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A study on a numerical simulation of the leakage and diffusion of hydrogen in a fuel cell ship

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ABSTRACT

A hydrogen fuel cell has many advantages, such as no pollution, high efficiency, low noise and continuous operation. Therefore, it has the potential to be widely applied in both the power propulsion and power supply of a ship. However, the consequent hydrogen safety and leakage issues have attracted much attention and become key issues that need to be resolved urgently. In this paper, based on the component transportation and chemical reaction modules in Fluent software, a ferry is selected as the research object, and a diffusion model of the high pressure hydrogen leakage in a cabin is established. The hydrogen concentration distributions at different leakage positions after the leakage occurs are obtained by making transient numerical calculations of the hydrogen leakage diffusion at the corresponding leakage positions in the cabin. At the same time, the effects of different ventilation conditions on the diffusion trend of hydrogen are analyzed. The simulation results have ascertained the optimal positions for hydrogen sensors and ventilations and it is hoped that these results can provide guidance for the design of a fuel cell ship that uses high pressure gaseous hydrogen.

1. Introduction

As a major part of the globalized economy, the shipping industry has not only made a great contribution to the international economy and trade, but has also led to serious emission problems with regard to pollutants and greenhouse gases. According to some statistics, the CO_2 emissions of the shipping industry account for approximately 3 ~ 5% of global CO_2 emissions, while the SO_X emissions exceed 5% [1,2]. Due to the hydrogen fuel cell's advantages, which include environmental protection, high energy efficiency and exceptional reliability, it has gradually attracted a great deal of attention in the shipping industry [3]. Moreover, these cells are distinguished from other clean energies (such as solar energy, wind energy, and hydro energy) by their characteristics of high energy density, and high stability and the fact that they are not easily affected by the environmental factors. Therefore, the application of hydrogen fuel cells in ships has promoted the development of clean energy vessels [4,5]. At present, there are many applications of hydrogen fuel cells in ships, which are summarized in Table 1 [6–8].

In 2016, Sandia National Laboratories, the Red and White Fleet, and the Elliott Bay Design Group jointly carried out the zero-emission, high-speed, fuel cell passenger ship project, "SF-BREEZE", in the San Francisco Bay, which had a maximum design speed of 35 nm/h. To data, a number of related feasibility study has been completed [9,10]. Although a lot of research has been carried out on power system design, energy efficiency improvement and control, benefit analysis and energy management strategies [11–20], and the prototype fuel cell ship has already demonstrated the ability to be used as an actual ship, a large-scale application is still some way off. During the various studies and attempts to popularize and apply the technology of a fuel cell ship, the high risks associated with hydrogen has been the major concern; therefore, safety is one of the key technologies that urgently needs to be solved in the development of a hydrogen fuel cell ship [21].

Hydrogen has the following characteristics: easy leakage and diffusion; low ignition energy; large potential for a fuel explosion; and large explosion energy [22]. The ignition volume fraction range is 4–74%, the explosion volume fraction range is 18–59%, and the minimum ignition energy is 0.02 mJ [23], which cause a certain level of risk when a hydrogen fuel cell is being applied to a ship. In order to

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Table 1
Application cases of hydrogen fuel cells in ships.

Year	Nationality	Vessel	Characteristic
2002	China	Fuyuan One	Fuyuan One is a fuel cell yacht: propulsion power of 400 W, speed of 7 km/h.
2005	China	Tianxiang One	Tianxiang One is an experiment ship: propulsion power of 2 kW, speed of approximately 7 km/h.
2006	Germany and other members of the European Union	Alsterwasser	Alsterwasser is the world's first operating fuel tanker, which can carry more than 100 people and 50 kg of hydrogen fuel: propulsion power of 100 kW, sailing for 2–3 days without refueling
2009	Norway and Germany	Viking Lady	Viking Lady, is the vessel passed the marine fuel cell certification of Det Norske Veritas: fuel cell generation power of 320 kW
2015	Japan		It is the first Japanese fuel cell ship, which was a fishing vessel equipped with 450 L of hydrogen fuel: speed of up to 37 km/h, sailing for 2 h without refueling

meet a ship's endurance and power requirements, the hydrogen storage capacity on a fuel cell ship needs to be substantial. However, a ship is a large-scale, powerful piece of equipment, which has a long service life and works in a relatively harsh and complex environment. Moreover, once the equipment has been in operation for a long time, it is difficult to avoid the aging process, and maintenance issues might be neglected in a hydrogen fuel cell ship. If problems relating to the sealing of the hydrogen supply pipelines and valves arise, and the pipelines are damaged due to a collision, resulting in a hydrogen leakage and the consequent fire and explosion, there would be extremely serious consequences.

