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Effect of Guide Vane on the Performance of Impulse Turbine for Wave Energy Conversion

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KEY WORDS: Wave Energy, Impulse Turbine, CFD, Guide Vane, 2-D and 3-D Methods

ABSTRACT: *This paper deals with the performance analysis of the impulse turbine for a OWC type wave energy conversion device. Numerical analysis was performed using the commercially-available software FLUENT. This parametric study includes variation of the setting angle of the guide vane. Since parametric study at various flow coefficients requires a tremendous amount of computing time, two-dimensional cascade flow approximation was employed to determine the optimum principal particulars in a rather simple manner. A Full three-dimensional calculation was also performed for several cases to confirm the validity of the two-dimensional approach. Results were compared to other experimental data, such as Setoguchi et al. (2001)'s extensive set of data, and found that the usefulness of 2-D analysis was well demonstrated. The advantages of each method were also evaluated.*

1. INTRODUCTION

Because of its simple and efficient operation, a Wells turbine combined with OWC(Oscillating Water Column) has been widely applied for an ocean-wave energy absorption for almost 20 years. It's a self-rectifying turbine, that provides a uni-directional torque in a reciprocating airflow inside a duct without any stator or valve to control the airflow direction. At approximately the same time, an impulse turbine was developed and tested by several researchers. While each turbine has obvious advantages and drawbacks, an impulse turbine is gaining more support, mainly because of its wide operating range of flow rates, low rotor speed, good self-starting characteristics and so on. For more information, on impulse turbine, see Setoguchi et al.(2001) for information on Wells turbine, see Raghunathan et al.(1991) for Wells turbine. In fact, the Setoguchi group has studied Wells and impulse turbines for nearly 20 year since the early 1980s: the group has led this area of research. finding many valuable pieces of information. Recently the Thakker group also joined the field of wave energy conversion by publishing a couple of key papers with numerical and experimental methods(Thakker et al., 2003a and 2003b)

The present study has been conducted as part of an on-going project on the development of a prototype OWC-Impulse turbine system commenced last year at Korea Research Institute of Ships and Ocean Engineering in Korea. In this paper the performance of impulse turbine at various design parameters as well as flow conditions was investigated using the commercially-avaliable software FLUENT. It consists of two parts in general; a 3-D analysis to determine the effects of flow coefficient, guide vane and to show the accuracy and usefulness of a numerical method, and a 2-D method to see the possibility of utilizing very simple and quick calculation capability of 2-D analysis to determine if it successfully provides dependability, at least qualitatively. To see the effectiveness of the 2-D analysis, the variation of setting angle of guide vane was examined and compared with the available experimental data and with 3-D calculation. (Setoguchi et al., 2001). It was found that the 2-D method provides more than enough accurate information in selecting the design parameters, and consequently can be successfully utilized to predict the performance of impulse turbine in most cases.

2. TURBINE GEOMETRY, NUMERICAL METHOD AND TEST CONDITIONS

Impulse turbine rotor with the diameter of 38cm was designed for the present purpose and manufactured for experimental validation. It was designed after that of Setoguchi et al.(2001). It contains 30 rotor blades 26 guide vanes, and has a hub ratio of 0.7. Blade axial chord and span are 6.84cm and 5.7cm., respectively. Figuer 1 shows the turbine geometry and provides some brief dimensions. More details can be found in Hong et al.(2003): the present paper will only introduce the numerical side of study.

A commercial CFD code, FLUENT 5.4.8, was used in the present numerical analysis. The continuity and momentum

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equations were discretized by the finite volume method, and solved by SIMPLE algorithm. A relative moving reference frame was adopted for the rotor blade. Axial reciprocating flow was considered as a constant axial velocity for the numerical approach using steady analysis. In the OWC-impulse turbine system, axial flow introduced into the duct with turbine rotor blades is generated by wave action inside OWC, and the frequency of wave is directly dependent upon the wave period. Since its frequency is considerably low compared to the harmonics of a rotational blade-to-blade flow of turbine, the unsteadiness imposed by the wave action could be considered by quasi-steady or steady analysis(Hyun et al. 1993). Although the size of the turbine and the magnitude of axial velocity components were set to be 38cm in diameter and 15m/s a for standard case, those values were not strictly controlled for calculation, since the effect of Reynolds number was found to be relatively minor based on the results of preliminary analysis.

