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# Investigation on the Aerodynamic Performance of a Wells Turbine for Ocean Wave-Energy Absorption

by

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# 파력발전용 웰즈터어빈의 공기역학적 성능연구

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Abstract

This pape deals with the experimental and theoretical investigations on the aerodynamic performance of the Wells turbine. The two-dimensional cascade theory is used to estimate the thrust and torque of turbine, and finally to yield an efficiency of turbine. The turbine is assumed to rotate with a constant rotational speed in a sinusoidally varying unsteady flow field. Experimental approach is made in a wave simulator, producing a sinusoidally-reciprocating air flow corresponding to the wave motion in an Oscillating Water Column (OWC) chamber. Performance data of turbine measured at various operating conditions are analyzed and compared to numerical results in order to understand the overall features of a Wells turbine.

요 약

파력발전용 웰즈터어빈의 유체역학적 성능파악을 위한 이론 및 실험적연구를 다루고 있다. 터어빈에 의한 압력강하, 토오크 및 효율을 구하기 위하여 2차원 캐스캐이드 이론을 사용하였는데, 터어빈은 비정상 왕복류중에서 일정한 속도로 회전한다고 가정하였다. 실험은 파의 운동에 대응하는 왕복류를 생성시켜주는 파도 시뮬레이터 내에서 실시되었다. 여러 작동조건에서 계측된 터어빈 성능특성치들은 웰즈터어빈의 전반적인 특성을 파악하기 위하여 수치적으로 구한 값들과 비교되었고 비교적 서로 잘 일치하는 결과를 얻었다.

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## Ⅰ. Introduction

A Wells turbine has been widely applied for ocean-wave energy absorption mainly due to its simplicity and effectiveness in operation. It provides a uni-directional torque in a reciprocal airflow inside a duct without the need for any other means to control the airflow direction. The experimental and theoretical investigations are presented here concerning the aerodynamic performance of the Wells turbine, a self-rectifying turbine for wave energy absoption.

Studies in this problem have been carried out by several researchers. The prediction of the performance of a Wells turbine has been made either using a cascade theory (Gato and Falcao, 1984) or from aerofoil data and some typical Wells turbine data (Raghunathan et al., 1990). More practically, many experimental studies have been made in Japan to apply a Wells turbine to a prototype wave power plant. Especially, a research group at Saga University (Japan) performed a comparative study among different types and features of turbines and reported a variety of experimental results (for example, see Kaneko et al., 1991). Their study includes the effects of various factors controlling the performance, the starting characteristics of a Wells turbine and some hysteresis effect of the turbine in a reciprocating flow. More information may be found in Raghunathan et al. (1991), who made a good review about a single plane Wells turbine.

The present paper is concentrated on the introduction of experimental program for the measurements of unsteady flow field as well as the calculation capability of predicting the performance of a Wells turbine. The effect of incident wave frequency as well as the effect of solidity on the efficiency of a Wells turbine is investigated. Since it is customary to assume the constant revolution of turbine and consider the oncoming flow velocity and pressure drop in a mean sense, the effect of wave frequency has been neglected so far.

In order to simulate a reciprocating air flow created in OWC chamber by the wave motion, a piston-type test rig is built. A 0.38-m diameter Wells turbine with six blades housed in a duct is attached to the test rig and tested to examine its performance at various operating conditions. Experimental results show that the effect of wave frequency on the performance of Wells turbine is negligible, and turbine efficiency is nearly constant throughout most of operating conditions.

A theoretical investigation using the two-dimensional cascade theory under quasi-steady flow assumption is also made to estimate the lift and drag at each blade section. The turbine is assumed to rotate steadily in a reciprocating flow field. The cascade interference effect and three-dimensional effects near blade tip are taken into account. The thrust and torque of a rotor are obtained by integrating the lift and drag at each section, and then yield an efficiency of the turbine. Result shows that the quasi-steady assumption of flow field is valid in predicting the performance of the turbine in a practical manner. Both experimental and theoretical results show good agreements each other, while there exist some discrepancies attributed to the assumptions employed in the analysis.

