Design of Water Deflection Mechanism for Ocean Current Energy Generation Device

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Abstract. Ocean current energy, as a large reserve and clean energy, has become an important direction for the development of renewable energy. Nowadays, many researches on ocean current energy have focused on the design of different kinds of generators and blades to make efficient use of currents, and there is a lack of research on how to use currents in a wider range. This paper has designed a water guiding mechanism through theoretical analysis and experimental verification, using a wider range of sea currents, increasing the kinetic energy of the impact blade and the blade energy efficiency, and improving the total power generation efficiency of the device. The water guiding mechanism is divided into a cylindrical current collecting and accelerating device, and a gradient tube based on a coupled electromagnetic field. In the current collecting and accelerating part, the cylindrical capacitor is designed, and the inductor coil is wound on it. The alternating current of the two is used to construct a composite electromagnetic field, so that the seawater undergoes deflection acceleration under the action of the electric field force, and the directional movement generates a current. The current is received in the magnetic field, making the water to accelerate the injection, so as to achieve the current acceleration effect. In the gradient tube part, the gradient tube parameters are calculated by the equal-area criterion and the law of energy loss according to the targeted increasing magnification of the flow rate. Large-scale currents flow through the current collecting and accelerating device to produce a convergent and accelerating effect, and then flow into the gradation tube. On the one hand, the velocity increases once more. On the other hand, the gradation tube can reduce the turbulence coefficient that increases due to deflection. A wider range of currents is used.

Key Words: Ocean current generation, turbulence factor, coupled electromagnetic field, the gradient tube.

1. Introduction

Ocean currents have the advantages of large reserves, cleanliness and renewable energy. With the increase of human demand for new energy, the effective use of ocean current energy has also attracted increasing attention. At present, the use of ocean current energy is mainly divided into wave energy and current energy. The wave energy velocity is fast but unstable, while the ocean current energy has the characteristics of slow flow velocity but stable electrical energy transmission and small impact on...
the power grid. The current is generally present in the sea at an area of 30-50 meters below sea level, and the flow velocity is generally 0.8 m/s, enabling stable power supply over a long period of time. Therefore, it is an important direction for the research and development of renewable energy to perform ocean current power generation in a certain depth of sea [11].

Current research on horizontal axis ocean current energy generators mainly focuses on blade design and performance analysis. For example, reference [5] designed a 150 kW horizontal-axis marine energy generator blade using the leaf-momentum theory to enable generators to obtain energy. The maximum coefficient, as well as axial force analysis and hydraulic balance device design; reference [6] designed a hydraulically controlled axial force automatic balance device to counteract the axial force fluctuations caused by water flow, thus protecting the generator bearing structure. However, this kind of research is limited to the improvement of the power generation device itself, and how to more effectively use the current, such as the artificial increase in the flow rate of the currents and the direction of the currents, so that there is a lack of innovation in the use of currents in a large area.

The purpose of designing this current-generating power generation device is to use abundant marine resources to develop new types of renewable energy sources and realize the efficient development and utilization of current energy. By designing the water guiding device to increase the current velocity of the sea current and enhancing the impact of the current on the blade, the kinetic energy captured by the blade is increased, thereby increasing the power generation efficiency. The main implementation method is a cylindrical current collecting and accelerating device based on coupled electromagnetic field and an independently designed gradient tube. The magnetic field force and physical structure are used to change the flow direction and flow velocity respectively, effectively increasing the flow velocity of the ocean current and adding the impact of the sea current on the blade. In addition, the device also replaces the function of the natural sea channel, which makes the application of the ocean current power generation device more flexible.

2. Key scientific and technical issues to be solved

1. Increase availability of currents. Still using the low-speed current (0.8m/s), which is widely available, the problem of large-area low-speed ocean currents cannot be directly used is solved by installing a water-conducting mechanism to increase the flow rate, which is equivalent to constructing a natural trench.

2. Solve the problem of low utilization of current energy in the sea today. The ability to accelerate the flow through the collecting and accelerating device and the accelerating buffer of the gradient tube increase the utilization of the current.