The GAMBIT 1.3.0 was used for grid generation. An unstructured grid system was adopted a triangle mesh for 2-D calculation and a tetrahedral mesh for 3-D calculation. Figure 2 depicts the example of meshes generated in 2-D and 3-D, respectively. For 2-D calculation the rotating motion of rotor blade was transformed into the transnational motion of the 2-D blade in expanded rotation direction of infinite diameter, just like the horizontal direction in a cascade flow show in Fig. 1. In order to examine the grid dependency on numerical accuracy, the number of meshes was varied from 1,000 to 10,000 for 2-D calculation to find out the optimum number of meshes was determined to be 3,600. For the 3-D case, the number of meshes was decided by similar examination: the number of meshes was determined to be 190,000(Hyun & Moon, 2004). This number for 3-D calculation is over 50 times more grids than for 2-D case, which is directly related to the computing time. In fact, it usually takes 30 seconds for one test condition in the 2-D case, while it takes 30 minutes for the 3-D case. Thus with the 2-D method a half day is more than enough time to complete the performance curve of an impulse turbine, which is a very efficient and convenient from of parametric study in the preliminary design stage, provided the accuracy of the numerical result is guaranteed mathematically and physically. The advantages and disadvantages of 2-D and 3-D calculations will be discussed later in details, and, in fact, this may be the major contribution of the present paper.

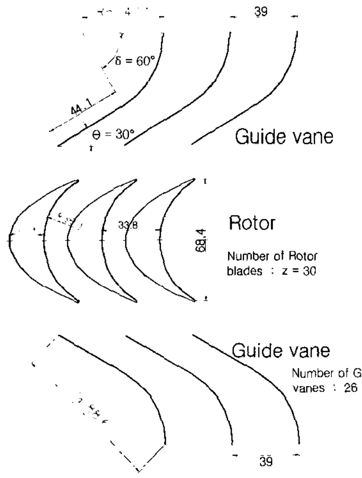
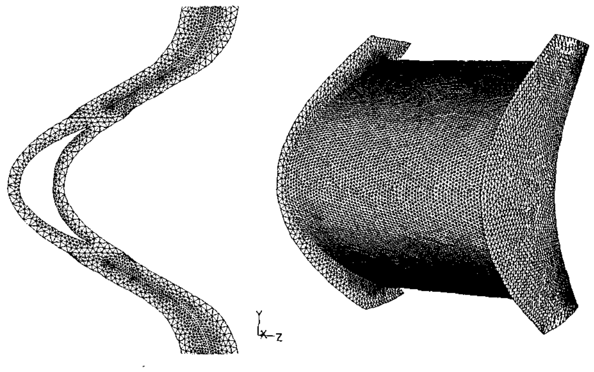


Fig. 1 Turbine geometry

Although the numbers of rotor blade and guide vane differ from each other (30 and 26), it was assumed that the number of guide vanes would be 30 in order to easily apply the periodic boundary condition easily and to eventually save considerable amounts of computing time.

Several kinds of boundary conditions were applied the no-slip condition for blade and guide vane surfaces; the uniform velocity inlet and pressure outlet boundary conditions; the periodic boundary condition on the boundary of a set of one blade and one guide vane; and relative velocities on the rotor. The range of blade Reynolds number varied from $5\text{x}10^4$ ~ $3\text{x}10^5$, where the Reynolds number was defined based on blade chord and the resultant flow velocity (vector sum of inflow and rotation speed of rotor blade). The axial velocity at the inlet section was set to be 15m/s in most of cases. While flow was assumed to be either laminar or turbulent based on Reynolds number, the results showed only a slight difference regardless of flow condition (Hyun and Moon, 2004). The $k-\varepsilon$ model was employed for turbulent flow (Hong et al. 2003). As previously discussed only steady calculation was made. The MRF (Moving Reference Frames) option was applied to the rotor area for rotating the turbine in steady flow.