## Ⅱ. Descriptions of the Problem

The operation of a Wells turbine is characterized by the aerodynamics of turbine blades with a plane symmetry with respect to the plane normal to the rotor axis. Due to the plane symmetry, the rotational force of the turbine is always generated in one intended direction regardless of the direction of the axial oncoming flow, and used for the operation of the turbine.

The oncoming flow produced by a wave motion can be expressed as :

$$u_d = (2\pi A/\tau)\sin(2\pi t/\tau) = u_o \sin(\omega_f t) \qquad (1)$$

provided the oncoming flow is sinusoidal. In Eq. (1), $A$, $\tau$, $u_o$ and $\omega_f$ denote the wave amplitude, period, maximum oncoming flow velocity and wave frequency, respectively.

The duct enclosing the rotor blades and the hub of the rotor are assumed to have long cylindrical walls at $r = R_h$ *and* $r = R_t$ in a cylindrical coordinate system $(x, r, \theta)$, so that we may consider the domain bounded by the coaxial cylindrical walls. The rotor consists of a number$(N)$ of symmetrical aerofoil blades of chord $c(r)$, located radially at the plane of rotation $x = 0$. For a simple numerical approach, the following assumptions are made : (i) The oncoming flow is uniform in space and sinusoidal in time, and has only an axial velocity component. (ii) The flow interference effect between different radii is neglected. (iii) The effect of a gap between the blade tip and the duct wall is ignored. (iv) The rotational speed of the rotor is constant.

The flow at each cylindrical streamsurface between the duct and the hub of the turbine may be represented by the two-dimensional flow about a rectilinear cascade of blades in the two-dimensional plane, as shown in Fig.1. The cascade is supposed to move with constant velocity $\Omega r$ along the negative $y$-direction, where $y = r\theta$. According to the mass conservation of an incompressible flow, the axial velocity $u_d$ would increase as the flow passes through the rotational plane of the rotor $x = 0$. Averaging the axial onset flow velocities at inlet and at the $x = 0$ plane, the oncoming flow velocity vector $q_1$ upstream of the rotor, relative to the blades, is given by,

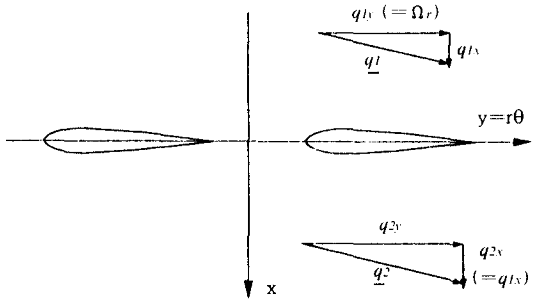


Fig. 1 Relative oncoming flow at the upstream and downstream location

$$\underline{q}_1 = q_{1x}\underline{i} + q_{1y}\underline{j} = u_d\{1 + \frac{A_d}{(A_d - A_b)}\}/2\underline{i} + \Omega r\,\underline{j} \tag{2}$$

where $A_d$ is the annular area of upstream section and $A_b$ the projected area of the rotor blades. Far downstream, the relative oncoming flow velocity vector $q_2$ can be written, for the potential flow about a cascade of flat plates (Gato & Falcao 1984), as :

$$\underline{q}_2 = q_{2x}\underline{i} + q_{2y}\underline{j} = q_{1x}i + \{(\Omega r + 2q_{1x}\tan(\frac{cN}{4r})\}j \tag{3}$$

Here $q_{2x}$ is set to $q_{1x}$ by mass conservation relation between the inlet and outlet for the bounded duct flow. From Eqs. (2) and (3), the incidence angle $(\alpha)$ of the relative mean flow to the blade section is given by

$$\alpha = \tan^{-1}\frac{2q_{1x}}{(q_{1y} + q_{2y})} \tag{4}$$

Such a flow would generate a section lift force $L$ and a section drag force $D$ normal and parallel to the relative mean flow, respectively.

