Investigation of Ship Vibration Effects on the Gas Distribution and Output Voltage of a Proton Exchange Membrane Fuel Cell

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ABSTRACT: The effects of ship vibrations on the mass transfer and performance of proton exchange membrane fuel cells (PEMFCs) have many vague aspects. Hence, the method of loading ship vibrations with the sliding mesh is first proposed in this paper. Furthermore, this method is adopted to form the solution of the simulation study of PEMFC performance under ship vibrations. In the framework of computational fluid dynamics, the ship vibration is loaded into the three-dimensional PEMFC model and successfully solved. Then, a series of special cases are performed to explore the gas distribution and output features of PEMFCs in ship environments with different vibrations. Finally, the results show that the ship vibrations have vectorial effects on the gas transfer in the PEMFC. Additionally, vibrations perpendicular to the channel evidently affect the gas transfer. Moreover, while the vibrations are parallel to the channel, they remain nearly normal. Relatively, a more significant influence on the output voltage of the PEMFC will occur under smaller frequencies and/or greater amplitudes of ship vibrations.

1. INTRODUCTION

The proton exchange membrane fuel cell (PEMFC) is a promising commercial energy module with zero emission1 that can be applied to many fields, such as shipping and aviation. However, in actual operation, external vibrations have a great impact on the durability of PEMFCs, which is an environmental factor that cannot be ignored.2 Thus, studying ship vibration in sea transportation is worthwhile. Moreover, scholars from various countries have conducted some experimental research work on the performance of PEMFCs under vibration conditions.

In 2015, El-Emam et al.3 investigated the effects of vibration direction on the performance of PEMFC stacks through an experiment that involved a PEMFC with a serpentine anode, straight cathode flow channels, and a 25 cm² active area. The test results showed that the vibration direction had a direct influence on the performance of the stacks. In addition, when stacked under low vibration excitation, the performance of the PEMFC improved slightly, which was consistent with the results of Wang et al.4 Hou et al.5 carried out a series of experiments to evaluate the efficiency of a proton exchange membrane fuel cell stack under a strengthened road vibration environment. The results showed6 that the steady-state hydrogen utilization rate decreased by 30.7%, and the maximum efficiency7 decreased by 21%, while the performance of a single cell worsened. Imen and Shakeri8 performed experimental studies on the relationship between the PEMFC performance and the load duration of mechanical vibrations. The test results showed that the performance of the PEMFC decreased by 0.6% when the vibration lasted for 4 h.

In 2019, Ahn et al.9 measured the vibration modes of PEMFCs through experiments and proposed a method to determine the effective dynamic characteristics of laminated structures.

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Recently, Xie et al.\textsuperscript{10} studied the cold start of a fuel cell reactor under vibration conditions for the first time. The results show that vibrations have no significant effect on the performance of the PEMFC at lower startup temperatures, while vibrations in the vertical direction are determined to be beneficial during a cold start. However, the effect of vibrations in other directions depends on the startup temperature.

In addition to these experimental studies, a few researchers have carried out simulations on PEMFCs under vibrations to predict their performance. In 2014, Deshpande et al.\textsuperscript{11} used the finite element method to analyze PEMFC stacks under vibration and observed that the hydrogen leakage rate increased linearly with vibration acceleration. In 2016, Liu et al.\textsuperscript{12} analyzed the response stress of the stacks under random vibrations by the finite element method (FEM) and assessed the fatigue lives of fuel cell components based on the Miner fatigue damage theory. The results show that the stress distribution on the gasket and PEM greatly affect their fatigue lives, and under the same total clamping force, increasing the bolt number may improve the bolt fatigue lives. In 2020, Jiao et al.\textsuperscript{13} proposed a stochastic method to reconstruct a 3-D gas diffusion layer with different porosities, which was validated by experiments, and concluded that vibrations enhanced water transport through the GDL zone and that the water saturations in vibration cases were higher than those in nonvibration cases.