Performance of the impulse turbine in the steady flow condition is expressed in terms of the input coefficient C_A



a) 2-D Grid (b) 3-D Grid

Fig. 2 Grid generations

and the torque coefficient C_T as follows

$$C_A = \frac{\Delta p Q}{\frac{1}{2}\rho_a (v_a^2 + U_R^2) b l_r z v_a}$$

$$C_T = \frac{T}{\frac{1}{2}\rho_a (v_a^2 + U_R^2) b l_r z r_m}$$

Here Δp, Q, T represent pressure drop, flow rate and torque, and v_a, U_R, b, l_r, z, r_m are axial mean velocity, rotational velocity of rotor blade at $r = r_m$, blade span, chord, number of blades and radius at mid-span respectively. The efficiency of the turbine η and the flow coefficient ϕ can be expressed as follows:

$$\eta = \frac{T_\omega}{\Delta p Q_d} = \frac{C_T}{C_A \phi}$$

$$\phi = v_a / U_R$$

where flow coefficient ϕ has a physically equivalent meaning with the angle of attack in wing theory.

3. RESULTS AND DISCUSS

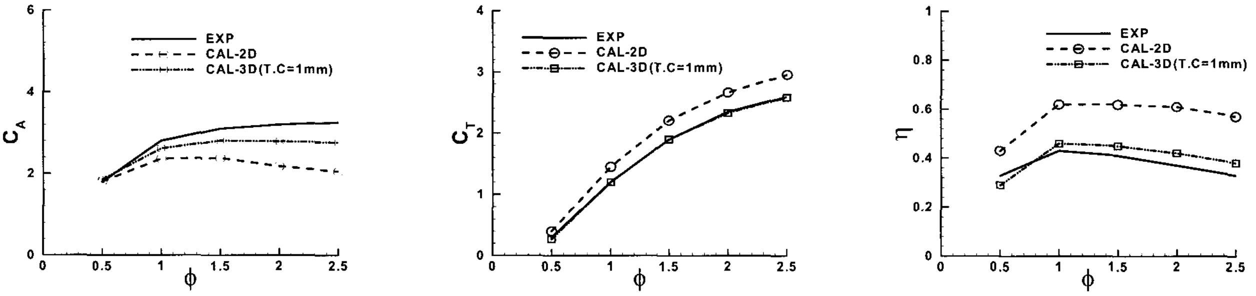
3.1 Comparison Between 2-D and 3-D Analyses

To demonstrate the accuracy and general tendency of 2-D and 3-D calculations, calculated results of FLUENT were reprocessed to obtain input coefficient C_A, torque coefficient C_T, and turbine efficiency η. That is, C_A can be obtained from the calculated pressure and velocities at inlet and outlet sections. Torque can be calculated by integrating the pressure and frictional stresses on blade surfaces into rotational direction. The 2-D calculation was made at mid-span of rotor blade r_m. Tip clearance of 1mm was assumed in 3-D calculation because 1mm allowance is practically the most common situation.

Fig. 3 shows the computed results together with Setoguchi et al. (2001)'s experimental data at various flow coefficients. Calculated results generally provide a lower pressure drop (lower C_A) and higher torque (i.e. higher C_T) although 3-D calculation produces better agreements with experimental data. C_T in 3-D calculation is surprisingly well coincident with the experimental result. Discrepancies between calculation and experiment increase with an increasing flow coefficient, supposedly due to the three-dimensionality of the flow field whose effect is more prominent on the input coefficient. The present results were considered satisfactory, and even the 2-D result shows a qualitatively similar trend with experimental data even though its quantity is rather different from experiment.