3. Design, related calculations and simulation

3.1. Gradient tube design based on equal-area criterion

3.1.1. Gradient tube size design. Although currents in the ocean are widespread, the general flow rate is 0.8m/s, and the suitable flow rate of the ocean current is 3m/s. Nowadays, the current use of ocean currents is mostly in areas where there are trenches, which has certain limitations. In this article, based on the difference in flow rate, according to the relationship between the area and flow rate, and the diffusion angle of the gradient tube, etc., the gradient tube is designed independently, and the flow rate is increased to the condition suitable for the use of the generator through the gradient tube (the calculated value is 3 meter/s, there is a slight error in reality), which replaces the effect of the natural sea channel, increases the flow rate of the current of the impact marine current generator, and expands the usable range of the marine power generating device.

The inlet end of the gradient tube is a large port, the outlet port is a small port, the impeller is placed in the small port, and the diameter of the inlet end of the gradient tube is designed according to the principle of constant flow, that is, the relationship between the area and the flow rate:
According to the fluid mechanics, the formula for the local loss of the pipeline (head) is:

$$h_f = \zeta \frac{V^2}{2g}$$

In the formula, $\zeta$ is the local loss factor, the gradient tube is generally about 0.05; $V$ is the average speed in the tube.

According to the energy capture formula:

$$P = \frac{1}{2} \rho V_1^3 S C_p$$

It can be found that the power is proportional to the third power of the flow rate. The water guiding mechanism designed in this paper can effectively increase the flow rate. If calculated according to this article, the flow rate of the sea current can be increased from 0.8 m/s to 3 m/s to increase the capturing power by 42 times. According to this design, the size of the gradient tube is: 2.57m in diameter at the inlet end, 1.1m in diameter at the outlet end, and 3m in length. The reference [9] pointed out that when the diffusion angle of the gradient tube is between 6° and 12°, the energy loss is minimal, and the length of the minimal gradient tube can be obtained as 3.3m.

3.1.2. Turbulence factor distribution calculation. For the turbulent flow of an adverse pressure gradient in an axisymmetric tapered gradient tube, it is assumed that: (1) the fluid is incompressible viscosity without swirl; (2) isotropic; (3) neglecting the influence of gravity. Velocity is inlet speed $U_0$, coordinates are front nozzle diameter $D_0$, turbulent kinetic energy $U_0^2$, turbulent flow dissipation rate $U_0^3 / D_0$, pressure $dU_0^2$, and time $D_0 / U_0$ dimensionless respectively, then the basic equation set of dimensionless DLR X-k turbulence model in cylindrical coordinates is[12] (partial):

$$\frac{\partial \bar{u}}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r}(r \bar{u} v) = 0,$$

$$\frac{\partial \bar{u}}{\partial t} + \frac{\partial (\bar{u} \bar{v})}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r}(r \bar{u} v) = \frac{1}{Re} \left[ \frac{\partial}{\partial x} \left( \frac{1}{Re} + g \right) \left( \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial x} \right) \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[ \frac{r}{Re} + g \right] \left( \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial x} \right) + \frac{\partial}{\partial x} \left( \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial x} \right) - \frac{\partial}{\partial x} \left( \frac{\partial}{\partial x} \left( \frac{p}{3} \right) \right),$$

$$G = g \left\{ 2 \left( \frac{\partial \bar{u}}{\partial x} \right)^2 + \left( \frac{\partial \bar{v}}{\partial r} \right)^2 + \left( \frac{\partial \bar{v}}{r} \right)^2 \right\} + \left( \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial r} \right)^2,$$

$$g = C_0 f^2 / X,$$

In the equations: $x$ represents the axial distance; $r$ represents the radial distance from the axis, $P$ represents the time-averaged pressure; $g$ represents the eddy viscosity; $Re$ represents the Reynolds number; $k$ represents the turbulent kinetic energy; $X$ represents the turbulent energy consumption Dispersion; $\bar{u}$ and $\bar{v}$ express the mean velocity component.

