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Conceptual design of high-speed underwater jet engine using high concentration of hydrogen peroxide

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ABSTRACT

The conceptual design of high-speed underwater jet engine was conducted and demonstrated using high concentration of hydrogen peroxide as a green propellant. On the basis of the principles of steam jet ejector, the central water jet configuration was applied for the engine where a central water jet was surrounded by an annular steam flow. The annular steam flow as the primary fluid was the decomposition gas of hydrogen peroxide and cold water was the secondary fluid. The catalyst pack was composed of the alumina pellets doped with manganese oxides. The performance evaluation of the engine was performed without the flow field of the secondary fluid. The demonstrator successfully generated a practical propulsive force, which could be applied for the systems of unmanned underwater vehicles. For design of experiments, the nozzle exit areas were dealt with. It should be ensured that the exit area of nozzle was sufficiently large to prevent thrust instabilities due to the disturbance in the high-speed flows. In contrast, the excessively large area of the nozzle exit might decrease the efficiency of the engine performance in that the geometry of the engine failed to encourage the heat energy transfer between the primary and the secondary fluids.

1. Introduction

Underwater exploration has drawn considerable interest in recent years with respect to resource observation, submarine topography, oceanography, an early warning of natural disaster or military purposes. In response to these actions, a majority of cost-effective and efficient approaches have been devised. Unmanned underwater vehicles such as autonomous underwater vehicle (AUV) and unmanned undersea vehicles (UUV) are regarded as one of the appropriate options to perform the future missions because they are able to explore an extensive area of the seabed without the need to be tethered to a mother ship. In addition, it is expected that the unmanned underwater vehicles will carry out multifarious duties at the same time via constellation operations.

Various kinds of unmanned underwater vehicles were developed and tested, and the propulsion system played an important role to determine the performance of the vehicles (Mooney et al., 2001). In general, screw propellers have been widely utilized to provide propulsive force for the vehicles because it was simple and inexpensive. The propellers were usually powered by diverse electric supply equipment such as batteries, fuel cell, solar cell and hybrid configurations (Bradley et al., 2001). Even though unmanned underwater vehicles should have high driving capability for a large maneuvering range, the conventional propellers carried heavy performance penalties at high speeds (Xin et al., 2013). When the propeller rotates at a high speed to produce huge amount of thrust, the phenomenon of cavitation is caused on the blade surfaces at a certain point. Once such cavitation events are triggered, severe noise and performance degradation occur. From that perspective, the use of conventional propellers seems to be barely suitable for the application of high-speed unmanned underwater vehicles.

As an alternative to the conventional propellers, the technology of underwater jet propulsion has been studied (e.g. Gongwer, 1960; Korde, 2004; Guo et al., 2011). Underwater jet propulsion can be classified depending on the state of the jet condition. First, liquid water itself as working fluid can jet out after increasing its local pressure through a pump-fed system. In that situation, it would not be expected to deliver high performance because the potential energy of the working fluid is inherently low. Second, the mechanism of steam generation can be applied for underwater jet propulsion. There are several ways to generate high temperature steam using the inflowing water; a heat exchanger can be utilized for the steam jet engine as a representative example. However, the concept of steam-jet engine seems fairly difficult to be adapted for a small unmanned underwater vehicle because the mechanical

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components required for the heat exchanger increase the complexity of the overall system. Moreover, the combustion process for the heat source of the heat exchanger might cause marine pollution. Lastly, a propulsion unit of torpedoes can be employed to produce propulsive-jet flow in water by directly ejecting the combustion exhaust gas through the nozzle. The propulsion system is similar with a rocket propulsion system. The use of the method makes it easy for an underwater vehicle to travel at a very high speed, but the combustion plume could severely pollute the ocean environment.

It is apparent that hydrogen peroxide is a one of the promising propellants for underwater jet propulsion. Hydrogen peroxide has been recognized as a non-toxic and environment-friendly propellant, and it is easily decomposed by a catalyst with the result that steam and oxygen are produced (Musker et al., 2006). The products are also environmentally sound substances. The process of the catalytic decomposition is an exothermic reaction, which can be utilized as a heat source for underwater jet propulsion. Meanwhile, hydrogen peroxide has been used for the jet propulsion system of torpedoes (Ventura and Mullens, 1999). However, the propulsion system also caused significant environmental pollutants because the rocket plume was injected into the ocean where hydrogen peroxide was used as an oxidizer for the combustion process with hydrocarbon fuels. To resolve the problems, a new concept of underwater jet propulsion using only hydrogen peroxide was recently suggested (Claussen et al., 2014; Marr et al., 2015). In the preceding studies, relatively low concentration of hydrogen peroxide, 30–50 wt.%, was utilized as a propellant, and the platinum-based catalysts were produced in a peculiar manner. The micro-underwater vehicles were designed by using these factors, and the performance of the vehicles was evaluated in water. Although the previous researches demonstrated the concept of H_2O_2 monopropellant propulsion system for the application of the micro-underwater vehicle, there is still room for improvement.