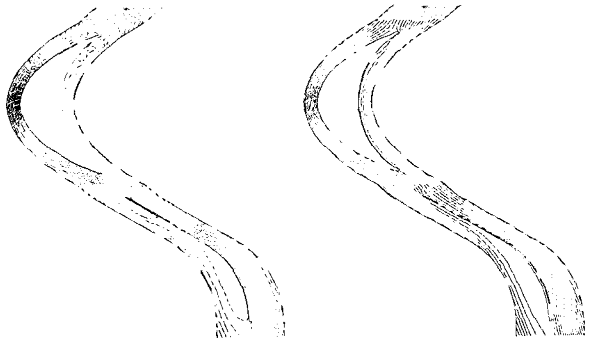
A more detailed flow field can be found in Fig. 4 and Fig. 5. In Fig. 4, streamlines at the mid-span of the rotor blade were shown for ϕ = 0.5 and ϕ=1 which clearly demonstrate the differences. Flow separations are shown near the leading edge of the pressure side of rotor blade and at the left side of the outlet guide vane when ϕ=0.5. As a result, more unnecessary pressure drop and less torque are expected. On the other hand for ϕ=1 the flow pattern looks much more favorable, and weaker separation only occurs at the left side of the outlet guide vane, yielding better efficiency than for ϕ=0.5.

Because the impulse turbine is operating under the reciprocation flow condition, this separation is almost unavoidable, unless a self-controlled guide vane is adopted. The pressure distributions at mid-span of the rotor blade were shown in Fig. 5, where more contour lines imply steeper pressure gradient. For ϕ = 0.5, a more pronounced pressure drop in axial direction (vertical direction in this figure) is expected from the figure and an unfavorable flow situation is also anticipated from the steeper pressure variations near the leading edge of the blade and outlet guide vane. These are the reasons why this impulse turbine becomes more effective at ϕ = 1.



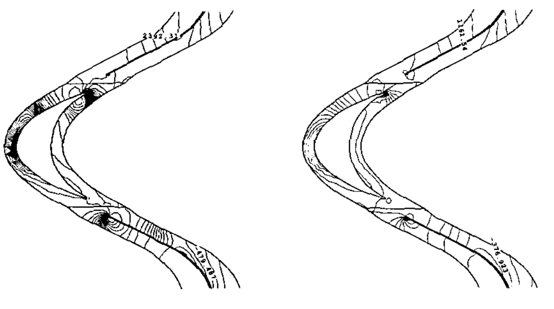
(a) Input Coefficients C_A (b) Torque Coefficients C_T (c) Turbine Efficiency η