Table 1. Limited Values of Ship Equipment Vibrations

| type | frequency/Hz | displacement/mm | acceleration/g |
|------|--------------|----------------|---------------|
| conducting, control device, and others | 2–13.2 | 1.0 | 7 |
|   | 13.2–100 | 1.6 | 40 |
| violent vibration | 2–25 | 25–100 | |
| equipment installed on diesel engine, air compressor, and others | 15–50 | 2.5 | 22.5 |

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The above studies show that the output performance of the PEMFC is affected by the general vibration environment, and its internal hydrogen consumption increases compared with normal conditions. However, the ship vibration environment is much more severe than the land vibration environment, and according to ISO 20283-5:2016, the maximum allowable vibration load of a ship reaches 214 mm/s\textsuperscript{14}, which is much higher than the 4.6–144 m/s\textsuperscript{15} specified in IEC 61373:2011 for vehicle vibration; therefore, accurately evaluating the PEMFC operation under the ship vibration environment is impossible through the literature. Simultaneously, most of the current research projects are conducted experimentally, but these methods cannot accurately measure the spatial distribution of hydrogen in the PEMFC to analyze the operation law of the PEMFC under vibration conditions. However, the computational fluid dynamics (CFD) method can effectively reveal the

Figure 1. Loading process of the ship vibration.

Figure 2. Geometric model with grid.

Table 2. Grid-Independence Verification Data

| serial number | number of grids | calculation results | error with the experiment (%) |
|---------------|-----------------|---------------------|------------------------------|
| 1             | 34 320          | 0.580771            | 8.6                          |
| 2             | 51 060          | 0.576676            | 7.8                          |
| 3             | 74 000          | 0.569922            | 6.5                          |
| 4             | 91 300          | 0.567123            | 5.6                          |
| 5             | 128 000         | 0.551664            | 3.1                          |
| 6             | 196 350         | 0.546396            | 2.1                          |
| 7             | 325 200         | 0.545359            | 1.9                          |
gas transfer pattern inside the PEMFC through higher spatial and temporal resolution and fidelity. Compared with experimental methods, simulations of PEMFCs are inexpensive and efficient. In addition, the performance of microfluidic fuel cells with a structure similar to that of PEMFCs under vibration conditions has been studied in the literature by CFD methods. Thus, using this proposed method for this study is reasonable and valid.

In summary, this paper takes the CFD method as the main research method to investigate the internal mass transfer and external output law of PEMFCs under ship vibration. For the vibration loading problem, a new vibration loading method based on sliding grid technology is first implemented in a conventional PEMFC model. With the purpose of simulating the actual ship vibration environment, the ship vibration is loaded from three directions to the conventional model. The vibration is assumed to be a simple harmonic, and its intensity is referred to in the relevant provisions of the International Maritime Organization (IMO). In addition, the hydrogen distribution inside the PEMFC and the relationship between the external output voltage and the vibration parameters will be reported under the influence of ship vibration.

### 2. MODELS DEVELOPMENT

#### 2.1. Method of Loading Ship Vibration

Ship vibrations on PEMFCs mainly occur in the form of accumulation or periodicity, such as random vibration, sinusoidal vibration, and mixed vibration, which result in performance degradation and structural fatigue damage. The ship equipment is connected rigidly with the hull, so various vibrations can be transferred and coupled. Meanwhile, according to the source of vibrations, the ship vibrations mainly come from the hull vibration, super-

![Figure 3. Velocity distribution of flow channels with no vibration.](https://doi.org/10.1021/acsomega.2c00273)
structure vibration, shafting vibration, mechanical equipment vibration, and fluid vibration. For the equipment in the engine room, the vibration amplitude as displacement will not exceed 1.6 mm, and the applicable range of vibration frequencies will be 0–100 Hz,\textsuperscript{22} as shown in Table 1. The influence of ship vibrations on the PEMFC is generally transient, and the appropriate loading method of marine vibration is the key work for the following simulation. The zone motion and user-defined function (UDF) from the ANSYS-FLUENT platform are adopted to construct a new method of loading vibration, which is known as the zone motion by a user-defined function referred to ZM-UDF. In ZM-UDF, one macro (DEFINE_ZONE_MOTION) is defined to describe the vibration, and the process of vibration loading is shown in Figure 1. In Figure 1, steady solving is performed by the PEMFC module in FLUENT, and the steady flow field that is obtained becomes the initial condition of the transient simulation. Simultaneously, the sliding mesh is reset by a macro named DEFINE_ZONE_MOTION, which includes the direction, frequency, and amplitude of the ship vibrations.

