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Short Communication

# Numerical investigation on hydraulic performance of backward bend duct buoy

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ABSTRACT

A 3-D mathematical hydrodynamic model was conducted to investigate the regular wave motion on the backward bend duct buoy (BBDB), and it was validated with the theoretical wave surface well. It was used to compute the wave heights in the gas chamber and after the BBDB. It was found that the wave transmission coefficient in the gas chamber increased firstly and then decreased with increasing horizontal duct height or the gas chamber length respectively. However, it after the BBDB decreased firstly and then increased with increasing horizontal duct height or the gas chamber length respectively. The gas chamber length plays a more important role in wave transmission coefficient in the gas chamber than horizontal duct height does. The flow rate per unit width increased firstly and then decreased with the increasing horizontal duct height or gas chamber length respectively.


## Introduction

The ocean contains large numbers of energy in seawater, including the wave energy, current energy, tide energy, heat energy and other forms. The development and utilization of ocean energy plays a significant role in alleviating the energy crisis and environmental pollution, due to its clean and renewable advantages.

To our knowledge, ocean wave energy utilization is an important way to exploit ocean energy, and it attracts a series of investigation with theoretical analysis, numerical simulation and physical experiments method. Falcao et al. [1] studied the diameter of buoy and the mechanical damping influence on buoy power. Ambüh et al. [2] conducted the reliability theory to analyze the fatigue damage and the safety factor of wave energy conversion device. Wu et al. [3] developed a new type of piezoelectric coupling buoy system connecting the multiple cantilever buoys and improve the utilization and conversion efficiency of wave energy. Shi et al. [4] found the optimum value of the hydraulic damping for the highest efficiency of oscillation float power generation with the physical experiments method. Zhang and Yang [5] studied the capture effect of oscillation buoy for irregular wave energy

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and found that the device has higher efficiency for low-frequency waves energy.

The scholars aforementioned focused much on the development and utilization of wave energy, and promoted the utilization process obviously. However, the wave energy conversion efficiency of the device is still low with considerable difficulties in practice. A floating type backward-bent duct buoy (BBDB) is a new wave energy conversion device with an oscillating water column at the front gas chamber, which attracted particular attention. Hong et al. [6] evaluated the hydrodynamic properties related to BBDB numerically. Kim et al. [7] found that the available power of the round-corner BBDB was generally greater than that of the sharp-corner BBDB, due to the less energy loss caused by its body shape and motion. Lee et al. [8] proposed a special viscous damping for the chamber free surface to represent the viscous energy loss due to the BBDB's shape and motions. Suzuki et al. [9] determined the BBDB size and the turbine diameter by considering the cost corresponding to the smallest size under the same output. Sullivan and Murphy [10] used the energy period to evaluate the hull shape for the BBDB. Koo et al. [11] investigated the hydrodynamic performance of BBDB with the potential theory, boundary element method and the mixed Eulerian-Lagrangian approach. In this paper, the hydrodynamic behavior of BBDB was investigated using a 3-D mathematical model after a good validation with experimental data. The numerical results were used to analyze the influence of BBDB geometrical parameters on the wave transmission coefficient.

## Methods

### *Governing equations*

The Reynolds Averaged Navier–Stokes (RANS) equation was used to compute the wave motion. The stand $k$-$\varepsilon$ turbulence model was utilized to denote the wave turbulence.

The continuity equation was written as follows,

$$\frac{\partial}{\partial t}(\rho_m) + \nabla(\rho_m u_{mi}) = 0 \tag{1}$$

The momentum equation was denoted as follows,

$$\frac{\partial}{\partial t}(\rho_m u_{mj}) + \nabla(\rho_m u_{mi} u_{mj}) = -P + \nabla\left[\mu_m\left(\nabla u_m + \nabla u_m^T\right) + \rho_m g\right] + F \tag{2}$$

The turbulent kinetic energy, $k$, equation was written as follows,

$$\frac{\partial}{\partial t}(\rho_m k) + \frac{\partial}{\partial x_i}(\rho_m u_{mi} k) = \frac{\partial}{\partial x_j}\left[\alpha_K \mu_{eff} \frac{\partial k}{\partial x_j}\right] + G_K - \rho_m \varepsilon + G_b - Y_M + S_k \tag{3}$$