For the aerodynamic forces at several incidence angles of the relative flow to the blade section at a radius $r$, we may use the appropriate values from the results of two-dimensional wind-tunnel tests of an isolated airfoil (Abbott & Doenhoff 1959). The section lift force due to the cascade interference is given by Durand (1935), based on the plane potential flow for a flat plate cascade with a stagger angle of 90-degrees,

$$C_l = \frac{4r}{cN}\tan(\frac{cN}{4r})C_{l0} \tag{5}$$

where $C_l$ and $C_{lo}$ are the section lift coefficient for a cascade and for an isolated airfoil, respectively. Since we have taken the approximation of a two-dimensional strip sense (with each section treated as a two-dimensional cascade of an airfoil), it is necessary to account for the three-dimensional effects due to finite aspect ratio of the rotor blades on both the section lift and drag forces. A simple hypothesis may be that of an elliptic lift distribution across the radial distance of the rotor blade (i.e., across the span of a wing). Denoting the values corresponding to finite aspect ratio by the subscript $c$, an appropriate correction to the lift and to the drag coefficients could be

$$C_{lc} = \frac{A}{A+2} C_l \tag{6}$$

$$C_{dc} = C_d + \frac{C_{lc}^2}{\pi A} \tag{7}$$

where $A$ is the aspect ratio of blade (for a rotor blade of constant chord along the radius, $A$ is $2(R_t - R_h)/c$).

Integrating the corresponding section force components at different radii gives the total forces acting on the rotor. These forces can be resolved into tangential and axial directions to obtain the torque and the axial force :

$$T = \int_{R_h}^{R_t} (L(r) \sin \alpha(r) - D(r) \cos \alpha(r)) r dr \tag{8}$$

$$F_A = \int_{R_h}^{R_t} (L(r) \cos \alpha(r) + D(r) \sin \alpha(r)) dr \tag{9}$$

The magnitude of $T$ and $F_A$ will cyclically vary during a period of the sinusoidal onset flow. The torque $T$ eventually results in the generation of electric power and the axial force component $F_A$, which has to be balanced mechanically by bearings, is directly related to pressure drop $\Delta P$ between far upstream and downstream by the principle of momentum conservation (i.e., $\Delta P = F_A/A_d$). From the pressure drop and the generated torque, we define the turbine efficiency $\eta_t$, in a time-everage sense, by

$$\eta_t = \frac{\overline{T}\Omega}{\Delta \overline{P} \overline{Q}} \tag{10}$$

where $-$ denotes the time-everage of a quantity and $\overline{Q}$ is the mean flow rate of the axial onset flow. It is, therefore, important in wells-turbine design to determine the optimum operating condition toward a generation of maximum output power and an efficiency by ballancing suitably $T$ and $\Delta P$.

## Ⅲ. Experimental Approach

In order to simulate the behavior of the Wells turbine in a sinusoidally-varying air flow, a specially-designed test rig "Wave Simulaor" was built, which creates sinusoidal waves equivalent to the ocean regular wave. Experimental apparatus used in this study is shown in Fig. 2. The test rig consists of a 1.5m diameter piston, drum and settling chamber. Various oscillating flow conditions can be obtained by controlling the frequency up to maximum 1Hz and the piston stroke up to maximm 0.5m. A 0.38-m diameter Wells turbine with six blades housed in a duct is attached to the test rig and tested to examine its