Generally, the ship vibration can be described by displacement as calculated through eq 1 or speed as calculated through eq 2. These equations can be derived from each other

\[
\begin{align*}
x &= A_x \cos(\omega t) \\
y &= A_y \cos(\omega t) \\
z &= A_z \cos(\omega t) \\
V_x &= A_x' \sin(2\pi f_x t + \pi) \\
V_y &= A_y' \sin(2\pi f_y t + \pi) \\
V_z &= A_z' \sin(2\pi f_z t + \pi)
\end{align*}
\]

where \(x, y,\) and \(z\) are three-dimensional directions, \(A\) is the amplitude of the vibration (displacement), \(A'\) is the amplitude of the vibration (speed), \(\omega\) is the angular speed of the vibration, \(f\) is the frequency of the vibration, and \(t\) is the time of the vibration. The relation between \(A'\) and \(A\) can be described through eq 3, and as a result, eq 2 can be adopted in this paper. The terms \(A_x', A_y', A_z', f_x, f_y,\) and \(f_z\) are the main parameters for the ZM-UDF method.

\[
\begin{align*}
A_x' &= A_x \omega_x \\
A_y' &= A_y \omega_y \\
A_z' &= A_z \omega_z
\end{align*}
\]

### 2.2. Mathematical Models

According to the basic principle of fluid dynamics and the application of PEMFCs, the following assumptions are made for the mathematical model:\textsuperscript{23,24}

1. All gases are assumed to be under ideal conditions.
2. Reaction gases exhibit laminar flow in the channel and are incompressible.
3. Materials of the catalytic layer, gas diffusion layer, and proton exchange membrane are porous media with isotropy.
4. Gravity is ignored.
5. The electrochemical reaction only occurred on the surface of the catalyst layer during the PEMFC working process.
6. The PEMFC works in an ideal state.

A PEMFC is a complex system that is associated with multiple physical fields, such as the flow, mass concentration, and electrical fields.\textsuperscript{23} Therefore, the governing equations include the mass conservation equation, momentum conservation equation, energy conservation equation, component conservation equation, charge conservation equation, and liquid water transport equation.

The mass conservation equation is depicted in the following equation

\[
\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \bar{v}) = S_m
\]

where \(\rho\) is the density, \(\varepsilon\) is the porosity, \(\bar{v}\) is the velocity, \(S_m\) is the mass source term, \(\nabla\) is the dispersion, and \(t\) is the time. The source term of the mass is used to describe the hydrogen consumption in the anode catalytic layer and oxygen consumption and water generation in the cathode catalytic layer.

The momentum conservation equation is shown in the following equation

\[
\frac{\partial(\rho \varepsilon \bar{v})}{\partial t} + \nabla \cdot (\rho \varepsilon \bar{v} \bar{v}) = -\varepsilon \nabla P + \nabla \cdot (\rho \varepsilon \mu \nabla \bar{u}) + S_u
\]

where \(P\) is the pressure, \(\mu\) is the dynamical viscosity, and \(S_u\) is the source term of the momentum. In this study, the momentum source term is derived in eq 6

\[
S_u = -4A_i \pi f_i^2 \cos(2\pi f t)
\]

Combining eq 5 with eq 6, the momentum conservation equation of the PEMFC under the influence of ship vibrations is obtained as shown in eq 7

\[
\frac{\partial(\rho \varepsilon \bar{v})}{\partial t} + \nabla \cdot (\rho \varepsilon \bar{v} \bar{v}) = -\varepsilon \nabla P + \nabla \cdot (\rho \varepsilon \mu \nabla \bar{u}) + (-4A_i \pi f_i^2 \cos(2\pi f t))
\]
The energy conservation equation is as follows
\[ \frac{\partial (c_p T) \rho}{\partial t} + \nabla \cdot (c_p \rho u T) = \nabla \cdot (k_{\text{eff}} \nabla T) + S_Q \] (8)
where \( c_p \) is the specific heat at constant pressure, \( k_{\text{eff}} \) is the effective heat conductivity, and \( S_Q \) is the source term of energy.

The species conservation equation is represented in the following expression
\[ \frac{\partial (\rho X_k)}{\partial t} + \nabla \cdot (\rho u X_k) = \nabla \cdot (D_{\text{eff}}^k \nabla X_k) + S_k \] (9)
where \( X_k \) is the species conservation, \( D_{\text{eff}}^k \) is the effective diffusion coefficient of the species, and \( S_k \) is the source term of the species.

