow intake is investigated in comparing with the case of straight duct (normal intake). The design guideline of simplified structure for ducted Darrieus-type turbine with narrow intake is proposed.

2. Referable Geometry of Ducted Darrieus Turbine for High Efficiency

The working principle of the Darrieus turbine is illustrated in Fig.1. The Darrieus runner rotates in the same direction independent of the direction of oncoming flow with velocity \( V \) across the runner by the circumferential component \( F_u \) of the resultant force \( F \) acting on the turbine blades with aerofoil section for the relative flow velocity \( W \) and attack angle \( \alpha \). The blade force and then the load on blade vary periodically due to the cyclic change of \( (W, \alpha) \) to the blade. Assuming that flow is uniform at any cross sections, the runner efficiency \( \eta \), the generated power of the runner \( L \) and the consumed power of water \( L_{th} \) are evaluated from the next expressions (1):

\[
\eta = \frac{\bar{L}}{\bar{L}_{th}}, \quad \bar{L} = \int_0^{2\pi} F_u U d\theta / 2\pi, \quad \bar{L}_{th} = \int_0^{2\pi} (F_u U + F_d W) d\theta
\]

(1)

where \( F_u \) is the drag force, \( U \) is the peripheral velocity of blade and \( \theta \) is the blade rotating position as defined in Fig.1.

![Fig. 1 Working principle of Darrieus runner](image)
Figure 2 shows the recommended parameters of the runner geometry for normal intake. The turbine performance is the best in the case of $S/D = 1.08$ where $S$ and $D$ are denoted as the duct width [m] at section of rotating shaft and the diameter [m] of runner pitch circle. Three bladed ($Z=3$) runner with blade profile of NACA0018 is recommended as compromise between high efficiency and little torque ripple in one revolution. The chord of Darrieus blades is tangential to the pitch circle at 50% chord point as the blade attitude. The Darrieus blade should be supported parallel to the shaft by streamlined arms with taking notice of reducing a frictional torque loss. The blade end plate, the area of which has seventh the cross-sectional area of blade profile, have to be attached at the blade edge due to avoiding the induced drag. For the detail of optimum design, see Refs.(1)-(4).

![Fig. 2 Preferable Darrieus runner configuration](image)

Figure 3 illustrates a design concept of a power generation system with the Darrieus turbine under constant low head condition (5). The flow passage consists of the intake, the runner and the draft tube sections. In this case, the width of the intake with $S_{in}/D=0.80$ is recommended to obtain higher turbine efficiency $\eta_w$ as compared with the case of normal intake with $S_{in} = S$ when the draft tube is used with the enlargement parameters of the divergent angle $\theta_d = 9.5^\circ$ and the outlet/inlet width ratio $S_d/S = 2.25$.

![Fig. 3 Firstly conceivable system of Darrieus turbine](image)
Figure 4 shows effects on the narrow intake and the draft tube on turbine characteristics. Normalized rotational speed $N_1$, flow rate $Q_1$, runner generated power $L_1$ and runner efficiency $\eta_w$ are defined as the following equations;

$$N_1 = \frac{\pi DN}{(60 \sqrt{2gH_t})}$$

(2)

$$Q_1 = \frac{\bar{Q}}{BD \sqrt{2gH_t}}$$

(3)

$$L_1 = 2\bar{L}/[\rho BD(2gH_t)^{3/2}]$$

(4)

$$\eta_w = \frac{L_1}{Q_1}$$

(5)

where $N$, $H_t$ and $Q$ are the rotational speed [min$^{-1}$], the total head difference [m] between the up- and down-stream ponds and the flow rate [m$^3$/s]. In the case of normal intake with $S_{in}/D=S/D=1.08$ without the draft tube, the best efficiency of $\eta_{wmax}=0.46$ is obtained at $N_1=1.59$ as (A) in Fig.4. By installation of the draft tube as shown in Fig.3 the best efficiency is improved as $\eta_{wmax}=0.54$ at $N_1=1.72$ as (B) in Fig.4. Furthermore by addition of the narrow intake with $S_{in}/D=0.80$, the best efficiency is improved as $\eta_{wmax}=0.60$ at $N_1=1.64$ as (C) in Fig.4. Those comparisons are shown in Table1. It is found from the characteristics of $N_1$, $Q_1$ that the values of $N_1$ and $Q_1$ in operation range of Darrieus turbine are higher than those of axial flow type (7). This implies essentially that Darrieus turbine, which is high speed type, is appropriate for hydropower of low head and large flow rate.

