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DEVELOPMENT OF DUCTED DARRIEUS TURBINE FOR LOW-HEAD HYDROPOWER UTILIZATION

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After introducing the present situation of micro-hydropower utilization in Japan, it is mentioned that how to extract an extra-low head power is one key-solution of problems on fossil fuels exhaustion and greenhouse gas emissions. Since extra-low head sites of rivers are available near urban-sides with high population where there is a demand for electricity, an appearance of suitable turbine, which has high cost-effectiveness, maximum reliability, easy maintenance and little environmental impact, is expected. In the present paper, a guiding principle of design parameters of a ducted Darrieus-type water turbine for high performance is shown based on authors' experimental results. Then the advantage and disadvantage of Darrieus turbine are reviewed and the key problems, which are settled as urgent works in future in order to diffuse the utilization of extra-low head hydropower, are finally suggested.

Key Words: Renewable energy, Darrieus-type water turbine, Hydropower, Extra-low head, Power generation system.

INTRODUCTION

Fossil fuels exhaustion and greenhouse gas emissions problems have to be settled for civilized life of descendants on the earth. One solution of these problems is hydropower utilization as renewable energy. Hydropower is well-known as having the highest cost advantages, which is expressed as a ratio of cost to generated power, but known as the environmental destroyer for dam construction. As the result, hydropower stations for large power > 100 kW has been already developed or stopped planning for construction, especially in Japan. Hydropower generation P is extracted as an expression of $P=\eta\rho gQH$, where η is the efficiency of hydro turbine, ρ the water density, g the acceleration of gravity, Q the flow rate and H the head. Figure 1 shows a selection chart of appropriate turbine system for Q and H. Micro-hydropower is generally called for P<100 kW and often nano- and pico-hydropower for P<10 kW, and <1 kW. Each turbine system depicted in Fig.1 cannot be explained for want of space for description here. 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 so low pollution 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 [1]. For developing micro hydropower, low head sites should be therefore focused and on account of low head in this case the increase of generating power depends on taking lots of flow rate into the turbine.

In this paper, the present situation on developing low head power utilization in Japan is described and the today's problems for the development are shown at first. Then, a ducted Darrieus turbine system, developed by authors for extra-low head hydropower, is focused. The guiding principles for designing high efficiency runner are reviewed at first and the applications of the Darrieus turbine to constant head sites as a river and industrial wasted flow are demonstrated based on up-to-date data of small-sized model tests.

PRESENT SITUATION ON LOW HEAD HYDROPOWER UTILIZATION IN JAPAN

As seen in Fig.1, in the head range of H > 4m the tubular or bulb turbines are used as commercially based type. Even in the range of H > about 1.5-2m, the same type of turbine is applied as the extension as shown Fig.2. There are lots of appropriate site for micro-hydropower station as (1) weirs in river and flume, (2) idle head in water treatment plants, (3) surplus pressurized water in industry and so on. Engineers on hydropower make effort with promotive policies, which are (1) new energy foundation, (2) law of renewable portfolio standard and (3) kyoto protocol, to introduce the system to these appropriate sites in Japan. It is not easy, however, to introduce it because of