The electric charge conservation equation is the following
\[ \nabla \cdot (\sigma_{\text{sol}} \nabla \phi) + S_{\text{el}} = 0 \] (10)
\[ \nabla \cdot (\sigma_{\text{mem}} \nabla \phi) + S_{\text{mem}} = 0 \] (11)
where \( \sigma_{\text{sol}} \) is the electron conductivity, \( \sigma_{\text{mem}} \) is the proton conductivity, \( \phi \) is the electrical potential of the solid phase, \( \phi \) is the electrical potential in the membrane, \( S_{\text{el}} \) is the source term of the electron, and \( S_{\text{mem}} \) is the source term of the proton.

The liquid water transport equation is derived in the following manner
\[ r_w = c_r \max \left( 1 - s, \frac{P_{\text{sat}}}{P_{\text{wv}} - M_{\text{H}_2\text{O}} \rho l \phi_{\text{wh}}} \right) \] (12)
\[ r_w = \frac{\partial (\rho \phi_{\text{wh}})}{\partial t} + \nabla \cdot \left( \rho \phi_{\text{wh}} \nabla \phi_{\text{wh}} \right) \] (13)
where \( r_w \) is the water condensation rate, \( c_r \) is the condensation constant, \( s \) is the phase saturation, \( P_{\text{wv}} \) is the steam pressure, \( P_{\text{sat}} \) is the local saturated pressure, \( M_{\text{H}_2\text{O}} \) is the molar mass of water, \( \rho l \) is the density of water, \( \phi_{\text{wh}} \) is the water content of electromigration, \( \phi_{\text{wh}} \) is the water content of the concentration diffusion, \( \phi_{\text{wh}} \) is the water content of the pressure diffusion, and \( \mu_l \) is the dynamic viscosity of liquid water.

2.3. Geometric Model and Boundary Conditions. A PEMFC with a single channel is adopted for this simulation study. The geometric model is composed of an anode channel, anode gas diffusion layer, anode catalyst layer, proton exchange membrane, cathode catalyst layer, cathode gas diffusion layer, and cathode channel, which are shown in Figure 2. The principal dimension of the PEMFC is 50 mm \( \times \) 1.1 mm \( \times \) 1.435 mm. The length of the channel is 50 mm; the width and depth of the channel are 0.5 mm \( \times \) 0.4 mm, respectively; the thickness of the collector plate is 0.5 mm; the thickness of the gas diffusion layer is 0.2 mm; the thickness of the catalyst layer is 0.01 mm; and the thickness of the proton exchange membrane is 0.015 mm.

Designing a reasonable calculation grid makes the calculation results more accurate and does not need many computational resources. In addition, the grid-independence verification was carried out in this study. Seven grids were designed to calculate...

Figure 5. Velocity distribution of flow channels with different direction vibrations (2 Hz, 1.6 mm/s): (a) anode channel and (b) cathode channel.

Figure 6. Output voltage of the PEMFC at 1.5 A/cm².
Figure 7. continued
the output voltage of the PEMFC under the 1.5 A/m² condition, and the calculation results were compared with those in the literature. The details are shown in Table 2.

As shown in Table 2, the error between the calculated and experimental results shrinks to less than 5% after the total number of grids reaches 128,000. Continuing to increase the total number of grids does not further reduce the error.

Figure 7. Molar concentration distribution of the reaction gas at different frequencies: (a) H₂ in the anode (1.5 A/cm², 2 Hz) and (b) O₂ in the cathode (1.5 A/cm², 1.6 mm/s).
grids does not make much improvement in the calculation accuracy and will take up more computational resources. In summary, based on the grid sensitivity verification, the number of grids is set to 128 000.

The gas of the anode channel is pure hydrogen with 100% humidity, and the gas of the cathode channel is air. The inlets of the anode and cathode are both set to the mass flow inlet, and the outlets are set to the absolute pressure outlet with one standard atmospheric pressure. Simultaneously, the working temperature is set to 343 K, the working pressure is set to 0.2 MPa, the current density is set to 1.5 A/cm², and the excess coefficients of the gas in the cathode and anode are 2.5 and 1.5, respectively. At the gas inlet, the mass fraction of the hydrogen in the anode and the oxygen in the cathode are 0.37 and 0.23, respectively; more detailed parameters are shown in Table 3. The main operating parameters of the PEMFC are shown in Table 4.

2.4. Model Validation. To validate the macro mathematical model, a baseline case is set up with parameters from the literature on a nonvibration design to ensure the rationality and accuracy of the model. The simulation results are compared with those of the experiment in the literature, as shown in Figure 3. Altogether, the error between the simulation and experimental data is below 5%; thus, the mathematical model is viable.