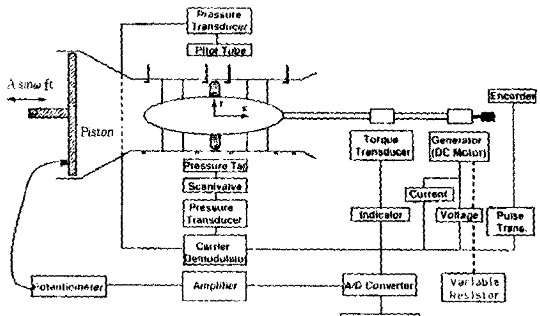


Fig. 2 Schematic of experimental system

Table 1 Principal characteristics of a wells turbine

| | Item | Symbol | Size | Unit |
|---|---|---|---|---|
| Duct | Diameter | $D_t$ | 38 | *cm* |
| | Length | $L$ | 80 | *cm* |
| Turbine Rotor | Radius | $R_t$ | 19 | *cm* |
| | Hub Radius | $R_h$ | 11.4 | *cm* |
| | Hub Ratio | $R_h/R_t$ | 0.6 | – |
| | Weight | $W_t$ | 4.0 | *kg* |
| Turbine Blade | Section | | NACA0020 | |
| | No. of Blade | $N$ | 6 | – |
| | Solidity | $\sigma$ | 0.6 | – |
| | Chord Length | $C$ | 9.5 | *cm* |
| | Span | $S$ | 7.6 | *cm* |
| | Sweep Angle | – | 0 | *deg* |
| | Tip Clearance | – | 1 | *mm* |

performance at various operating condition. The principal characteristics of turbine is given in Table 1. The turbine was installed in a duct by two sets of 5 supporting struts with airfoil shape. Turbine shaft was connected to torque transducer using flexible couplings, followed by an electric generator and a tacho generator.

The static pressure and axial velocity inside a duct are measured by using the pressure taps at 7 different locations and Pitot tubes at 4 locations in front of and behind a turbine. Pressure taps and Pitot tubes are connected to pressure transducer of Diaphragm-type through a 24 Port Scanivalve system. An electric generator is used not only to generate the electricity, but to initially rotate a turbine to a certain self-starting speed. A tacho generator is attached to a generator for RPM measurement of a turbine rotor. Generated power was obtained by measuring the voltage and current of electricity. On the other hand, a variable resistor was employed to apply an electric load to the generator. Analog signals from each instrument are transmitted to 16 channel A/D convertor and finally to P/C.

In order to express physical parameters in a nondimensional form, the following definitions are usually employed. First, the dimensionless torque and pressure drop coefficients are introduced :

$$C_T = 2\overline{T} / \rho\{\overline{u}_d^2 + (\Omega r_m)^2\} A_d r_m \qquad (11)$$

$$\triangle C_p = 2\triangle \overline{P} / \rho\{\overline{u}_d^2 + (\Omega r_m)^2\} \qquad (12)$$

Here $r_m$ is radial coordinate of a blade mid-span. The mean air flow incidence at the turbine inlet, $\alpha_i$ is defined by mean axial oncoming velocity and rotational speed of rotor at a mid-span of blade.

$$\alpha_i = \tan^{-1}\{\overline{u}_d / (0.8 R_t \Omega)\} \qquad (13)$$

It should be noted that $\alpha_i$ is used just for convenience, and different from the incidence angle ($\alpha$) of the relative flow to the blade section. Finally, the solidity of the turbine is defined by $\sigma = A_b/A_d$.

## Ⅳ. Results and Discussion

### Experimental Results and Discussion

Before presenting the measured results, the basic characteristics of duct flow were tested. Figure 3 shows the change of pressure drop ($\Delta\overline{P}$) along a duct wall in x-direction, where the sudden pressure drop across the turbine rotor is clearly seen. No difference is observed either among values inside a rotor or outside it. The distribution of axial oncoming velocity $\overline{u}_d$ along the radial direction is given in Fig. 4, and appears to be nearly uniform except regions close to the duct wall boundary.