<table>
<thead>
<tr>
<th>$S_{in}/D$</th>
<th>Draft tube</th>
<th>$N_1$</th>
<th>$\eta_{wmax}$</th>
</tr>
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<tr>
<td>1.08</td>
<td>w/o</td>
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<td>0.54</td>
</tr>
<tr>
<td>0.80</td>
<td>with</td>
<td>1.64</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**Table 1 Comparisons of best efficiency for various cases**

Figure 5 shows time-variation of generated power $L$ and consuming power $L_{th}$, estimated from Eq.(1) (4), in the operation condition near the best efficiency point at the case of normal intake with $S_{in}/D=S/D=1.08$. Indicating the blade position, the most up- and down-stream positions correspond to $\theta=90^\circ$ and $270^\circ$ respectively. The local efficiency $\eta_t$ is
obtained from $L/L_{th}$ at each position of $\theta$. When the blade position is located in upstream-side of runner ($0^\circ$ to $180^\circ$) $\eta_t$ is about 80% as shown in Fig.5. On the other hand, when the blade position is located in downstream-side of runner ($180^\circ$ to $360^\circ$) $\eta_t$ is about 30%. Then the design concept that improves the upstream-side characteristics is effective.

![Graph of $L/L_{th}$ and $\eta_t$](image)

**Fig. 5** Time variation of generated power in one revolution of Darrieus blade

### 3. Influences of Duct Casing Clearance on Efficiency

#### 3.1 Side wall effect

Influences of clearance between the runner pitch circle and casing wall on turbine performance were experimentally investigated with three bladed runner of $D=390$mm and the blade span length of $B=200$mm for the normal intake with $S_{in}/D=S/D$ and the narrow intake with $S_{in}/D=0.80$. Figure 6 shows the duct casing geometry of $S_{in}/D=0.80$ and $S/D=1.35$. Here, the intake part consists of a curved thin plate in place of a solid block as seen in Fig.3. There is no difference between performances between the curved plate and the solid block (where the figure is omitted in the present paper). In this experiment, total head, meaning of the water level difference between up- and down-stream ponds $H_t$, flow rate $Q$, output power from the shaft $L$, calculated from measured torque and rotational speed are evaluated and the static head on the wall and flow distribution with three-holes yaw-meter are measured at the sections of 0, 1 and 4 as shown in Fig.6. Figure 6 also shows measured distribution of velocity vector at the center of passage height in operation condition of $N_1=1.64$ and $Q_1=0.44$.

![Test casing geometry and measured velocity vectors](image)

**Fig. 6** Test casing geometry and measured velocity vectors at inlet and outlet sections of runner and draft tube
Figure 7 depicts change of turbine efficiency $\eta_w$ with $S/D$ for normal and narrow intakes. In the case of normal intake, the best efficiency $\eta_{w\text{max}}$ is deteriorated and the best efficiency point moves to the higher $N_1$ with increase of $S/D$. On the other hand in the case of narrow intake, the deterioration of efficiency is little and the best efficiency point is almost fixed.