Fig. 3 Comparison at standard condition calculations



(a) ϕ = 0.5 (b) ϕ = 1.0

Fig. 4 Comparison of streamlines



(a) ϕ = 0.5 (b) ϕ = 1.0

Fig. 5 Comparison of pressure distributions

3.2 Effect of the Guide Vane

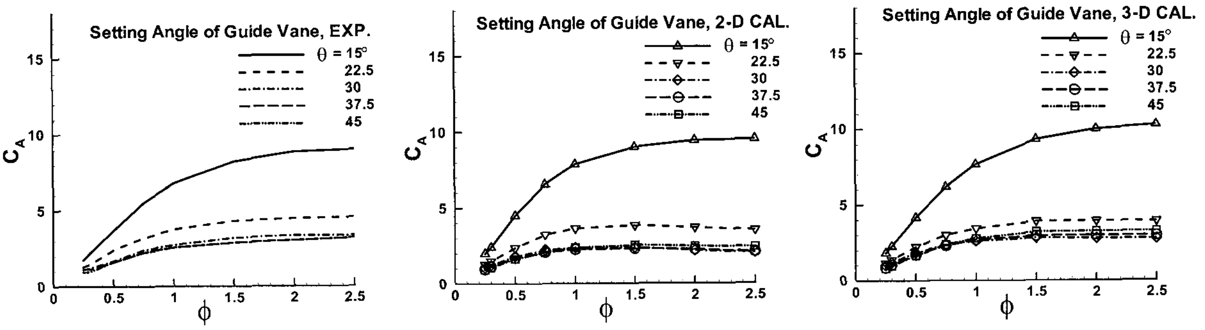
Now we see the dependability and practicality of 2-D a analysis by examining the effect of setting angle θ of the guide vane. Five different setting angles were chosen following Setoguchi et al.(2001); 15, 22.5, 30, 37.5 and 45 degrees. The input coefficient, torque coefficient and efficiency are plotted in Fig. 6. The results of Setoguchi(2001) are also plotted as a solid line. Based on the experimental data the value of C_A is largest at θ = 15 degrees, decreasing sharply with increasing θ and almost invariant after 30 degrees. The value of C_T is also largest at θ = 15 degrees and decreases gradually with increasing θ. On the other hand turbine efficiency gave a somewhat interesting result the optimum case being θ = 30 degrees. It was followed by 37.5, 22.5, 45 in sequence and the worst case turned out to be θ = 15 degrees. (However, at lower θ, the turbine efficiency in case of 22.5 degrees is better than in 37.5 degrees.) These sequences can be predicted by both 2-D and 3-D analyses surprisingly well. The only difference is that absolute values are overestimated consistently in 2-D calculation, for which we already accepted those discrepancies. The order between 22.5 degrees and 37.5 degrees is reversed in the 3-D calculation although the difference is relatively small. Since 3-D calculation requires at least 50 times more computing time than the 2-D case and moreover a lot of additional time for grid generation 2-D analysis can be a perfect answer when we want to perform parametric study in preliminary design stages requiring tremendous amounts of computing efforts. Of course we should use the 3-D method if flow three-dimensionality is expected to play an important role a typical example is the effect of tip clearance. Also 3-D analysis must be utilized for the performance analysis in the final stage of turbine.

In order to interpret the flow physics embedded in Fig. 6, pressure distributions at mid-span and streamline patterns are shown in Figs. 7 and 8 in case of ϕ = 1, where only three setting angles of 15, 30 and 45 degrees are shown for brevity. Initially for θ = 15 degrees, more pressure drop in axial direction is expected based on the obvious trend expressed by the higher pressure gradient in axial direction. Flow approaching the rotor blade was increased and the flow is deflected further in circumferential direction. This steep change of flow direction both inlet and outlet passages creates the acceleration of flow in front of the rotor blade (aft-part of inlet guide vane) as well as through the downstream guide vane. This could reduce the higher torque, but a very unfavorable flow pattern at the outlet was unavoidable. The guide vane at the outlet passage acts like as a blockages, which is the main reason foe the high loss of pressure. In fact the loss of pressure resulting from this separated downstream flow far exceeds the gain of torque produced by the acceleration of flow in the rotor blade. Overshoot of the flow direction at the outlet was also observed although it is not clearly shown here.

