Effects of Hub-to-Tip Ratio and Reynolds Number on the Performance of Impulse Turbine for Wave Energy Power Plant

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The objective of this paper is to present the performance comparison of the impulse turbines for different diameters. In the study, the investigation has been performed experimentally by model testing for some diameters, especially 0.3 m and 0.6 m. The experiment was performed for Reynolds number range of $0.17\times10^5-1.09\times10^5$ and for different values of hub-to-tip ratio ν ranging from 0.6 to 0.85. As a result, it was found that the critical Reynolds number is to be around 0.5×10^5 for $\nu=0.6$ and 0.4×10^5 for $\nu=0.7$. For the hub-to-tip ratio, the optimum value is 0.7 when the turbine is operated at lower Reynolds number. However, its value seems to be 0.6 at higher Reynolds number in the tested range.

Key Words : Fluid Machinery, Impulse Turbine, Reynolds Number, Hub-to-Tip Ratio, Wave Power Conversion

Nomenclature

a : Semi-major axis of ellipse (see Fig. 1)
b : Semi-minor axis of ellipse (see Fig. 1)
C_A : Input coefficient, $=\Delta pQ/\{\rho(v_a^2+U_R^2)hl_rzv_a/2\}$
C_T : Torque coefficient, $=T_o/\{\rho(v_a^2+U_R^2)hl_rz_rr_R/2\}$
G : Distance between rotor and guide vane
h : Rotor blade height
l : Chord length
l_s : Length of straight line (see Fig. 1)
Q : Flow rate
r_r : Radius of circle of rotor blade profile (see Fig. 1)
r_R : Mean radius
R_a : Radius of camber (see Fig. 1)
Re : Reynolds number, $=wl_r/(\mu/\rho)$
S : Blade pitch
t_a : Width of flow path (See Fig. 1)
T_o : Output torque
U_R : Circumferential velocity at mean radius
v : Mean axial flow velocity
w : Relative inflow velocity at peak efficiency point

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z : Number of blades

Greek symbols

Δp : Total pressure drop between settling chamber and atmosphere

ϕ : Flow coefficient, $=v_a/U_R$

η : Efficiency, $=T_O\omega/(\Delta pQ)=C_T/(C_A\phi)$

η_p : Peak value of η

μ : Viscosity of air

ν : Hub-to tip ratio

ρ : Density of air

σ : Solidity at mean radius

ω : Turbine angular velocity

Subscripts

g : Guide vane

r : Rotor

1. Introduction

Several of the wave energy devices being studied under many wave energy program in the United Kingdom, Japan, Ireland, Portugal, India and other countries make use of the principle of an oscillating water column (OWC) (Clement et al., 2002 ; Falcão et al., 1993 ; Osawa et al., 2002 ; Santhakumar et al., 1998 ; Thorp, 2001). In such wave energy devices, a water column which oscillates due to wave motion is used to drive an oscillating air column which is converted into mechanical energy. The energy conversion from the oscillating air column can be achieved by using a self-rectifying air turbine such as a Wells turbine which was introduced by Dr. A. A. Wells in 1976. This turbine rotates in a single direction in oscillating airflow and therefore does not require a system of non-return valves. Many reports describe the performance of the Wells turbine both at running and starting conditions (Gato and Falcão, 1990; Inoue et al., 1988; Raghunathan and Tan, 1982). However, according to previous studies, the Wells turbine has inherent disadvantages : lower efficiency, poorer starting characteristics and higher noise level in comparison with conventional unidirectional turbines.

Meanwhile, in order to develop a high performance self-rectifying air turbine for wave energy conversion, some authors have proposed the impulse turbine with self-pitch-controlled guide vanes and have clarified that the turbine can be operated with higher turbine efficiency and lower rotational speed than the Wells turbine (Setoguchi et al., 1993, 1996). This type of impulse turbine, however, has a disadvantage of maintenance of pivots on which the guide vanes are rotated automatically in a bi-directional airflow. In order to overcome this drawback, an impulse turbine with fixed guide vanes has been also proposed by the authors (Setoguchi et al., 2000). There are many reports which describe the performance of the turbine both at starting and running conditions (Setoguchi et al., 2000, 2001, 2002 ; Thakker et al., 2000, 2001a, 2001b, 2002). However, comparison of the performances of the impulse turbines for different diameters have not been shown so far. It is important for practical use to clarify the scale effect of the impulse turbine with fixed guide vanes.