Figure 8 shows the distributions of axial velocity $V'$ and head difference in direction of passage width at the runner outlet section 1 in Fig.6 in operation condition near the best efficiency point ($U/V'=3.7$) for various $S/D$ of normal and narrow intakes. The referential velocity $V'$, total and static head drop coefficient $C_H$ and $C_h$ in Fig.8 are expressed as the following equations. The subscripts of 0 and 1 mean the inlet and outlet sections of the runner respectively, and the subscript of 4 means the exit of the draft tube as shown in Fig.6.

$$V' = Q/(BD)$$  \hspace{1cm} (6)

$$C_{H1} = (H_0 - H_1)/(V'^2 / 2g)$$  \hspace{1cm} (7)

$$C_{h1} = [H_0 - H_1 + V_a^2 / 2g] \sqrt{(V'^2 / 2g)}$$  \hspace{1cm} (8)

where $H$ and $V$ are measured values of total head and velocity at width-directional position $Y$ in each section. It is found from Fig.8 as follows. In the case of normal intake, with increase of $S/D$ higher speed regions appear in both sides near the casing wall, where fluid does not work to the runner and head is never dropped. The flow rate through the runner is, then, decreased with increase of $S/D$ and generated power by runner is also deteriorated. On the other hand in the case of narrow intake, all fluids always flow through the region of the maximum generated torque of the runner near $\theta=\approx120^\circ$. Therefore even when $S/D$ is increased, the region of zero head drop is not observed and the degree of head drop is almost not changed. Figure 8(c) demonstrates that the static head becomes almost uniform in the direction of passage width for all cases. It is shown from this fact that the amount of static head drop due to work to the runner in mid-passage of the duct is agreement with the static head change due to velocity increasing in both sides near casing walls. In the case of narrow intake, the change of flow distributions with $S/D$ appears almost as the difference of static head drop, not as that of total head drop.

Figure 9 shows measured time-variations of generated torque of a Darrieus blade in one revolution at $U/V'=3.7$ in cases of normal and narrow intakes. $C_t$ is torque coefficient as $T/(\rho BD^2 V'^2)$, where $T$ is instantaneous torque evaluated from adding measured torque and torque loss due to rotating arm before installing blades. As the Darrieus runner is cross-flow type, the relative oncoming velocity and attack angle are varied with the blade position of $\theta$, as mentioned in the previous section, and generated torque takes the maximum near $\theta=\approx120^\circ$. The effects of narrow intake are (1) to control flow distortion to side-walls and (2) to improve torque generation in the rotating region near $\theta=120^\circ$ where the original efficiency is higher as shown in Fig.5.
Fig. 7 Change of turbine efficiency with duct width

Fig. 8 Flow distributions at section 1 in condition of maximum efficiency point of turbine

Fig. 9 Time variation of generated torque of Darrieus blade in one revolution
3.2 Effect of draft tube

The total head difference $H_t$ consists of consuming head through the runner, flow loss in duct and discharge loss at the exit of draft tube and that is approximated as the following equation.

$$H_t \approx H_0 - H_4 + V_a^2 / 2g$$

Figure 10 shows a comparison of the efficiency in the case of narrow intake. Figure 10(a) shows $\eta_v$, that is based on $(\rho g Q H_t)$ as the denominator of $\eta_v$, while Fig.10(b) shows $\eta_w$, obtained by using the sectional averaged head drop which is evaluated from Eq.(9) as the denominator of $\eta_w$. Though the efficiency $\eta_w$ is slightly different from $\eta_v$ including influences of the additional flow losses in the upstream passage of the section 0 and the downstream passage of the section 4, the tendency of efficiency change with $N_t$ and $S/D$ agrees well. This fact implies that the turbine efficiency can be discussed by use of $\eta_w$ based on flow parameters at the section 4 instead of $\eta_v$.

As further considerations, $\eta_{at}$ is estimated as the efficiency in the case without the draft tube, meaning that the exit of runner section is directly connected to the downstream pond. Figure 11 shows the effect of the draft tube on the efficiency in the case of narrow intake $S/D=0.80$. The efficiency in the case of $S/D=1.08$ is improved from $\eta_{at}=0.53$ to $\eta_{at}=0.60$ by installing the draft tube. On the other hand, the efficiency in the case of $S/D=1.35$ takes $\eta_{at}=0.59$ with draft tube and $\eta_{at}=0.57$ without draft tube. This result indicates that the effect of installing the draft tube becomes weakened in the case of $S/D=1.35$ in comparison with the case of $S/D=1.08$.