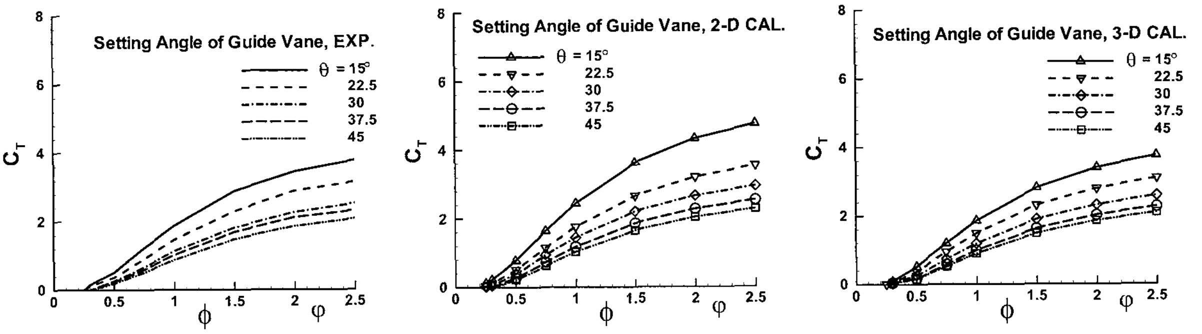
The situation becomes a little better, but has the reverse affect for θ = 45 degrees, where flow is not effectively accelerated. Smooth transition of the flow into the rotor blade was not effectively achieved either, indicated by a small separation region on the pressure side near the leading edge of the blade. However flow at the outlet was pretty smooth though because the guide vane at the outlet didn't block the flow passage. As a result, the least amount of torque, i.e. least C_T, was produced by rotor, even though the serious pressure loss at the outlet was avoided. Again the loss in torque by ineffectiveness of the inlet guide vane exceeds the gain of avoiding additional pressure loss by the downstream guide vane. While both 15 and 45 degrees have some advantages as well as disadvantages, the most adequate flow field could be achieved though a setting θ = 30 degrees. Flow was moderately accelerated and adequately aligned to increase the flow velocity in front of the blade avoiding flow separation on the rotor blade. Also this could minimize the effect of pressure loss produced by unavoidable separation on the outlet guide vane.

In summary the simple 2-D analysis was found to be very successful in estimating the effect of the guide vane; thus, it

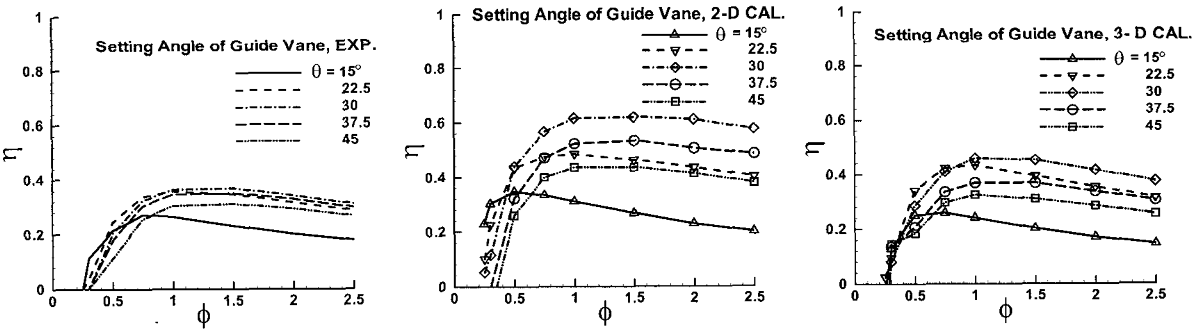
EXPERIMENT 2-D CALCULATION 3-D CALCULATION