The objective of this paper is to present the performance comparison of the impulse turbines for different diameters. In the study, the investigation has been performed experimentally by model testing for some diameters, especially 0.3 m and 0.6 m. The experiment was performed for Reynolds number range Re of $0.17\times10^5-1.09\times10^5$ and for different values of hub-to-tip ratio ν ranging from 0.6 to 0.85.

2. Experimental Apparatus and Procedure

The experiments have been carried out by using the test facilities of Saga University (Japan) and Wave Energy Research Team at University of Limerick (Ireland) (these are named as SU and WERT respectively in the following discussions). A schematic view of the test rig of SU is shown in Setoguchi et al (2001, 2002). This test rig consists of a large piston-cylinder (diameter : 1.4 m, length : 1.7 m), a settling chamber and a 300-mm-diameter test section with the inlet and outlet bell-mouth. The turbine rotor is placed at the center of the test section and tested under any flow conditions. In testing the turbine characteristics, the variations of turbine performance with flow coefficient ϕ were examined by changing the rotational speed of the rotor step by step from a low speed to high speed, so as to cover the effective operating range of the turbine. The uncertainty with 95% confidence interval is ±1% for the measured turbine efficiency η.

The detail information of the test apparatus of WERT is shown in Thakker et al (2002). It consists of a bell mouth entry, 0.6 m test section, drive and transmission section, a plenum chamber with honeycomb section, a calibrated nozzle and a centrifugal fan. The turbine was mounted on a shaft in a cylindrical annular duct. The shaft coupled to a motor/generator via a downstream hub of the rig. The uncertainty with 95% confidence interval in the results, based on instrument's accuracy was within ±1.5%.

In both the above facilities, the overall performance was evaluated in term of the turbine angular velocity ω, the output torque T_o, the flow rate Q and the total pressure drop Δp between the settling chamber and the atmosphere. Tests were performed under steady flow conditions.

As shown in Fig. 1, the turbine configuration employed is the impulse turbine having fixed guide vanes both upstream and downstream, and these geometries are symmetrical with respect to the rotor centerline. The rotor blade profile consists of a circular arc on the pressure side and part of an ellipse on the suction side. For the size of the ellipse, the ratio of the semi-major axis to semi-minor axis a/b is 3.0. The ratio of the radius of the circle on the pressure side to the chord length r_r/l_r is 0.56. The blade inlet (or outlet) angle and the thickness ratio are 60° and 0.3, respectively. The specification of rotor blades used is shown in Table 1. The guide vanes are symmetrically installed at the distance of G downstream and upstream of the rotor. The camber line of guide vane consists of a straight line and a circular arc. The specification of the guide vane adopted in the experiments is shown

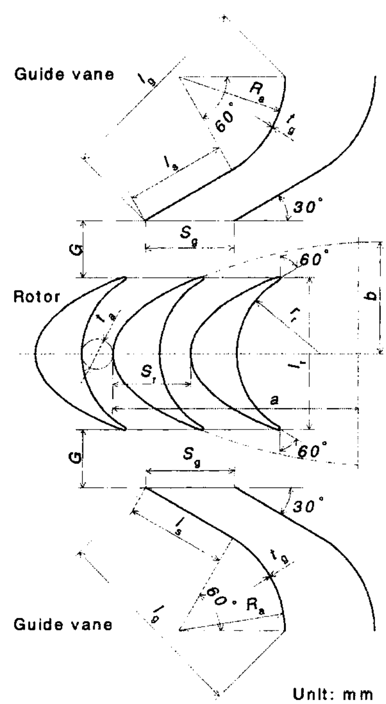


Fig. 1 Turbine configuration

Table 1 Specification of rotor blades

Research institution	Hub-to-tip ratio ν	Tip diameter [mm] (Tip clearance[mm])	Solidity σ_r ($=l_r/S_r$) (No. of blades z_r)	Reynolds number at peak efficiency point $Re[\times 10^5]$	Chord length l_r[mm]
Saga University (SU)	0.6	298(1.0)	2.01(28)	0.17−0.45	54
	0.65		2.01(29)	0.38	
	0.7		2.02(30)	0.22−0.51	
	0.75	278.6(0.7)	2.03(29)	0.44	
	0.85	246(0.5)	2.03(27)	0.60	
University of Limerick (WERT)	0.6	598(1.0)	2.00(30)	0.38−1.00	100
	0.7		1.99(30)	0.40−1.09	106