Figure 12 shows the axial velocity and head distributions in direction of passage width at the sections 1 and 4 in the operating condition near the best efficiency point ($\theta=120^\circ$). The Darrieus blade generates the same power at this $\theta$ and $\eta_w=1.08$ is improved from $\eta_{at}=0.59$ with draft tube and $\eta_{at}=0.57$ without draft tube. This result indicates that the effect of installing the draft tube becomes weakened in the case of $S/D=1.35$ in comparison with the case of $S/D=1.08$.

Next, the direct effect of the clearance between runner pitch circle and side-wall of duct casing on the runner performance in the case of narrow intake is discussed here by focusing on the change of runner efficiency $\eta_v$ with $S/D$. The runner efficiency $\eta_v$, defined as Eq.(10), is also shown in Fig.11(b), where it is recognized that the best efficiency $\eta_{max}$ is obtained in the case of $S/D=1.14$.

$$\eta_v = L / \left[ \rho g Q (H_0 - H_1) \right]$$

The reason for the change of $\eta_v$ with $S/D$ is presumed from Figs.5 and 9 as follows. In the case of narrow intake, as all fluids flow through the region of the maximum generated torque of the runner near $\theta=120^\circ$. The Darrieus blade generates the same power at this region as symbols of $\bullet$ and $\circ$ in the range of $\theta=0^\circ$–$120^\circ$ of Fig.9, and the local efficiency $\eta_{up}=L_{up}/L_{chup}$ takes about 80% independent of $S/D$. On the other hand, when the blade passes in the downstream path of $\theta=180^\circ$–$360^\circ$ in the case of narrow clearance like $S/D=1.08$, the generated power of Darrieus blade is lower and the local efficiency is deteriorated as about 30% ($=L_{down}/L_{chdown}$) as seen in Fig.5. As the result, the averaged efficiency of the runner,
evaluated roughly from $\eta_t = (L_{up} + L_{down})/(L_{chup} + L_{chdown})$, takes 65% in the case of narrow clearance. With increase of the clearance like $S/D=1.35$, the local efficiency in upstream path keep about 80% high, which is the same in narrow clearance, because all fluids flow through the maximum generated torque region independent of $S/D$. And the powers of $L_{down}$ and $L_{chdown}$ in downstream path are decreased due to flow distortion as symbols of ♦ and ■ in the range of $\theta=180^\circ$–$360^\circ$ of Fig.9. If the local efficiency in downstream path takes the same of about 30 %, the averaged efficiency of $\eta_t$ is improved as shown in Table 2, where results of tentative calculation are shown on efficiency change.

<table>
<thead>
<tr>
<th>$L_{up}$</th>
<th>$L_{down}$</th>
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<th>$\eta_{down}$</th>
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</table>

Fig. 10  Comparison of evaluated efficiency by different methods

Fig. 11  Draft tube effects on efficiency in case of $S_n/D=0.80$
3.3 Concept of simplified structure

Figure 13 depicts changes of the best efficiency $\eta_{w1,max}$ and $\eta_{w4,max}$ with $S/D$. In the case of normal intake, with increase of $S/D$ $\eta_{w1,max}$ and $\eta_{w4,max}$ are decreased together so that higher efficiency is obtained in the case of casing clearance is small with draft tube. On the other hand in the case of narrow intake, with increase of $S/D$ the efficiency in the case of flow discharge directly to downstream pond from the runner outlet becomes close to the efficiency in the case of installing the draft tube as $\eta_{w1,max} = \eta_{w4,max}$. This result implies that there are no side-walls of duct casing at runner section and no draft tube in the case of narrow intake that is simplification of structure of the hydro turbine system. Figure 14 finally illustrates the conceivable structure of turbine system.
4. Concluding Remarks

It is considered that a ducted Darrieus-type turbine is applied for low head hydropower utilization. Influences of the clearance between runner pitch circle and side-wall of duct casing on turbine efficiency in the cases of normal and narrow intakes were investigated. As the result, there is little influence of the casing clearance on the efficiency in the case of narrow intake. It is clarified that without deteriorating turbine efficiency the structure of turbine enables to become simplified by removing the side-wall at the runner section and the draft tube downstream of the runner.

References