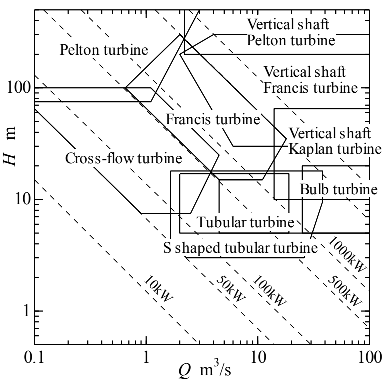


Fig.1 Selection chart of appropriate turbines

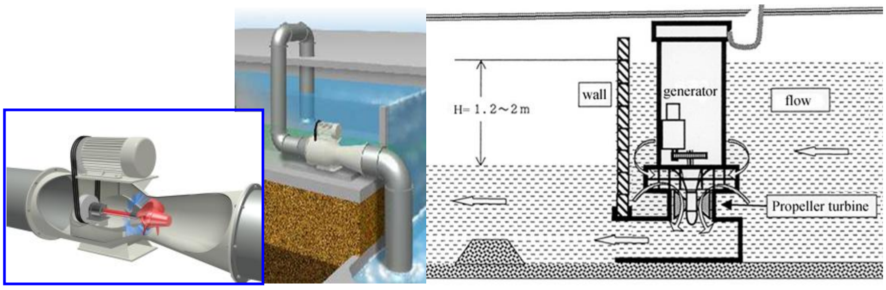


Fig.2 applications of propeller turbine for low head power [2] some troubles to settle, that are (1) law of electric work, (2) law of river keeping clean and (3) right on water utilization by farmers and fishers. In additions, the utilization of further lower head hydropower yields more poor cost-effectiveness as shown in Fig.3. Then, another new type of turbine, which has simplified structure and higher performance, is required, different from conventional type.

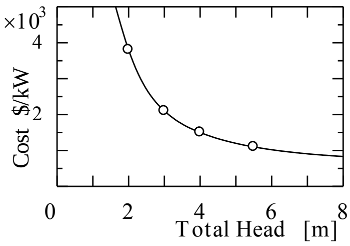


Fig.3 Cost-effectiveness of propeller turbine [3]

DEVELOPMENT OF DUCTED DARRIEUS-TURBINE AND ITS APPLICATION

The working principle of Darrieus turbine is depicted in Fig.4, where blade forces of lift F_l and drag F_d for the relative flow of velocity W and attack angle α in the operating condition of the oncoming absolute velocity V and the peripheral speed of the blade U. The generated average power in one revolution of the runner L and the runner efficiency η_t are evaluated theoretically from the next expressions [4]. Here θ is the blade rotating position as defined in Fig.4.

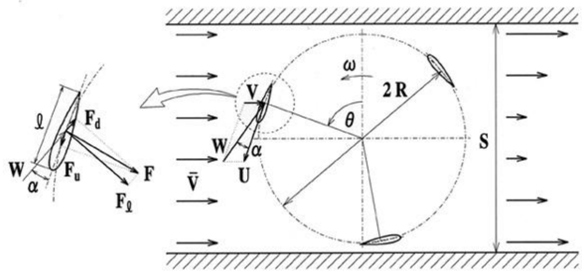


Fig.4 Working principle of Darrieus runner

$$\overline{L} = \int_0^{2\pi} F_u U d\theta \Big/ 2\pi \quad ,$$

$$\overline{\eta_t} = \int_0^{2\pi} F_u U d\theta \Big/ \int_0^{2\pi} (F_u U + F_d W) d\theta \qquad (1)$$

As Darrieus turbine is cross-flow type, the relative flow varies in one revolution of runner and the instantaneous generated power and efficiency of a single bladed turbine is also changed as shown in Fig.5. This result is obtained theoretically in a operation condition near the best efficiency point (the ration of rotational speed to oncoming inlet velocity U/V^*=3.2) at the case of parallel walled duct ($S_{in}/D = S/D$ =1.08) as Fig.4 [5], where the runner geometry is selected as preferable for high η_t as (1) a symmetric blade of NACA0018 with the ratio of blade chord length to the radius of the runner pitch circle l/R =0.3, (2) a blade setting attitude tangent to the pitch circle at its mid-chord point, (3) attaching the blade end plates to both edges of the Darrieus blade, (4) streamlined supporting arms. For the detail of optimum design, see Refs. [4] and [5]. In Fig.5 L_{th} means the consuming power of F_uU+F_dW. It is found from Fig.5 that the Darrieus blade yields higher efficiency of η_t =about 80% in the range of the upstream passing from $\theta=\pi/6$ to $5\pi/6$ and the average efficiency in one revolution takes about 60%. This result demonstrates the effectiveness of installing the narrow inlet nozzle.

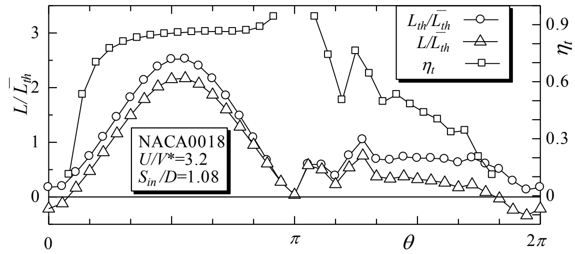


Fig.5 Time variation of powers and efficiency

Then, the inlet nozzle effect was investigated experimentally. with the diameter of runner pitch circle of D=370mm and the Darrieus blade span length of B=200mm. Figure 6 illustrates the horizontal cross-section of test duct, where the inlet nozzle width is denoted as S_{in} , the duct width at runner section as S, and the outlet width of draft tube as S_d. In this experiment, flow rate Q , output power L from the shaft, calculated from measured torque and rotational speed, were evaluated and flow distribution of head H and velocity V with three-holes yaw-meter were 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 three