The purpose of the main experiment is to vali-

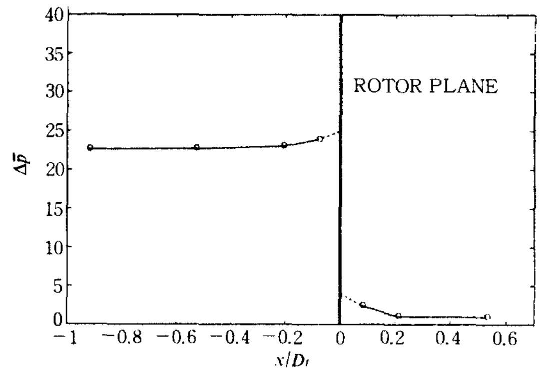


Fig. 3 Pressure drops along a duct wall

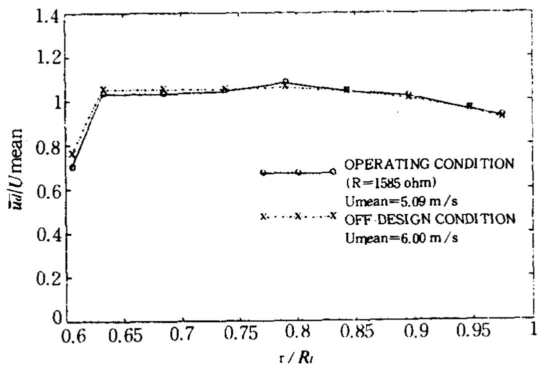


**Fig. 4 Axial oncoming velocity distribution**

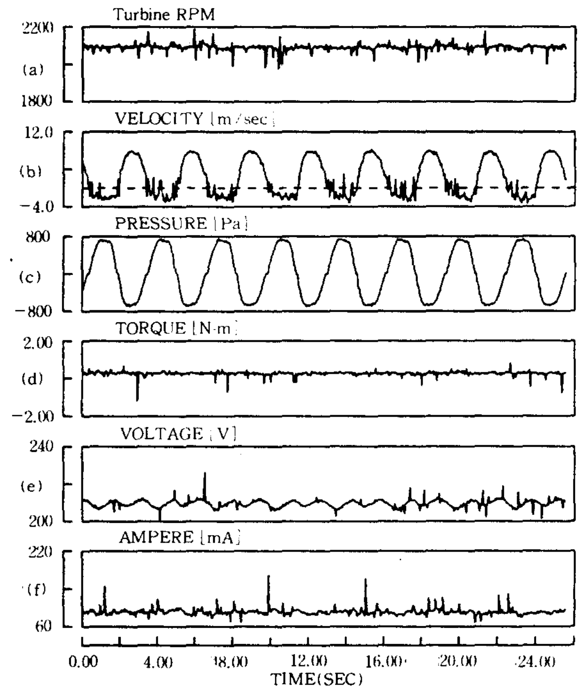


**Fig. 5 Typical example of measured data($A$ = 40cm, $\omega_f$ = 0.333$Hz$, Electric Loading =2533 $ohm$)**

date the quasi-steady (or steady) flow assumption, having been used by Raghunathan et al (1990), Gato et al (1984) and also by the present study. Since it is customary to assume the constant revolution of turbine and consider the oncoming velocity and pressure drop in a mean sense, the effect of wave frequency on Wells turbine has been neglected so far.

The effect of flow unsteadiness was investigated by varying the flow condition, but keeping the oncoming flow velocity constant. As the oncoming velocity $\overline{u}_d$ in a sinusoidally-varying wave is expressed in Eq. (1), it is straightforward to reduce its mean value of $\overline{u}_d = 4A/r$, so that the combination of piston stroke and frequency yielding the same values of $\overline{u}_d$ can be used to investigate the effect of wave frequency.