Table 2 Specification of guide vanes

Research institution	Hub-to-tip ratio ν	Solidity $\sigma_g(=l_g/S_g)$ (No. of vanes z_g)	Chord length l_g[mm]	Radius of camber Ra[mm]	Length of straight line l_s[mm]
Saga University (SU)	0.6	2.23(24)	70	37.2	34.8
	0.65	2.25(25)			
	0.7	2.27(26)			
	0.75	2.27(25)			
	0.85	2.24(23)			
University of Limerick (WERT)	0.6	2.27(26)	131.4	69.6	65.3
	0.7	2.27(26)	139.5	73.9	69.2

in Table 2. It may be noted that the rotor solidity σ_r and the guide vane solidity σ_g at the mean radius r_R for the tested turbines are almost the same as the most promising one in the previous studies (Setoguchi et al., 2000, 2001).

The values of hub-to-tip ratio ν adopted in the study are 0.6, 0.65, 0.7, 0.75 and 0.85 for SU, and 0.6 and 0.7 for WERT. In the SU test rig, the effect of Re was tested for ranges of $0.17\times10^5-0.45\times10^5$ for $\nu=0.6$ and $0.22\times10^5-0.51\times10^5$ for $\nu=0.7$, respectively. For the facility of WERT, the ranges of Re are $0.38\times10^5-1.00\times10^5$ for $\nu=0.6$ and $0.40\times10^5-1.09\times10^5$ for $\nu=0.7$. The above experiments have been performed by changing the flow rate Q and the angular velocity ω. The detail information is shown in Table 1.

3. Experimental Results and Discussions

3.1 Effect of hub-to-tip ratio

The turbine performance under steady flow conditions is evaluated by turbine efficiency η, torque coefficient C_T and input coefficient C_A against flow coefficient ϕ.

Figures 2 and 3 shows the effect of hub-to-tip ratio ν on turbine characteristics under steady flow conditions, which are obtained by the facility of SU. It can be observed that the turbine peak efficiency η_p increases with ν for $\nu\leq0.7$ (Fig. 2), though the trend of all the tested hub-to-tip ratio is qualitatively the same {Fig. 3(a)}. Now, let us discuss the reason using both the

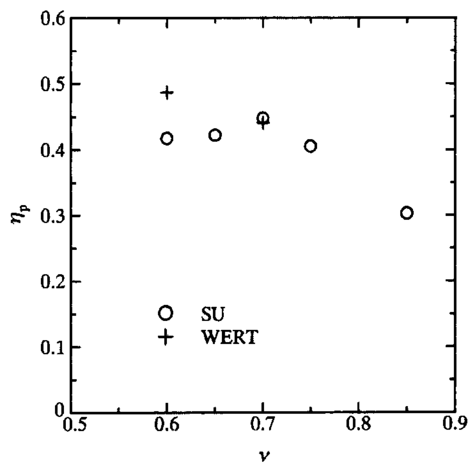


Fig. 2 Effect of hub-to-tip ratio on peak efficiency

$C_T-\phi$, $C_A-\phi$ characteristics {Figs. 3(b) and 3(c)} and the velocity diagram. Comparing the values of C_T and C_A for $\nu=0.6$ with that for $\nu=0.7$, a rate of decrease in C_T is larger than that in C_A. We consider that this phenomenon is because a difference between the incidence angle at tip and at near the hub increases with decreasing ν for a turbine operating at a certain speed. That is, it should be expected that the incidence angle at tip becomes large when the ν is small, and then the boundary layer separation occurs on the pressure side at the leading edge and on the suction side at maximum thickness point of the rotor blade (Kinoue et al., 1999). Consequently, the decrease of hub-to-tip ratio leads to the deterioration of T_o and η. Meanwhile, the η_p decreases with increasing ν for $\nu\geq0.7$ because the C_T decreases with the decrease of ν in a whole