3. RESULTS AND DISCUSSION

3.1. Influence of Vibration Directions. To discover the difference in the effect on the performance of the PEMFC from the vibration directions, four cases, the nonvibration, transverse vibration (x-direction), vertical vibration (y-direction), and longitudinal vibration (z-direction), are simulated. The designated frequency of 2 Hz and amplitude of 1.6 mm/s are set in the simulation for all cases except for the nonvibration case. The middle-longitudinal section of the channel in the z-direction is designated as the monitor surface. The velocity fields of the anode channel and cathode channel in different cases are compared, and the differences in the effects are analyzed. In Figures 4 and 5, the vertical vibration has the most significant effect on the hydrogen distribution of the PEMFC, while the vibration in the other directions has little effect on the anode. In the cathode, the vibration has no significant effect on the oxygen distribution. Generally, the effect of the vibration on the mass transfer of a PEMFC has obvious directionality, i.e., vectorially, and the influence on the gas in the anode is more significant.

![Figure 8](image_url)  
**Figure 8.** Schematic diagram of the detection line position of the anode catalytic layer.

![Figure 9](image_url)  
**Figure 9.** Monitoring data of the central line (x = 0.55 mm) of the catalytic layer under different vibration frequencies: (a) hydrogen concentration, (b) temperature, and (c) current density.

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The relationship between the current density and output voltage of the PEMFC under four different modes is further compared, as shown in Figure 6. Figure 6 shows the output voltage of the PEMFC when the current density is 1.5 A/cm². In the nonvibration, transverse vibration, vertical vibration, and longitudinal vibration modes, the corresponding output voltages of the PEMFC are 0.551664, 0.551846, 0.534, and 0.55188 V. Compared with the four-output voltage, the transverse vibration and longitudinal vibration of the ship have little influence on the PEMFC performance, while the vertical vibration has a more significant impact, which can cause the performance of the PEMFC to significantly decline by 3.2%.

3.2. Influence of the Vibration Frequency. For the vector property of the vibration effect on the performance of the PEMFC, the vertical vibration is applied to study the effect of the vibration frequency on the PEMFC. In the following cases, the current density of the PEMFC and vertical vibration amplitude are kept constant at 1.5 A/cm² and 1.6 mm/s, respectively. The vertical vibration frequencies are set to 2, 4, 6, 8, 10, and 20 Hz in sequence. In the anode, the vertical vibration has a significant effect on the hydrogen concentration, as shown in Figure 7a. In Figure 7a, the six sections along the channel direction (z-direction) express the hydrogen molar concentration distribution nephogram. Except for the normal decrease due to hydrogen consumption in the electrochemical reaction, the hydrogen molar concentration at the outlet of the PEMFC increases with an increasing vertical vibration frequency.

Therefore, the uneven distribution of the hydrogen molar concentration in the anode increases to a certain extent. Relatively, the oxygen molar distribution basically remains normal in the cathode, as shown in Figure 7b, which only shows a normal downward trend of the oxygen molar concentration from oxygen consumption in the electrochemical reaction.

As shown in Figure 7, the ship vibration frequency has a weak effect on the mass transfer of the PEMFC at the cathode end. As a result, this study will extract the data at the catalytic layer midline (x = 0.55 mm) for 1 s under vibration conditions and conduct an in-depth analysis of the internal mass transfer and electrochemical law of the PEMFC (Figure 8).

As shown in Figure 9, under steady-state conditions, the concentration is larger at the entrance, and after diffusion, the concentration reaches a maximum. This diffusion region is defined as the rising region. Then, the hydrogen diffuses approximately linearly toward the outlet. At 20 mm from the inlet, the linear diffusion gradually changes to nonlinear diffusion. Thus, the linear diffusion region can be defined as the stable stage, and the rest of the stage is defined as the sensitive stage. The distribution of fuel in the catalytic layer under steady-state conditions is more uniform, and the diffusion is reasonable. Moreover, under vibration conditions, the trend of decreasing hydrogen concentration in the sensitive stage is more obvious, which is due to the increase in the fuel consumption rate under vibration load. This finding shows the inhomogeneity of gas diffusion, and this phenomenon is similar to the fuel cell output conditions under dynamic load. In summary, the performance change mass transfer law of PEMFCs under vibration conditions is similar to that under dynamic loading, and the temperature field, current density distribution, and fuel concentration distribution in the cell differ significantly from the steady-state condition when the vibration load changes rapidly.