Shown in Fig. 5 is the typical example of measured data. Indices a) - f) represent the turbine RPM, axial oncoming velocity, pressure drop ($\Delta P$), torque, voltage and current. From this figure, the velocity and pressure drop show a sinusoidally varying inflow condition well. Here, it is mentioned that the measured velocity is meaningful for a half period only. It is observed that while the turbine RPM, torque, violtage and current are nearly constant at a reciprocating flow, the voltage oscillates slightly with a half period of inflow. The rotational speed of turbine rotor is nearly constant in a sinusoidally varying velocity and pressure fields, implying the effect of flow unsteadiness to be negligible. The turbine efficiency, torque coefficienct and pressure drop Coefficient defined by Eqs. (10) through (12) are shown in Figs. 6 through 8 for five different wave frequencies tested, where the measured time series data are precessed in a mean sense. All the coefficients are plotted against the mean angle of attack at $0.8R_t$. It is clearly seen that the effect of the variation of wave frequency is negligible both for the pressure drop and torque coefficients, whose values are linearly increasing with an angle of attack. Subsequently, the turbine efficiency is shown to be nearly constant over all the operating region of turbine, the trend being consistent with results of other references. (For example, see Raghunathan et al, 1991) It is therefore concluded that the Wells turbine can operate in a stable manner at wave conditions usually occurring in ocean environment, provided it is in a self-starting condition. Generally, the turbine employed in this study yields its ef-

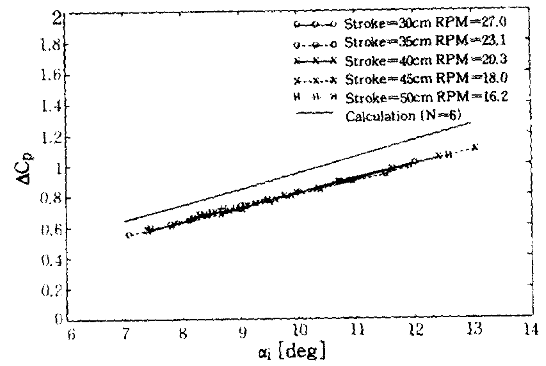


Fig. 6 Comparisons of pressure drop coefficients

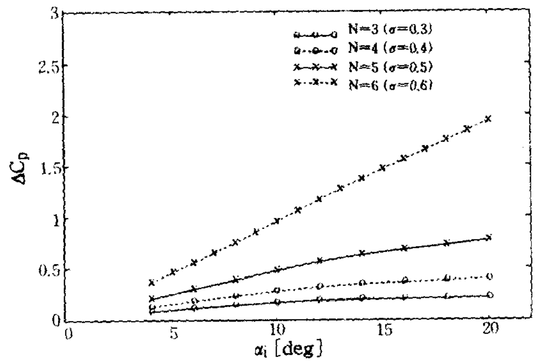


Fig. 9 Effect of solidity on $\Delta C_p$ (calculation)

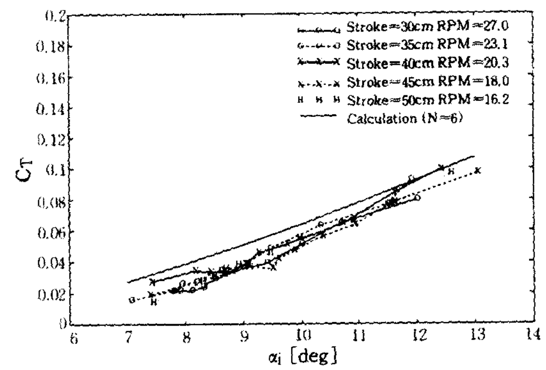


Fig. 7 Comparisons of torque coefficients

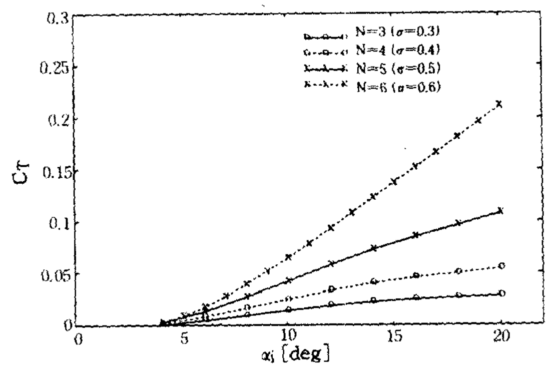


Fig. 10 Effect of solidity on $C_T$ (calculation)

