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Numerical study on a modified impulse turbine for OWC wave energy conversion

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ABSTRACT

Impulse turbine is used in recent times as a self-rectifying turbine in OWC wave energy convertor. It has been found from field test data in Indian OWC plant that the profiles of air flow velocity is not symmetric in exhalation and reverse directions. The velocity is higher during the exhalation (chamber to atmosphere) than in the reverse direction. The modification proposed in this paper is to set the rotor blade pitch asymmetrically with a non-zero value of setting angle. It is expected to give a better performance in a wave cycle under the above air flow conditions. A 3D CFD model based on Fluent is validated by corresponding experimental data and is used for the numerical simulation of the turbine performance for different setting angles under steady conditions. All the calculations were carried out under the steady conditions. Pseudo-sinusoidal velocity pattern was used to represent the realistic air flows in the pilot plant. Quasi-steady analysis was then employed for calculating the mean efficiency for a certain variation of air flow velocity with time during a wave cycle. The clear flow separations were found at the suction side near the trailing edge and the high velocity domain occurs at the suction side near the midstream flow path. The pressure distribution show similar characteristics on both pressure and suction sides. Input coefficient, torque coefficient and mean efficiency are calculated for evaluating the turbine performance under various rotor blade setting angles. For the typical value of 0.6 for the ratio of velocity amplitude at inhalation to that at exhalation, the rotor blade setting angle of 5° was found to be optimum for the modified impulse turbine to achieve the best mean efficiency in a wave cycle.

1. Introduction

Impulse turbine, operating as a self-rectifying turbine, was proposed by Kim et al. (1988) for wave energy conversion. It can rotate in one direction under the reciprocating air flow conditions, because of which, it can be employed in the pneumatic energy conversion for the Oscillating Water Column (OWC) systems. The optimum flow coefficient of the impulse turbine is significantly larger than that for the traditional Wells turbine. The impulse turbine also has better self-starting and no stall condition, which has been reported by Setoguchi et al. (2001). The above characteristics make the impulse turbines appropriate for the wave conditions (small wave heights and periods) in the sea area around the west Pacific. Impulse turbines have been applied in the pilot OWC plants in Japan and India (Cruz, 2008). They will also be utilized in Asia's largest OWC system – Yongsoo 2×250 kW Plant in Jeju Island of Korea.

Being one of the most actively studied areas, many efforts have been made to improve the efficiency and operating performance of the impulse turbine, such as the method combining the optimization of thickness distribution with a camber line iterative design method for 2D geometry development (Pereiras et al., 2011). In addition to the axial type, several radial type impulse turbines have also been proposed and studied by Falcao et al. (2013a, 2013b). Numerical predictions on operating performance and effects of guide vanes were reported.

It also should be noted that the flow rate profiles of flow rate through the OWC air chamber are not symmetric with respect to the direction (Santhakumar et al., 1998; Setoguchi et al., 2003), as shown in Fig. 1. The axial air flow velocity amplitude during exhalation (from chamber to atmosphere) is higher than that during inhalation (from atmosphere to chamber). It could be assumed that a proper modification of the rotor blade profile to suit the air flow characteristics will yield a superior performance as compared to the original symmetric blade profiles. Maeda et al. (2001) extended only one side of

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Nomenclature

b	blade height
C_A	input coefficient
C_T	torque coefficient
E_a	semi-major axis of ellipse
E_e	semi-minor axis of ellipse
G	gap between guide vane and rotor blade
l_g	chord length of guide vane
l_r	chord length of rotor blade
l_s	length of straight line of guide vane
Q	air flow rate
r_R	mean radius of blade
$R_a(R_b)$	radius of camber of guide vane on exhalation (inhalation) side
Re	Reynolds number
R_i	radius of circular arc at the intersection of pressure and suction sides
R_p	radius of circular arc of pressure side
S_r	rotor blade pitch
t_1	exhalation period
t_a	width of flow path
t_g	thickness of guide vane
T	wave period
T_O	turbine output torque
$T_{OE}(T_{OI})$	output torque in exhalation(inhalation) cycle
U_R	circumferential velocity at r_R
v_a	mean axial flow velocity
$v_E(v_I)$	amplitude of exhalation(inhalation) part of pseudo-sinusoidal air flow
z	number of rotor blades
γ	setting angle of rotor blade
δ	camber angle of guide vane
$\delta_E(\delta_I)$	camber angle of guide vane on exhalation (inhalation) side
Δp	total pressure drop between setting chamber and atmosphere
η	turbine efficiency
$\overline{\eta}$	mean turbine efficiency under pseudo-sinusoidal flow condition
θ	setting angle of guide vane
$\theta_E(\theta_I)$	setting angle of guide vane on exhalation (inhalation) side
ν	hub-to-tip ratio
ρ_a	air density
ϕ	flow coefficient
Φ	flow coefficient under pseudo-sinusoidal flow condition
ω	angular velocity of turbine rotor