To further elucidate the hydrogen transport pattern in the catalytic layer, the hydrogen distribution acquired by the monitoring line for each operating condition was averaged, and the standard deviation, which is the arithmetic square root of the variance, was calculated for each operating condition to obtain the results shown in Figure 10. The standard deviation reflects the degree of dispersion of a data set. When the standard deviation is larger, and if the dispersion of the data is greater, then the more uneven the data distribution is. Furthermore, in the problem studied in this paper, the higher the standard deviation of the hydrogen concentration is, the less uniform the transmission is, which eventually affects the transmission of the current density and causes the output voltage to decrease. When the standard deviation is small, the hydrogen distribution is more uniform, and if the transmission standard deviation of a certain condition is lower than that of the steady-state condition, the performance of the battery will be improved. Figure 10 shows that when the velocity amplitude is constant, if the vibration frequency is higher, then the dispersion of hydrogen gas in the PEMFC anode is lower. This result occurs because when the velocity amplitude is constant, the vibration frequency becomes higher and the actual displacement amplitude of the PEMFC increases. When the displacement amplitude increases, the gas diffusion inside the PEMFC becomes more uneven. Additionally, in this study, the higher the frequency is, the smaller the actual vibration displacement is, and the hydrogen gas is uniform.

Furthermore, the influence of the vertical vibration frequency on the electrical performance of the PEMFC is analyzed. The output voltage values of the six cases are extracted, and the
Figure 12. continued
relationship curves between the vertical vibration frequency and output voltage are shown in Figure 11. In Figure 11, the output voltage of the PEMFC increases gradually with an increasing vertical vibration frequency, and the influence intensity varies greatly in different vibration frequency ranges. In general, the output voltage of the PEMFC increases, but the increase tends
to be gentle with an increasing vibration frequency. According to the influence intensity, the curve is divided into three zones. Zone I is the rapid change area (≤5 Hz), Zone II is the slow change area (5, 10 Hz), and Zone III is the slight change area (≥10 Hz). In Zone I, the lowest theoretical value occurs when the specific vertical vibration is 1 Hz and 1.6 mm/s, and its output voltage value is 0.508 V, which is 8% lower than that under the nonvibration condition. Therefore, the influence of the vertical vibration in Zone I is relatively significant. In Zone II, a critical point occurs at Point C (6.9 Hz, 1.6 mm/s), which is consistent with the output voltage in the nonvibration condition. The influence of the vertical vibration presents a slowly linear trend near the critical point, while the vertical vibration’s effect further weakens and tends to be stable in Zone III. When the vertical vibration frequency increases by 10 Hz in Zone III, the output voltage increase is only 0.18%.

3.3. Influence of Vibration Amplitude. Similarly, vertical vibration is used to analyze the relationship between the ship vibration amplitude and PEMFC performance. Additionally, eight simulation schemes are designed. In these simulation schemes, the current density is set to 1.5 A/cm², the vertical vibration frequency is set to 2 Hz, and the vertical vibration amplitudes are 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, and 1.6 mm/s. The effect of the ship’s vertical vibration on the mass transfer of the PEMFC can be characterized by the nephogram of the hydrogen molar concentration distribution in the anode (Figure 12a) and that of oxygen in the cathode (Figure 12b). In Figure 12a, the distribution of the hydrogen concentration at the outlet of the PEMFC decreases with an increasing vertical vibration amplitude, which indicates that the inhomogeneity of the hydrogen distribution in the PEMFC becomes more serious than the increase in the vertical vibration amplitude. This factor may lead to an insufficient hydrogen supply in the catalytic layer in some regions, inhibit the electrochemical reaction, and significantly decrease the overall performance of the PEMFC. In Figure 12b, the distribution of the oxygen molar concentration presents a normal downward direction due to the electrochemical reaction along the channel direction. Thus, the amplitude of the marine vertical vibration has little effect on the mass transfer law in the cathode.