The purpose of the present research is to suggest the conceptual design of high-speed underwater jet engine for unmanned underwater vehicles. In general, the vehicles can weigh from tens kilograms to hundreds kilograms. Thus the jet engine on board should have the capability to propel the whole system at a high speed. There are two ways to effectively increase the speed of the vehicle. The first is to use a propellant having high energy density. The second is to design the shape of the vehicle to decrease the drag force induced by high speed maneuvers. In this work, high concentration of hydrogen peroxide (90 wt.% of H_2O_2) was introduced as a propellant to increase the energy density of the working fluid. A high-speed underwater jet engine was conceptually designed on the basis of the principles of steam jet ejector (Heinze, 2015). The catalyst pack was also designed to catalytically decompose the propellant, and it was composed of the gamma-phase alumina pellets doped with manganese oxides.

2. Experimental approach

2.1. Hydrogen peroxide and catalyst pack

Hydrogen peroxide is easily decomposed by a catalyst without the preheating process of the catalyst pack, which contributes to reduce the electric energy consumption required for the preheating method. Furthermore, the mechanism of the catalytic decomposition makes a gas production method simple and light. In this work, 90 wt.% of high-test peroxide was utilized as a propellant, which indicates that the contents of stabilizers in hydrogen peroxide were strictly controlled to prevent the catalyst poisoning. The adiabatic temperature of 90 wt.% high-test peroxide was approximately 750 °C. Thus, once the propellant was catalytically decomposed, superheated steam and oxygen were produced. The hydrogen peroxide was purchased from Shanghai HABO Chemical Technology Co., Ltd.

Manganese oxides (MnO_x) were prepared as active materials and gamma-phase alumina (γ-Al_2O_3) pellets were used for the catalyst support. Sodium permanganate ($NaMnO_4$) solution was used as the catalyst precursor; it was purchased from Sigma-Aldrich Co., Ltd. The alumina pellets were purchased from Alfa Aesar. The original size of the pellet was about 3.18 mm in diameter, and herein they were ground to 1.18–2.00 mm. The production process of the catalyst was similar to that of the previous research (An et al., 2010; Kang et al., 2017). The refined pellets were washed in the running water and dried in the convection oven (120 °C, 5 h). The active materials were loaded on the pellets by wet impregnation method. After that, the pellet-type catalysts were dried (120 °C, 24 h) and calcined in the furnace (500 °C, 7 h). After finishing the calcination, the pellets were washed with water to remove the sodium ions, and they were dried (120 °C, 24 h) to take the moisture out. Fig. 1 shows the configuration of the catalyst pack. Hydrogen peroxide was injected into the catalyst pack via a showerhead-type injector. The design capacity of the catalyst pack was overestimated with the intention of fully decomposing the propellant injected. The distributor was located in the downstream of the catalyst pack to physically support the pellets.

2.2. Design of underwater jet engine

An underwater jet engine should be designed to minimize the drag force during high speed maneuvers. To do that, the jet engine should operate while inhaling sea water. Herein, a high-speed underwater jet engine was conceptually designed on the basis of the principles of steam jet ejector because this concept facilitates breathing cold water as a secondary fluid at a high speed. The concept was originally suggested by Todman and Wallis (2002). They supplied hot steam gas as the primary fluid into the engine by using a heat exchanger. The heat exchanger produced the hot steam gas through the heat transfer process from the combustion zone between diesel fuel and air. They demonstrated that their engineering model generated the propulsive force in water. The jet engine had several features that were not in any of the current propellant driven systems. They claimed that the engine had no rotating underwater parts so that it was very quiet, efficient, virtually impossible to block, and cheap to manufacture. However, there are still parts to be improved. First of all, the heat exchanger was too bulky and complicate to be placed on board in a small-size unmanned underwater vehicles. Moreover, the enthalpy of the hot steam gas was significantly lower than that of high concentration of hydrogen peroxide when considering that the adiabatic decomposition temperature of 90 wt.% H_2O_2 reached about 750 °C.

Fig. 2 presents the schematic view of the conceptual design of high-speed underwater jet engine using high concentration of hydrogen peroxide. In the beginning stage of this research, the central water jet configuration was applied for the engine. For this type of engine, a central water jet was surrounded by an annular steam flow; herein, the annular stream flow was the decomposition gas of high concentration of hydrogen peroxide. These two flows interacted in the mixing chamber, i.e. heat transfer between the superheated gases and cold water occurred. The area of the intake was designed to be gradually shrinking along the axial direction in order to increase the velocity of the incoming flow. The

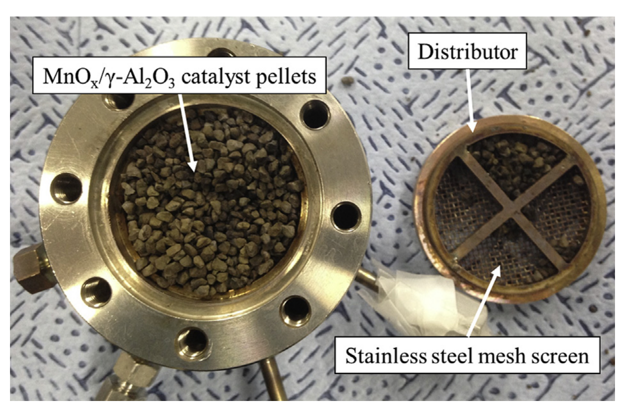

Fig. 1. Catalyst pack for the decomposition of 90 wt.% H_2O_2.