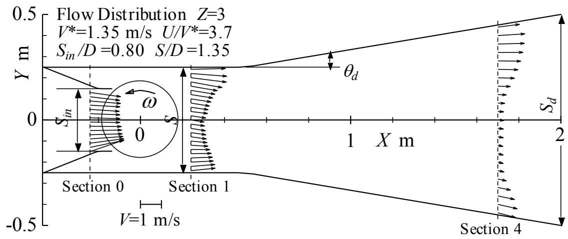


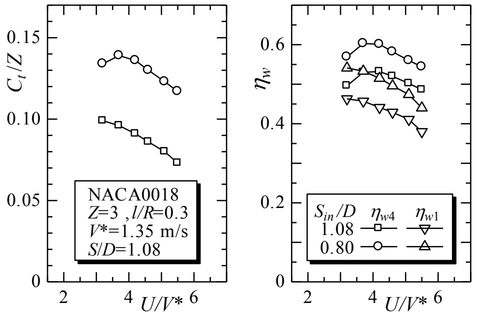
Fig.6 Horizontal cross-section of Darrieus turbine duct (width S) with inlet nozzle (width S_{in}) and draft tube (outlet width S_d)

bladed Darrieus runner (Z=3) at U/V^*=3.7, where V^* means the velocity at inlet nozzle section. Figure 7 shows the performance in the cases of S_{in}/D=1.08 and 0.80 under S/D=1.08 and Z=3. Here the torque coefficient C_t and efficiencies η_{w4} , η_{w1} are defined as follows.

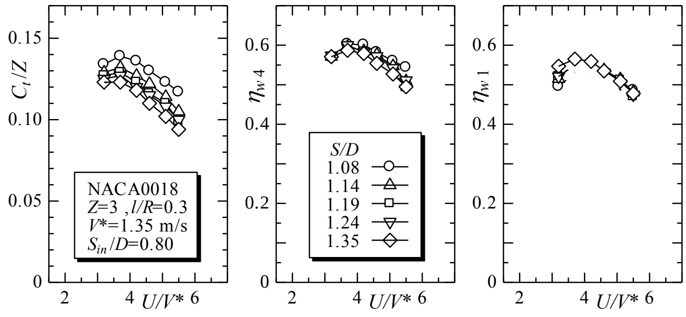
$$\overline{C_t} = (\overline{L}/\omega)/(\rho B D^2 V^{*2}) \quad , \quad \overline{\eta_{w\cdot j}} = \overline{L}/(\rho g Q \overline{H_{t\cdot j}}) \quad ,$$

$$\overline{H_{t\cdot j}} = \overline{H_0} - \overline{H_j} + \overline{V_j}^2/2g \quad , \quad V^* = Q/(BD) \qquad (2)$$

where ω is the angular speed of rotation and the subscript of j means measuring sections of 1 or 4. It is found from Fig.7 that by installing inlet nozzle of S_{in}/D=0.80 the efficiency of η_{w4}, corresponding to the case with the draft tube, is improved from 0.54 in S_{in}/D=1.08



(a) Torque coefficient (b) Turbine efficiency
Fig.7 Change of turbine performance with S_{in}/D in case of S/D=1.08 with and without draft tube



(a) Torque coefficient (b) Efficiency η_{w4} (c) Efficiency η_{w1}
Fig.9 Change of turbine performance with S/D in case of S_{in}/D=0.80 with and without draft tube

