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Power cycle analysis of two-phase underwater ramjet

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ABSTRACT

To predict the cycle and propulsive performance, and further instruct the integral engine design, an ideal power cycle model for a two-phase underwater ramjet is established. Four performance parameters are defined to evaluate overall performance of the two-phase underwater ramjet systems: transmission efficiency, propulsive efficiency, overall efficiency and specific impulse. Then, a scaled-down experimental ramjet engine was tested in a direct-connect ground testing system to validate the present model, and the predictions with present model compare favorably with experimental results. Subsequently, the influences of cruise velocity, air/water mass ratio and cruising depth on the theoretical performance of the two-phase underwater ramjet are discussed. The results indicate that one of the most outstanding advantages of two-phase underwater ramjet is its high propulsive efficiency with the order of 50–95%. As a result, the overall efficiency magnitude are as high as 30% at cruise speed of 100 m/s. Furthermore, regarding rules of specific impulse vs cruise velocity under a certain air/water mass ratio, the occurrence of peak specific impulse of order 400 s is observed.

1. Introduction

As a crucial part of marine crafts, propulsion system is always a hot research area in maritime industry. According to propulsion models, the marine propulsion system can be divided into two categories: propeller-driven and jet-driven. When a propeller is working at high rotational speed, cavitation will occur and reduce the thrust and consequently decrease the propulsive efficiency of the system. Therefore, in case of marine vehicles driven by impellers, the advance velocity of the system is usually bounded to 70 knots. Considering different types of fluid used in jet propulsion, two major propulsion systems have been widely employed in maritime industry: first type is waterjet propulsion system, whose use was initially confined principally to small high-speed pleasure craft and work boat situations where high maneuverability was required [1]. Nevertheless, when working at high rotational speeds, pump impellers are prone to suffer from cavitation problems which will lead to serious erosion and poor performance in high-speed navigation. The other type is gas jet propulsion, which was initially introduced for high-speed underwater missile where rocket engine was used as propulsion system [2]. Because water resistance is much greater than air, the speed of underwater rocket engines is much lower than those in the air, consequently, the propulsive efficiency of underwater rocket is quite low. Water ramjet is another kind of underwater gas jet propulsor that simply utilizes hydroreactive fuel combusting with seawater to generate thrust. Due of the absence of the oxidant onboard, a water ramjet possesses a great potential to increase the cruise range and improve specific impulse [3]. A number of studies have analyzed water ramjet cycles where chemical or thermal energy is used to vaporize the incoming water, generating a steam exhaust jet. Hacker and Lieberman [4] analyzed the thermodynamic cycle of an underwater ramjet propulsion system using a thermite fuel to generate steam. Their conclusion showed that the huge portion of overall energy absorbed in heating and vaporizing the water leads to a relatively poor energetic performance. Yang and He [5] regarded the ideal thermodynamic cycle model as a combination of Brayton cycle and quasi-Ranline cycle and predicted thermal efficiency, propulsive efficiency and specific impulse of a water ramjet engines using magnesium-based fuel. The results indicated that propulsive efficiency was less than 20% in most cases, which led to a poor overall efficiency of ramjet engine.

As a new type of water ramjet, the two-phase underwater ramjet (TPURJ) has been paid more and more attention by researchers, and Fig. 1 shows how it works: after being decelerated and pressurized by the diffuser, the water flow is mixed with injected high-pressure gas, resulting in a two-phase bubbly flow, which is then acceler-

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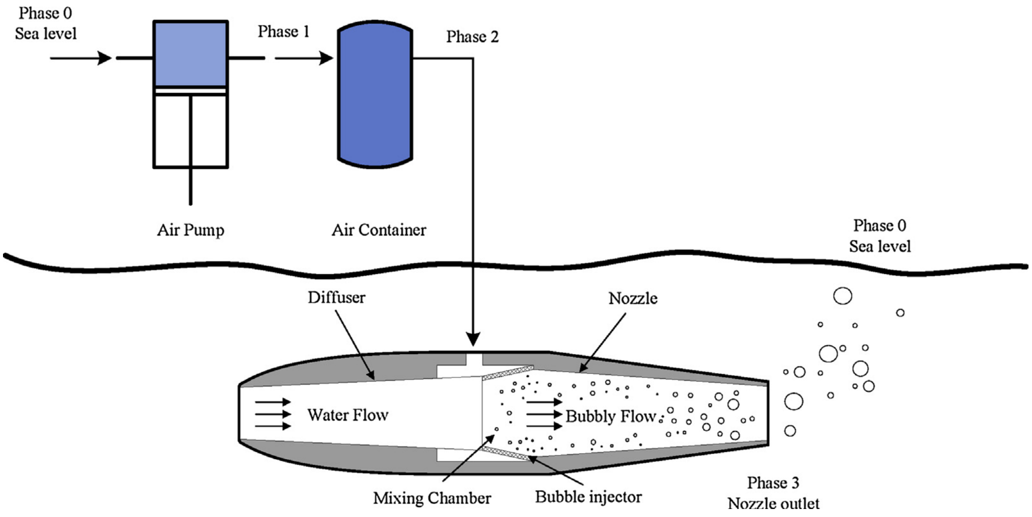