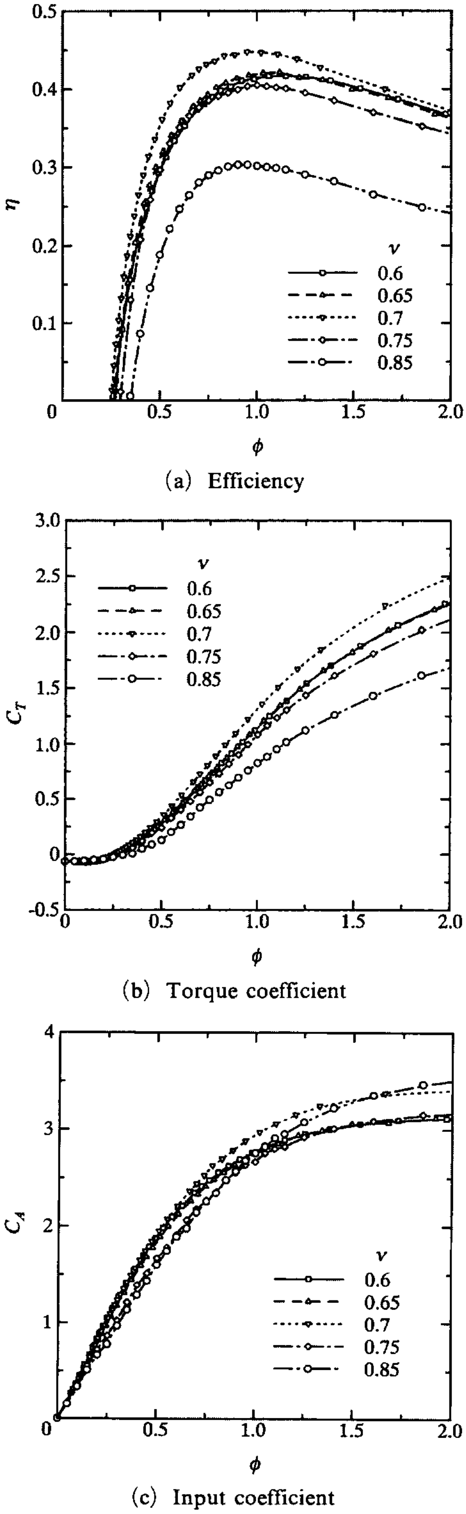


Fig. 3 Effect of hub-to-tip ratio on turbine characteristics (SU)