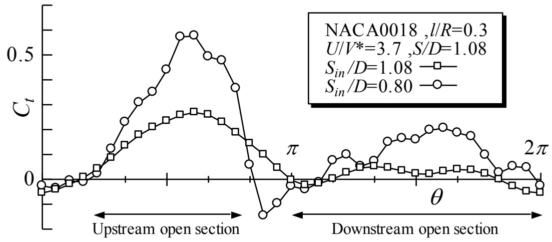
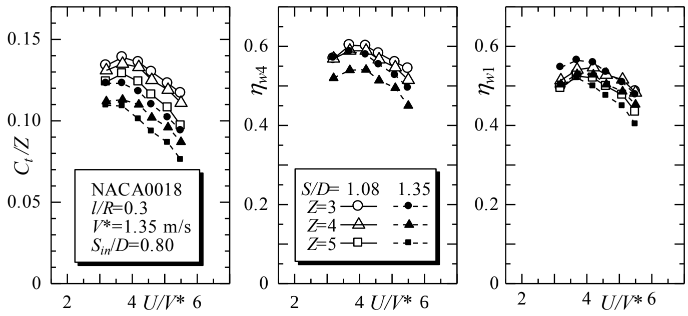


Fig.8 Change of time variation of generated torque with blade number in case of S_{in}/D=0.80



(a) Torque coefficient (b) Efficiency η_{w4} (c) Efficiency η_{w1}
Fig.10 Change of turbine performance with S/D in case of S_{in}/D=0.80 with and without draft tube

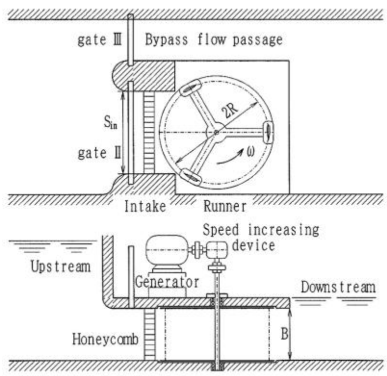


Fig.11 Simplified duct of Darrieus hydro-turbine

to 0.60 though the torque (power).is a little decreased. Figure 8 shows the time variation of measured torque in one revolution. As presumed from previous discussion with Fig.5, all water passes through so high efficiency range of upstream path that the torque is increased there with improvement of efficiency. In addition, as the flow becomes jet from the inlet nozzle against downstream path of Darrieus blade, the generated torque near $3\pi/2$ is also increased. In Fig.8, result in the case of S_{in}/D=1.08 and S/D=1.35 is also depicted for the later discussion.

In Fig.7, effect of installation of draft tube is also depicted as η_{w4}, for case with and η_{w1} for case without the draft tube. In general, the draft tube must be installed to reduce the discharge loss, corresponding to the velocity head at the outlet in Eq.(2), and to extract hydropower effectively. The result of $\eta_{w4} > \eta_{w1}$ in Fig.7 demonstrates that in the case of S/D =1.08, the draft tube is necessary to keep efficiency higher independent of S_{in}/D.

Next, the effect of duct width S/D was investigated under the case of S_{in}/D=0.80 and Z=3 to examine the simplification of duct. Figure 6 shows the duct casing geometry of S_{in}/D=0.80 and S/D=1.35. Figure 9 shows change of the performance with S/D under S_{in}/D=0.80 and Z=3. Under the case of S_{in}/D=0.80, the torque coefficient C_t and efficiencies η_{w4} are little decreased with increase of S/D. It is found from Fig.8 that the reduction of generated torque occurs at downstream path near $\theta=3\pi/2$, which is the range of poor efficiency as shown in Fig.5. On the other hand, the efficiency η_{w1} is increased with increase of S/D as the width of S/D is approached to the width of draft tube outlet S_d/D. The efficiency in the case of S/D=1.08 is improved from η_{w1}=0.53 to η_{w4}=0.60 by installing the draft tube while the efficiency in the case of S/D=1.35 takes η_{w4}=0.59 with draft tube and η_{w1}=0.57 without draft tube. This result indicates that the effect of installing the draft tube becomes weaken-ed in the case of S/D=1.35 in comparison with the case of S/D=1.08. Figure 10 depicts changes of the best efficiency η_{w1max} and η_{w4max} with S/D in the case of S_{in}/D=0.80 and various blade number. In the case of S_{in}/D=0.80, with increase of S/D the efficiency η_{w1max} becomes close to the efficiency η_{w4max} as $\eta_{w1max}=\eta_{w4max}$ in the case of Z=3. 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 11 finally illustrates the conceivable structure of turbine system.