Model functions $f_1$, $f_2$ are respectively,

$$f_1 = \left( 1 - \exp (-y^+ / A_\nu) \right)^2 \left( 1 + B_\nu / R_\nu \right)^3,$$

$$f_2 = \left( 1 - 0.3 \exp \left[ -(R_\nu / A_\nu)^2 \right] \right) \left( 1 - \exp (-y^+ / B_\nu) \right)^3$$
According to the above algorithm, data such as time-averaged speed $\bar{u}$, time-averaged pressure $\bar{p}$, turbulent kinetic energy $k$, eddy viscosity coefficient $\nu$, and turbulent flow dissipation rate $\chi$ can be calculated and plotted as curves. The turbulent kinetic energy curve is shown in the following figure:

![Chart 1. Distribution of turbulent kinetic energy across the gradient tube](image)

The dashed line and straight line in the figure indicate the parameters of the thin gradient tube and the gradient tube of this paper respectively. Since the front end increases the speed due to the constant water quality, the kinetic energy increases, and the end considers that a small part of the water hits the tube wall and loses part of the kinetic energy, so the kinetic energy is slightly reduced.

According to the flow rate of the import and export, the Reynolds number of the import and export can be calculated. The Reynolds number formula is:

$$Re = \frac{\ell vd}{\eta}$$

From the inlet speed of 0.8m/s and the outlet speed of 3m/s, the Reynolds number at the inlet can be calculated as $2.09\times10^6$, and the Reynolds number at the outlet is $3.5\times10^6$, indicating that the degree of disorder of the outlet fluid is higher than that of the import.

3.2. Cylindrical current collecting and accelerating device based on coupled electromagnetic field

3.2.1. Mechanism. In the collecting and accelerating device, according to the force analysis of the following figure, $Eq > Bqv$, it can be seen that the positive ions are deflected downward by the force $Eq-Bqv_{\text{horizon}}$ they receive, and the ions make a kind of flat-throwing motion with initial velocity. Since the ions have a downward velocity, in the vertical direction there produces a downward current component, thereby creating a water flow collection effect. As the magnetic induction intensity is inward, the ions will receive a force $F_{\text{horizon}} = Bqv_{\text{vertical}}$ of a magnitude in the horizontal direction, allowing the ions to perform accelerated motion. The capacitor part of the device consumes only the reactive power of the device and removes the weak conductance loss and the planned loss. It can be considered that it does not generate active loss, and the main active loss occurs in the inductor coil portion. However, in practical applications, the inductor coil can be set. For superconducting materials, there is no loss of active power. As a whole, the device can achieve the effect of current acceleration without loss [8] [9]. The schematic diagram is as follows:
The electric field inside the cylindrical capacitor is \[ E = \frac{U}{\ln(R_1/R_2)r} \]. The resistance of seawater in the entire capacitor is: \[ R = \frac{\rho l}{\pi(R_1^2 - R_2^2)} \], where \( \rho = 0.04 \). The four corners of the capacitor are coiled and sinusoidal alternating current is applied. The magnetic induction intensity of the coil is \[ B = B_1 + B_2 \]

\[
B_1 = 2 \mu_0 I \frac{4\pi l}{2} \left( \cos(\arctan(\frac{l}{R_1 - R_2})) - \cos(180^\circ - \arctan(\frac{l}{R_1 - R_2})) \right)
\]
\[
B_2 = 2 \mu_0 I \frac{4\pi (R_1 - R_2)}{2} \left( \cos(\arctan(\frac{R_1 - R_2}{l})) - \cos(180^\circ - \arctan(\frac{R_1 - R_2}{l})) \right)
\]

The force of water in a cylindrical capacitor is: \[ \overrightarrow{F} = Bv \frac{d}{d} \]