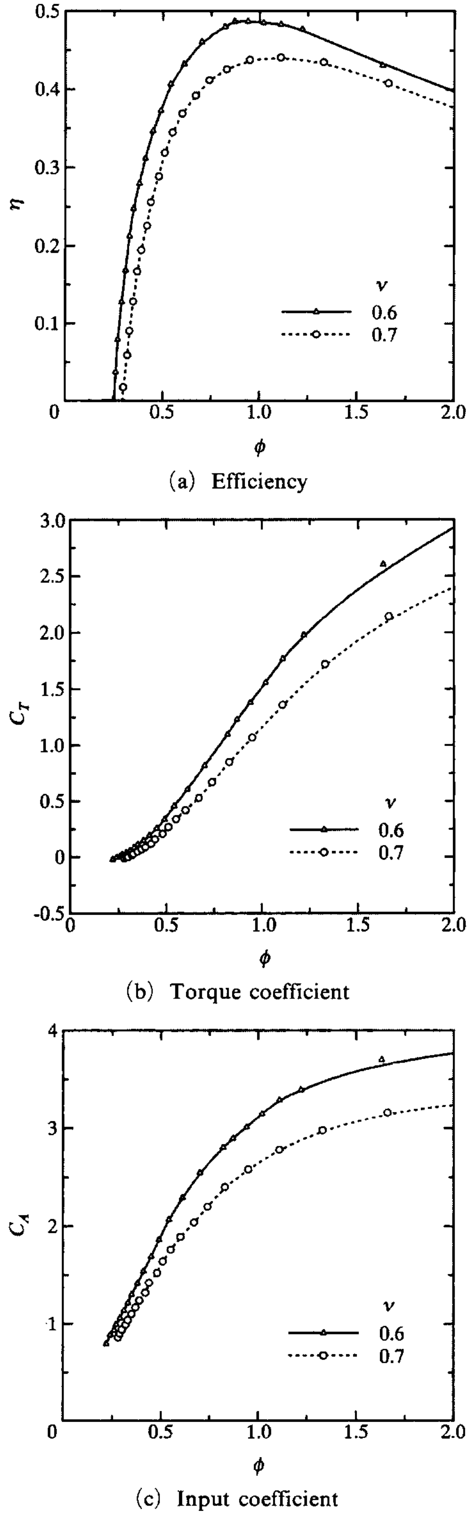
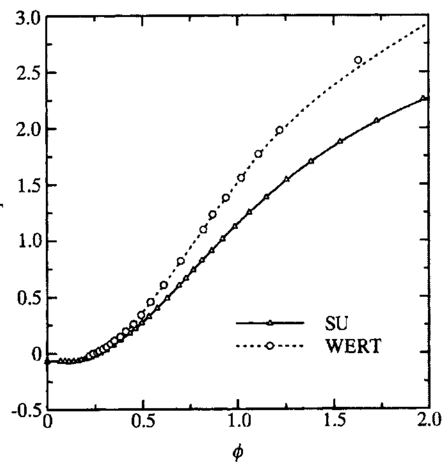


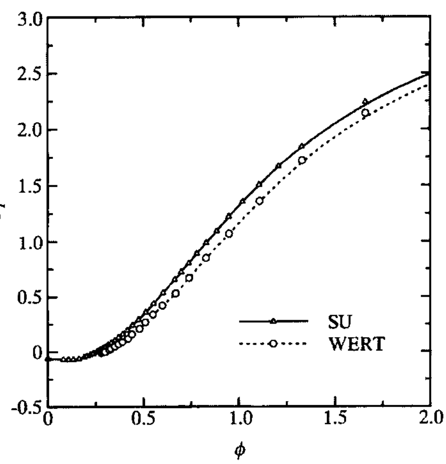
Fig. 4 Effect of hub-to-tip ratio on turbine characteristics (WERT)

of ϕ as shown in Fig. 3(b).

Conversely, in the case of WERT, the η_p for ν=0.6 is higher than that for 0.7 as shown in Figs. 2 and 4(a). This result is the opposite of SU's one. Particularly, it should be noted that the difference of η_p between WERT and SU is as much as seven percent at ν=0.6 (Fig. 2). The reason can be considered from the comparison of C_T for both the test facilities as shown in Fig. 5. In the case of ν=0.7, the C_T for SU is slightly higher than that for WERT {Fig. 5(b)}. However, for ν=0.6, the value for WERT is better than that for SU {Fig. 5(a)}. This is because boundary layer separation at tip is restrained by