Further analysis of the internal mass transfer in the PEMFC with different velocity amplitudes. The analysis is still performed with the anode catalytic layer midline, as shown in Figure 13. According to the conclusion in Section 3.2, the whole mass transfer process can be divided into three parts, that is, the rising stage, the stable stage, and the sensitive stage. From Figure 13a, at the vibration amplitude of 0.2−0.6 mm/s, the hydrogen fuel does not change much or even rises slightly compared with the steady-state condition. When the vibration amplitude reaches 0.6 mm/s, the hydrogen drop becomes larger and gradually increases with an increasing amplitude. The distributions of the temperature field and current density also remain the same as does the distribution of the hydrogen fuel concentration. When the velocity amplitude reaches 1.6 mm/s, the hydrogen consumption is larger, and the fuel in the sensitive area decays sharply due to the lack of fuel, as shown in Figure 13b,c.

From the aforementioned discussion, the standard deviation of the hydrogen concentration in the catalytic layer can effectively respond to the cell operating performance, as shown in Figure 14. When the frequency is constant and the vibration amplitude is 0.2−0.6 mm/s, the hydrogen fuel in the PEMFC undergoes a more adequate reaction, and the fuel supply is still adequate. Thus, the hydrogen fuel concentration is more uniformly distributed, and the output voltage increases. Above the 0.6 mm/s operating condition, the cell output voltage starts to weaken with the increase in the hydrogen consumption rate because the fuel is not sufficient to provide a complete and adequate response.

The effect of the vertical vibration amplitude on the electrical performance of the PEMFC is also very significant, as shown in Figure 15. In Figure 15, Point P is the strengthening peak point and Point C is the critical point. The output voltage in the
The nonvibration condition is used to define the reference baseline, i.e., 0.552 V. According to the curve characteristics, the vertical amplitude influence can be divided into the following three zones: slight-strengthening zone, strong-strengthening zone, and strong-weakening zone. Zone I is the vertical amplitude of the ship that has no obvious effect on the PEMFC’s performance, and Zone II is the relatively obvious strengthening trend. Moreover, the weakening effect is clearly displayed in Zone III. Compared with the baseline, the output voltage of the peak is 0.555 V, the corresponding vertical amplitude is 0.92 mm/s, and the maximum increase in the PEMFC’s electrical performance is 3.6%. At Critical Point C, the vertical amplitude is 1.34 mm/s, and the electrical performance of the PEMFC is consistent with that in the nonvibration condition. In Zone III, the electrical performance of the PEMFC decreases rapidly with an increasing vertical amplitude because the vertical vibration leads to the intensification of hydrogen concentration polarization during the process of enhancing the gas transfer (see Figure 13). As a result, the output voltage of the PEMFC decreases significantly. When the vertical vibration is 2 Hz and 1.6 mm/s, the output voltage of the PEMFC is 0.534 V, which is 3.3% lower than that in the nonvibration condition.

4. CONCLUSIONS

This study establishes a 3D model of a PEMFC under ship vibration based on the CFD method and proposes a technical solution for the loading ship vibration. Then, the external output performance and internal mass transfer law of the PEMFC under ship vibration conditions are obtained through multiple simulations with vibration direction, amplitude, and frequency as the variables. The research results will provide some guidance for the placement of marine PEMFC stacks and contribute to more accurate management of the stack system. Therefore, promoting their application in the field of marine engineering is helpful. The detailed conclusions are as follows:

1. The influence of ship vibration on the gas transfer in the PEMFC varies in the direction of the vibration, with the vertical vibration having the most significant influence. Therefore, during actual ship operation and installation, the PEMFC should avoid vibrations perpendicular to the flow channel as much as possible.

2. The frequency and amplitude of vertical ship vibration will enhance the effects on the gas transfer of the PEMFC, while the influence on the output voltage of the PEMFC...
may be enhanced or weakened. Thus, a critical value should be established for certain PEMFCs. The study shows that the displacement amplitude has a large effect on the performance of the PEMFC. When the vibration has a constant frequency and small displacement amplitude, the reaction of hydrogen will be promoted and the cell performance will improve. When the displacement amplitude increases, the internal mass transfer of the PEMFC slowly becomes uniform, and finally, the external output performance drops sharply.

(3) In contrast to the nonvibration case, the output voltages of the PEMFC decrease by 7.9, 0.48, and 0.5% when the ship’s vertical vibration is 1 Hz and 1.6 mm/s, 20 Hz and 1.6 mm/s, and 1 Hz and 1.0 mm/s, respectively. The results show that the amplitude value of ship vibration has more influence on the PEMFC. As a result, the PEMFC should avoid high-amplitude vibration or filter those vibrations as much as possible during ship operation. Alternatively, low-intensity vibration can be used to enhance the PEMFC.

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Notes

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