the rotor blade to increase the pressure side area under high incident air flow rates. Based on this idea, Javashankar et al. (2009) and Mala et al. (2011) designed a twin unidirectional impulse turbine to operate alternately in the exhalation and inhalation processes; this has been investigated experimentally and numerically by Takao et al. (2011) and Pereiras et al. (2014). The leading edge of the blade is made blunt and the trailing edge is extended along the camber line. The sectional shape of the modified blade looks like a bent airfoil. This type of turbine is mostly suggested for the unidirectional air flow design.

This paper proposes an impulse turbine, modified in a simple manner to make it suitable for pseudo-sinusoidal air flow, which refers to the condition where the exhalation air velocity amplitude is larger than that in the reverse direction. The profile of rotor blade remains unchanged and its setting angle is set to be non-zero, which makes the rotor blade asymmetrical to yield a higher operating efficiency in a sinusoidal wave cycle. The flow fields under steady state at different cross sections are compared in the 3D numerical model, which has been validated by experimental data. Pressure distributions around the blade are then illustrated for the fluid dynamic analysis. Typical dimensionless coefficients under steady conditions and mean efficiencies are compared to find the optimum blade setting angle.

2. Modified impulse turbine

Considering the asymmetric oscillating air flow pattern, it would appear that enlarging the area on the pressure side of the rotor blade, facing the exhaled air flows with higher velocity amplitude will have a superior performance than the original impulse turbine. The modified impulse turbine in the present study is illustrated in Fig. 2.

The sectional profiles of the impulse turbine is from the geometries summarized by Setoguchi et al. (2001, 2004 and 2008), as shown in Fig. 2(a). For the rotor blade, the ellipse curve of the suction side has the semi major axis E_a of 125.8 mm and semi minor axis E_e of 41.4 mm. The radius of circular arc of the pressure side R_p is 30.2 mm.

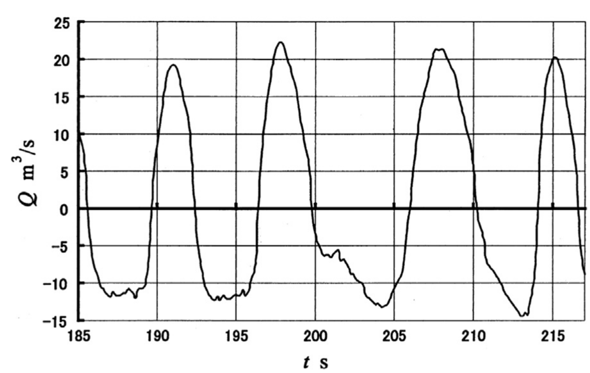

Fig. 1. Flow rate versus time in Indian OWC wave energy convertor.

The radius of circular arc at the intersection of pressure and suction sides R_i is 0.5 mm. The chord length of the rotor blade l_r is 54 mm. The flow path t_a and blade pitch S_r are 10.6 mm and 26.7 mm, respectively. The inlet angle of rotor blade is 60°. On the other hand, the fixed plate type guide vanes (the thickness t_g equals to 0.5 mm) are symmetrically installed and consist of a straight line with the length l_s equaling to 34.8 mm and a circular arc with the radius R_a equaling to 37.2 mm. The camber angle of guide vane δ equals to 60°. Consequently, the chord length of the guide vane l_g is 70 mm. In addition, the setting angle of guide vane θ is 30°. The gap between the guide vane and rotor blade G is 20 mm.

Furthermore, the blade rotates by a certain angle about an axis through the point P (midpoint of the symmetric axis on the blade section) to a new position, which sets the rotor blade pitch asymmetrically with a positive setting angle γ as shown in Fig. 2 (b). The subscripts E and I illustrate the blade side facing the exhalation and inhalation air flows, respectively. The above modification is conducted to make the pressure side of the blade facing the exhaled air flow within higher velocity, which is expected to be advantageous to yield a higher mean efficiency.

The upstream and downstream guide vanes are adjusted for better air flow guidance. Four sets of guide vane geometries are