At present, research on hydrogen leakage diffusion mainly consists of experimental studies and numerical simulations [24,25]. Due to the high risk associated with hydrogen and the high cost of conducting related experiments, experimental studies on hydrogen leakage diffusion are rare. The numerical simulation is still the mainstream method currently used to study the process of hydrogen leakage diffusion, and computational fluid dynamics (CFD) software is widely used in this respect.

General CFD software include Fluent, FlACS, CFX, STAR-CD, PHOENICS, etc. Many researchers have done these relevant studies using experiment or simulation. Some useful conclusions were obtained, which are summarized in Table 2.

According to the ignition status, the aforementioned studies of hydrogen leakage can be divided into leakage and diffusion research and fire and explosion research. These generally occur in time order, i.e., a fire and explosion will not occur until the concentration of hydrogen reaches a certain level. With regard to research techniques, the experimental method should be complementary to the numerical simulation method. Although the experimental method is costly and dangerous, the validity and applicability of various mathematical models of hydrogen leakage need to be verified by experiments. Subsequently, the verified mathematical model can be utilized to conduct a numerical simulation study through packaging and combination by software. The main research objects for hydrogen leakage have included a hydrogen fuel cell automobile parking lot, hydrogen fuel cell automobile cabin and hydrogen refueling station building. The risk of an accident is related to a number of factors, including the hydrogen phase, the initial pressure, the size of the leakage hole, the sealing of the leakage area, the wind speed and direction, the ventilation equipment, the temperature, the obstacle, the arrangement of facilities in the area and the ignition conditions. Through modeling a specific case and setting the corresponding boundary conditions, the accident process can be simulated after the hydrogen leakage. Moreover, studying the effects of certain factors related to the consequences of an accident can provide guidance for relevant safety measures and accident prevention.

Currently, few studies has been conducted into the hydrogen leakage diffusion in the shipping industry. Moreover, the amount of electrical equipment in a ship is substantial, and the hydrogen storage capacity is high. Consequently, the safety hazards and accident levels in a ship are much higher than those in an automobile. In addition, the risk to a ship is much greater than that to a hydrogen refueling station because of the sealing of a ship's cabin. Specifically, once a hydrogen safety accident occurs, it is more difficult for rescue measures to be carried out. The cabin environment of a ship is very different to those of previous research objects and the safety design and prevention measures used for these objects cannot be transferred to a ship. Therefore, the study of the hydrogen leakage of a ship's fuel cell is of great importance.

In this paper, the process of hydrogen leakage from the fuel cell cabins of a hydrogen fuel cell ship is numerically simulated by Fluent software. The effects of different leakage positions on the hydrogen concentration field in a cabin are analyzed by transient numerical calculations. At the same time, the influences of different ventilation conditions in cabins on the hydrogen diffusion trend are analyzed and verified by simulation; this provides guidance for the layout of hydrogen sensors and the ventilation design. Unlike previous studies on hydrogen leakage, this paper takes a different approach in making the ship the research object and taking the cabin layout into account. Moreover, a transient simulation can show the process of hydrogen leakage intuitively. The structure of this paper is as follows. In Section 2, the research object is introduced in detail, the fluid domain model is established, the meshing is generated, and the boundary conditions in Fluent software are selected and calculated. In Section 3, the simulation results of the hydrogen leakage diffusion at different leakage positions and under different ventilation conditions are described and analyzed. In Section 4, the research findings of this paper are summarized.

2. The research object and boundary conditions

2.1. The research object

In this paper, a hydrogen fuel cell ship from the "SF-BREEZE" project (mentioned in Section 1) is selected as the study object, which is currently in the research and development stage [10]. The overall design model of the ship is shown in Fig. 1. The maximum design speed is 35 nm/h, the capacity is 150 seats, the ship's length and width are approximately 30 m and 10 m respectively, and the ship is a twin-hull vessel. The ship consists of a top floor, deck and bottom floor. The top floor has a cockpit, hydrogen exhaust pipes, hydrogen storage tanks and accessories, and other facilities. The bottom floor has propulsion motors, gearboxes, batteries, heat exchangers, fire pumps, and other equipment. The ship's power is completely provided by 40 sets of 4×30 kW proton exchange membrane fuel cell packs, which located in the fuel cell cabins on the deck, with a total installed power of 4.92 MW (including 120 kW of reserve power). The deck consists of a bow cabin, passenger cabin, control cabin, fuel cell cabins and stern cabin, as shown in Fig. 2. The fuel cell cabins are two separate cabins on the left and right, each with 20 fuel cell packs. There are two converters on the left and right sides of the control cabin, and a power distribution cabinet in the center. There is a bathroom and a bar on one side of the passenger cabin close to the control cabin, with 150 passenger seats. Considering that the high-pressure gas storage is the most common hydrogen storage technology, the numerical simulation study of the high-pressure hydrogen leakage diffusion in the cabins of a fuel cell ship is conducted using with this ship's cabin layout. For hydrogen