3.2.2. Example of calculation. Due to the limitation of funds and actual conditions, the model of the device design is only used to indicate its function. The dimensions of the device are as follows: the radius of the two plates of the cylindrical capacitor is 2.5cm and 4cm respectively, and the height is 25cm, which is placed at the position facing the blade, and the supporting portion use insulated rods. Take a Na ion as the research object and analyze its motion process in this device: the charge-mass ratio of Na ion is 115.56 C/g, assuming that the velocity in the horizontal direction is constant, \( v = 0.8 \text{cm/s} \), 0.05m, and 0.03m. According to the above formula, the field strength \( E \) of the two plates can be obtained, so that the vertical acceleration \( a \) can be obtained, then the time \( t \) of the arrival of the ions in the vertical direction to the plate can be obtained. Finally, the horizontal movement of the ions can be obtained in the horizontal direction. The length of the device is designed to be 2.5cm.

\[
E = \frac{U}{\ln(R_1/R_2)r} = \frac{9}{\ln(0.04/0.025)(0.025+0.0075)} = 589.2 \text{V/m}
\]
\[
a = \frac{Eq}{m} = 589.2 \times 115.56 \times 10^{-3} = 68.097 \text{m/s}
\]
\[ l = v_0 \times t = 0.8 \times 0.021 = 0.017m \]

Take 1kg of seawater as the research object and analyze the overall force in the device. The charge in seawater is about 1.6mol/kg. With a current of 0.84A, the value of magnetic field strength \( B \) can be obtained according to the above formula, and then the magnetic field force of 1 kg of seawater is obtained, the acceleration of the device is finally obtained.

\[ B = 9.41 \times 10^{-5} \, T \]
\[ F = 1.5N \]
\[ a = 1.5m / s \]
\[ vt = v_0 + at = 1.115m / s \]
\[ \Delta v = \frac{v_f - v_0}{v_0} = 0.39 \]

It can be known from the above formula that the device can increase the flow rate of seawater by about 39% and increase the kinetic energy by 1.93 times. This value is obtained without considering the current collection and considering only the acceleration. Therefore, the current collection effect increases a higher increasing degree of kinetic energy.

Because this is a model-related calculation, in the physical design, only the similarity principle is used to simulate the relevant parameters that are actually needed.

4. Experiment platform

The experiment platform built for this device is a model of ocean current energy generation device. The model of the ocean current power generation device includes a cylindrical current collecting and accelerating device, a water guiding mechanism, a generator and a transmission device and a power generation device supporting structure based on a coupled electromagnetic field. The entire device is underwater. When the current passes through the waters near the device, it enters the electromagnetic field of the collector accelerator and is affected by the magnetic field force. On the one hand, the flow velocity is accelerated and it enters the inlet of the gradation tube. On the other hand, the direction of the sea current is changed to make more ocean currents into the gradation tube. After the sea current enters the gradient tube, the internal pressure increases, the flow rate increases again, and then the blades are impacted to rotate the blades, which in turn drives the rotor of the generator to convert the mechanical energy into electrical energy.

The device model diagram is as follows:

![Figure 2. Experiment platform](image-url)
5. Conclusions and application prospects

5.1. Conclusions

1). Gradient tube design based on the equal-area criterion: According to the relationship between the area and flow rate, and the diffusion angle of the gradient tube, etc., a gradient tube is designed to increase the water flow rate to a condition suitable for the use of the generator through the gradient tube (calculated value is 3m/s, there is actually a slight error), which replaces the effect of the natural trench, increases the flow rate of the impact generator's water flow, and expands the usable range of the ocean current generating device.

2). Design of a cylindrical drainage collecting and accelerating device based on a coupled electromagnetic field: A composite electromagnetic field is established and combined with its own ion concentration in the seawater to form a current in the seawater through the action of an electric field. The current is deflected by the electric field force and the magnetic field force when passing through the electromagnetic field. Accelerate, consolidate seawater with a certain amount of kinetic energy into the available area, and further increase the available energy.

5.2. Application prospects

1). The seawater current collecting and accelerating device in the power generating device can change the direction of the sea current, which has a certain impact on the development of the marine transportation industry. For example, the acceleration part can serve the corresponding marine traffic propulsion technology.

2). The selection of the 30-50m region of the ocean is due to the consideration of the stability of the emitted electric energy. If there is a stable flow of water in the seawater or other locations in the river, the device can still be applied.

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