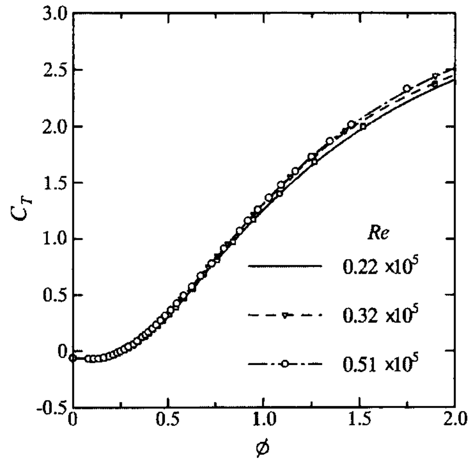


(a) ν=0.6

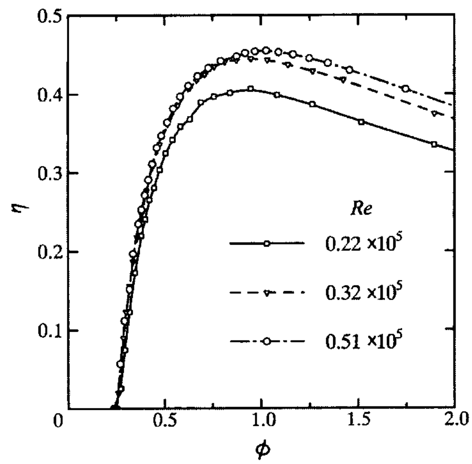


(b) ν=0.7T

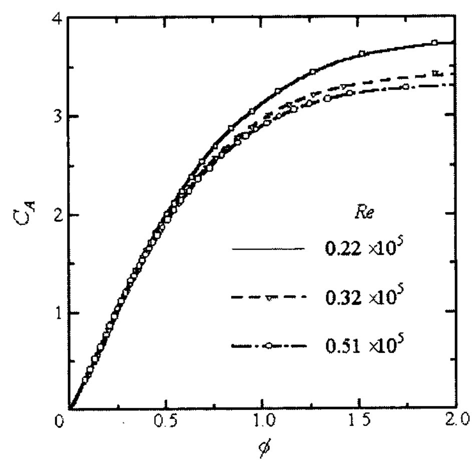
Fig. 5 Comparison of torque coefficient for impulse turbines with different diameters



(a) Efficiency



(b) Torque coefficient



(c) Input coefficient

Fig. 6 Effect of Reynolds number on turbine characteristics (SU, ν=0.7) the influence of Reynolds number effect.

Therefore, it is concluded from the results obtained in this study that the optimum value of ν of the impulse turbine with fixed guide vanes for wave power conversion is approximately 0.7 when the turbine is operated at lower Reynolds number. However, its value seems to be 0.6 at higher Reynolds number in the tested range.

3.2 Effect of reynolds number

For practical use, it is necessary to investigate the effect of Reynolds number Re on turbine performance. In the study, the experiments have been carried out for four turbines with various hub-to-tip ratios and diameters.

Figure 6 shows the turbine characteristics under steady flow conditions for three Reynolds number, for 0.3 m impulse turbine with $\nu=0.7$. The efficiency increases with Re in the entire range of ϕ{ Fig. 6(a)}. This is because the C_T slightly increases with Re, and the C_A decreases with Re due to the viscous influence at lower Re{ Figs. 6(b) and 6(c)}. Therefore, as is evident from the definition of η, the η increases with Re.

Figure 7 shows the effect of Reynolds number Re on peak efficiency η_p for $\nu=0.6$ and 0.7. The experiments have been carried for 0.3 m and 0.6 m turbines. The value of η_p for $\nu=0.7$ increases gradually in the case of both the turbines and

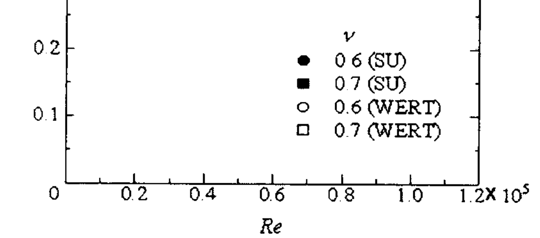


Fig. 7 Effect of Reynolds number on peak efficiency

then remains almost constant for $Re \geq 0.4 \times 10^5$. However, in the case of $\nu=0.6$, the value of η_p remains almost constant for $Re \geq 0.5 \times 10^5$. Therefore, it is believed from the fact that the critical Reynolds number of the impulse turbine seems to be approximately 0.5×10^5 for $\nu=0.6$ and 0.4×10^5 for $\nu=0.7$.

4. Conclusions

The effects of Reynolds number Re and hub-to-tip ratio ν on the performance of the impulse turbine for wave energy conversion have been investigated experimentally by model testing under steady flow conditions. As a result, it was found that the critical Reynolds number is to be around 0.5×10^5 for $\nu=0.6$ and 0.4×10^5 for $\nu=0.7$. For the hub-to-tip ratio, the optimum value is 0.7 when the turbine is operated at lower Reynolds number. However, its value seems to be 0.6 at higher Reynolds number. A future study may seek to clarify the effect of hub-to-tip ratio at higher Reynolds number for $\nu<0.6$.

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