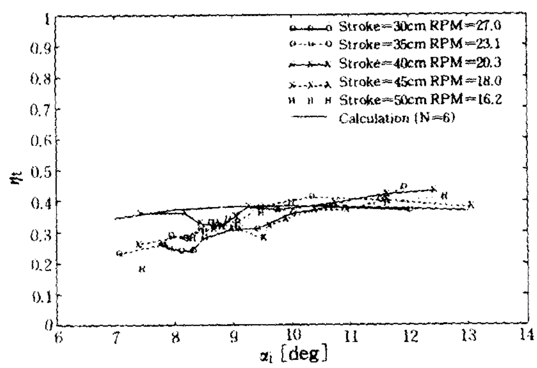


Fig. 8 Comparisons of turbine efficiency

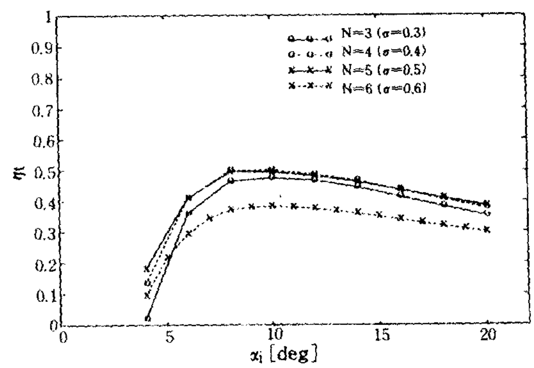


Fig. 11 Effect of solidity on $\eta_t$ (calculation)

ficiency of 35% independent of the flow angle of attack as well as the wave frequency.

### Numerical Results

Figures 6 through 8 show typical variation of $C_T$, $\Delta C_P$ and $\eta_p$ with a flow coefficient $\alpha_i$. While the results shown here are for the turbine for the model tests described in section Ⅲ, the experimental values of $C_{lo}$ and $C_d$ for calculation were taken from Abbott & Doenhoff (1959) for an NACA $65_4$ − 0021 at Reynolds number of 3.0 × $10^6$ since the corresponding data for an NACA

0020 are not available. It is observed that the value of $\alpha_i$ corresponding to the maximum efficiency equals about 10°. It is found that the semi-empirical results of the theoretical analysis have a good correlation with the measured values. There exist, however, some discrepancies between them which may be attributed to the assumptions mentioned earlier and the different blade shape applied. The solidity effects on the turbine performance are shown in Figs. 9 to 11. It was made by varying the number of the blades as $N = 3, 4, 5, 6$, keeping the other parameters of the blades and the operating conditions unchanged. It is observed that the pressure drop increases and the efficiency decreases with $N$ in the most range of $\alpha_i$ chosen. However, the value of $\alpha_i$ (about 10°) corresponding to the maximum efficiency does not change much with the solidity of the turbine.

## V. Conclusions

Theoretical investigation by using a two-dimensional cascade theory was made to estimate the lift and drag at each blade section of a Wells turbine. The turbine was assumed to rotate steadily in a sinusoidally-reciprocating flow field. Considering the cascade interference effect and the three-dimensional effects on turbine, it was found that the results of the theoretical analysis have a good correlation with the measured values. It was also shown that the value of $\alpha_i$ corresponding to the maximum efficiency appears to be about 10° and does not change much with the solidity of the turbine. Experimental approach was made in a newly-built wave simulator, producing a reciprocating air flow. The effect of the variation of wave frequency was found to be negligible both for the pressure drop and torque coefficients, whose values are linearly increasing with an angle of attack. Subsequently, the turbine efficiency is shown to be nearly constant over all the operating region of turbine. It is concluded that the Wells turbine can operate in a stable manner at wave conditions usually occurring in ocean environment, provided it is in a self-starting condition. Generally, the turbine employed in this study yield its efficiency of 35% independent of the flow angle of attack as well as the wave frequency.

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