The turbulent dissipation rate, $\varepsilon$, equation was expressed as follows,

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \frac{\partial}{\partial x_i}(\rho_m u_{mi} \varepsilon) = \frac{\partial}{\partial x_j}\left[\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_K + C_{3\varepsilon} G_b) - C_{2\varepsilon}\rho_m \frac{\varepsilon^2}{k} - R_\varepsilon \tag{4}$$

where $G_K = -\rho_m \overline{u_i' u_j'} \frac{\partial u_j}{\partial x_i}$, $G_b = -\frac{1}{\rho_m}\left(\frac{\partial \rho_m}{\partial T}\right)_p g_i \frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i}$, $R_\varepsilon = \frac{C_\mu \rho_m \eta^3 (1-\eta/\eta_0)}{1+\theta\eta^3}\frac{\varepsilon^2}{k}$; $t$ is the time. $T$ is the temperature. $\rho_m$ is the density of water and gas mixture, $\rho_m = \alpha_g \rho_g + \alpha_w \rho_w$, $\rho_g$ and $\rho_w$ are the densities of gas and water, respectively, $\alpha_g$ and $\alpha_w$ are the volume fractions of gas and water, respectively. $\mu_m$ is the dynamic viscosity of water and gas mixture, $\mu_m = \alpha_g \mu_g + \alpha_w \mu_w$, $\mu_g$ and $\mu_w$ are the dynamic viscosity of gas and water, respectively. $F$ is the volume force. $P$ is the pressure. $u_{mi}$ is the velocity component of water and gas mixture in $i$ direction. $x_i$ is the coordinate in $i$ direction, and $i = 1, 2, 3$, respectively. $Pr_t$ is the turbulence Prandtl number, $Pr_t = 0.07179$. $\eta = Sk/\varepsilon$, $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, $\alpha_K = \alpha_\varepsilon = 1.393$, $C_\mu = 0.0845$, $\eta_0 = 4.38$, $\theta = 0.012$.

The VOF technique was used for wave surface tracking (Hirt and Nichols [12]). The volume fraction equation of gas and water can be denoted as follows,

$$\frac{\partial \alpha_g}{\partial t} + \frac{\partial(u_i \alpha_g)}{\partial x_i} = 0 \tag{5}$$

$$\frac{\partial \alpha_w}{\partial t} + \frac{\partial(u_i \alpha_w)}{\partial x_i} = 0 \tag{6}$$

### *Computational domain partition and boundary conditions*

A 3-D numerical wave tank was established in the FLOW-3D software. The wave tank was divided into the wave generation area, work area and wave absorption area. The upper part of wave tank was set as gas, and the lower part was set as water. The wave boundary was utilized in wave generation area to achieve the desired regular wave. The open boundary was used in wave absorption area to eliminate the effect of reflected waves.

### *Mathematical model validation*

To validate the reliability of the 3-D mathematical model, the regular wave surface was calculated without the BBDB in a wave tank. The tank's length is 50 m, its width is 1.2 m and its height is 1.5 m. The incident wave height $H$ is 0.10 m, the still water depth is 1.0 m, and the wave period $T$ is 2.0 s. The computational wave surface was compared with the theoretical value of regular wave at $x = 10$ m position, as shown in Fig. 1. Fig. 1 shows that the relative errors between them are all less than 5%, and they agree with each other well.

## Results and discussion

Generally speaking, BBDB consists of 2 parts as shown in Fig. 2. The first is the buoy with low density material to assure the floating of BBDB. The second is the backward bend duct, including the gas chamber and the horizontal duct. The wave water body goes through the horizontal duct and enters the gas chamber. As a result, an oscillating water column occurs to drive the gas flowing through the steam turbine generator, and the electricity was produced. The buoy and the backward bend duct are bound together.

In order to investigate the hydraulic performance of the BBDB, the mathematical model aforementioned was used to