CONCLUDING REMARKS

It is considered that a ducted Darrieus-type turbine is applied for low head hydropower utilization. Guiding principle of Darrieus turbine design are clarified at first. Influences of the clearance between runner pitch circle and side-wall of duct casing on turbine efficiency in the cases of narrow intakes were investigated and results are shown. 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. Finally some drafts of conceivable application are illustrated in Fig.12.

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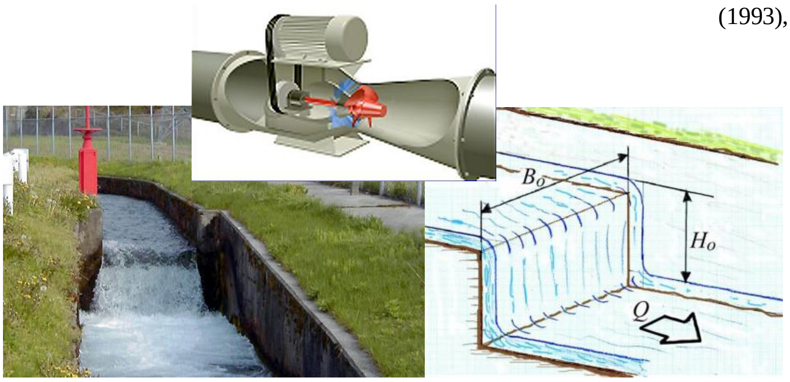
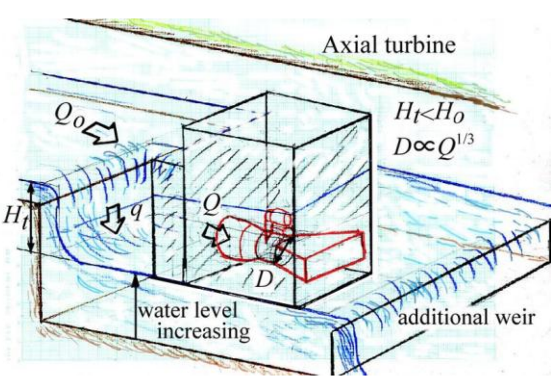
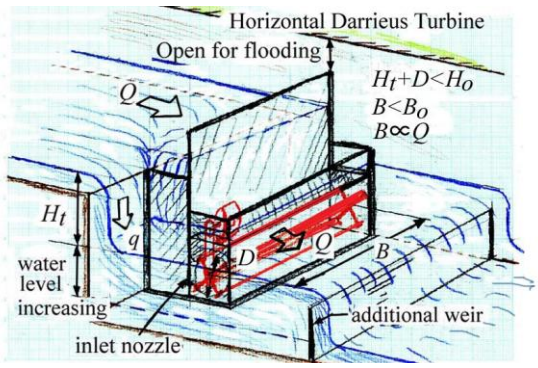


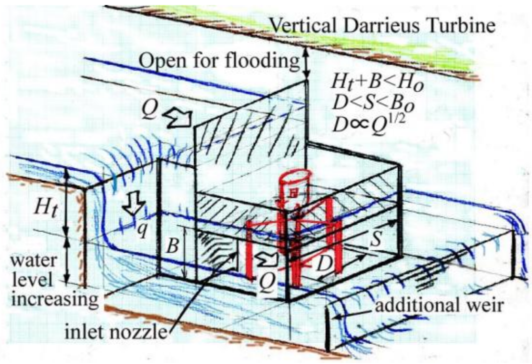
(a) Proper site for hydro-turbine installation



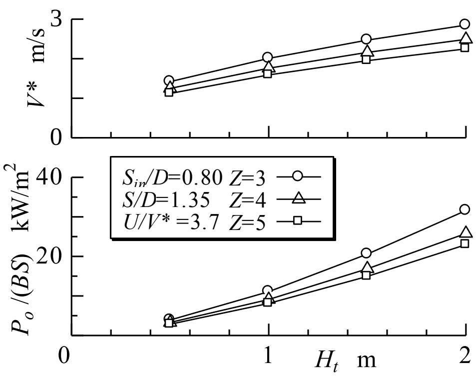
(b) Commercial based axial turbine



(d) Darrieus turbine with horizontal axis



(c) Darrieus turbine with vertical axis



(e) Simple estimation of output power from turbine

Fig.12 Conceivable applications for extra low head hydro-turbines