(a) Input Coefficients C_A

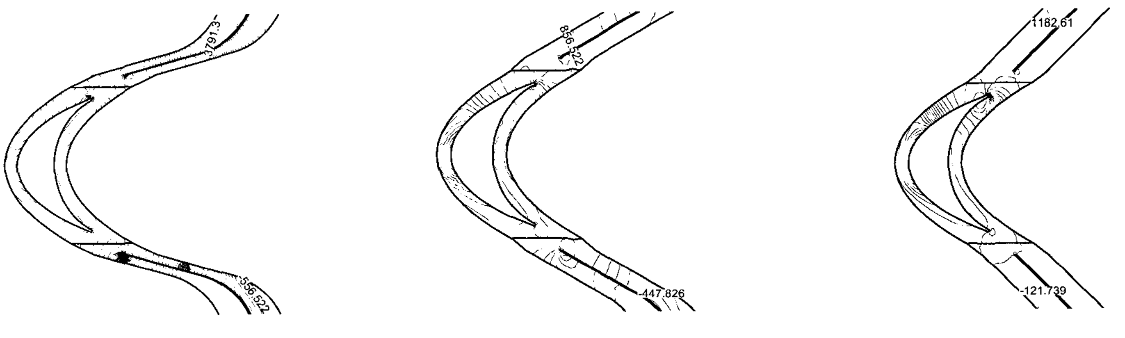


(b) Torque Coefficients C_T



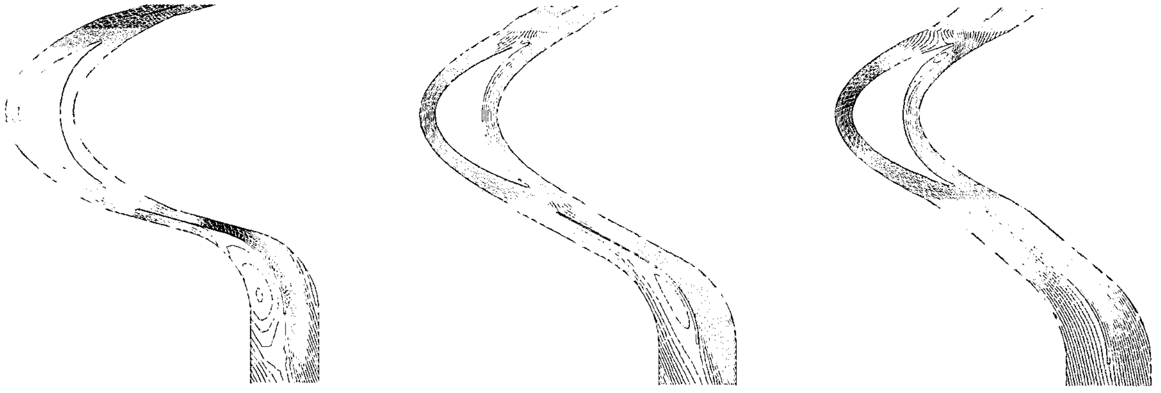
(c) Turbine Efficiency η

Fig. 6 Comparison of effect of setting angle of guide Vane



(a) θ = 15° (b) θ = 30° (c) θ = 45°

Fig. 7 Pressure distributions at several setting angles of guide vane



(a) θ = 15° (b) θ = 30° (c) θ = 45°

Fig. 8 Streamlines at several angles of guide vane

can be widely used for the parametric study in a qualitative sense. No further result is provided here due to the space limitation however parametric study to determine the effects of the number of rotor blade and the hub ratio has been successfully carryied out using the 2-D method. It is out intention to present those results in the future

4. SUMMARY AND CONCLUSIONS

A numerical approach was made by a commercial CFD software product. The performance of the impulse turbine designed after that used in Setoguchi et al. (2001) was systematically investigated under various flow situations. Calculations were made using both 2-D and 3-D methods, each having advantages and disadvantages. After testing grid dependency, the total number of meshes were chosen to be 3600 in the 2-D case and 190,000 in the 3-D case, meaning the 3-D method is at least 50 times more time-consuming. Results were compared with the experimental data available in Setoguchi et al.(2001). The followings is a summary of the findings obtained through the present study.

(1) Calculated results generally agreed well with the experimental data, while 3-D method showed better agreement. Discrepancies between calculation and experiment increased with the increasing flow coefficient due to the three-dimensionality of the flow field. The 2-D method was found to be acceptable in a qualitative sense.

(2) The dependability and practicality of the 2-D analysis was investigated by examining the effect of the setting angle of the guide vane. Both 2-D and 3-D analyses could predict the results surprisingly well. It was concluded that the simple 2-D analysis could be successfully utilized for parametric study in a qualitative sense. More numerical and experimental evaluations will solidify the present conclusions.

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