Fig. 1. Schematic diagram of system of underwater two-phase ramjet.

ated in the nozzle. During the acceleration process, bubbles expand and perform work on the water under favorable pressure gradient so that the water velocity at the engine outlet is greater than the velocity at the inlet, and thrust is produced. Compared with traditional propeller propulsion, the TPURJ has simpler structure and higher propulsive efficiency, and there are no rotating parts, so cavitation does not occur during high-speed navigation [6]. With its outstanding advantages, the TPURJ has very broad application prospects especially at high vehicle speeds.

Mottard and Shoemaker [7] first proposed the concept of an underwater ramjet which consists of the production of thrust by the transfer of the potential energy of a compressed gas to a flowing liquid through a mixing process. A series of tests was conducted in a towing apparatus and the hydroduct produced a positive thrust-minus-drag force at every test speed. Then, Witte [8] discussed the effects of scale, forward speed and nozzle length on propulsive efficiency and proposed a scheme for the TPURJ which is self starting. In recent decades, Gany [9] analyzed thermodynamic cycle of the TPURJ, and his study revealed that the TPURJ possesses high theoretical propulsive efficiency over a wide cruise speed range. Mor and Gany [10] presented the performance mapping of the TPURJ and the results indicated that the propulsive efficiencies of the TPURJ are in the range of 70–80%. Fu et al. [11] constructed a parametric study on the TPURJ using two-fluid model and investigated the influence of vessel velocity, air mass flow rate, inlet area, and initial bubble radius on ramjet thrust. They also declared that the thrust weakly depends on the advance velocity of the vehicle. Employing a finite volume computational fluid dynamics (CFD) package (FLUENT), Hayati et al. [12] investigated the performance of the TPURJ at different operating conditions and different configurations. In addition, Haustein et al. [13] proposed a new type of underwater ramjets using the method of phase transfer. In this case, multiphase flow was generated by injecting liquefied-gas droplets into the water, within the thrust unit. Injection led to a sudden drop in the liquefied gas's pressure, leading to boiling inside the water medium at ambient temperature, and additional expansion work was predicted to produce additional thrust. Haustein conducted a series of tests with a suitable liquefied-gas (R134a) in a tow-pool; the measured thrust by liquefied-gas boiling demonstrated comparable results to those of compressed air bubbles.

Unlike the TPURJ which merely depends on forwarding motion to pressurize water, air-augmented waterjet propulsion system uses pump to produce high-pressure water and it has also been studied by many researchers. Amos et al. [14] first studied the performance of an air-augmented waterjet, and the results indicated that a lower pump-outlet pressure and a higher gas/liquid ratio were both able to promote the engine, and thrust augmentation was found to be weakly dependent on air-injection temperature. Singh et al. [15,16] used an analytical model to optimize the geometry of the nozzle for maximum thrust enhancement. On the basis of Singh's work, Wu et al. [17] carried on extensive experiments to study the performance of the bubble augmented waterjet propulsion under different conditions and thrust increases as high as 100% were measured with a void fraction of 50%.

However, research on the power cycle and theoretical analysis of the TPURJ is quite limited [9] and the energy transformation process of the ramjet is still open to dispute [18]. Therefore, this study intends to establish an ideal power cycle model of the TPURJ and present some theoretical results of transmission efficiency, propulsive efficiency, overall efficiency and specific impulse.

2. Establishment of power cycle model

In order to highlight the dominant physical characteristics of working process of the TPURJ, power cycle model is established on the following assumptions:

(i) The liquid is an incompressible fluid, and effects due to its viscosity, surface tension and vapor pressure are neglected.
(ii) The working medium of the power cycle is air, which is an ideal gas with negligible viscosity and constant specific heat.
(iii) The gas and liquid are always at the same velocity and temperature.
(iv) The kinetic energy loss is ignorable and the mixing chamber pressure is equal to the stagnation pressure of the incoming water.
(v) The water inlet velocity is equal to the cruise velocity.
(vi) The air/water mass ratio μ is assumed to be less than 0.01, so that air bubbles are in a continuous medium of water.
(vii) The bubbly flow is completely expanded at the nozzle outlet, which means that the exit plane pleasure is equal to the ambient pressure.

Unlike most ramjet engines, the TPURJ is not a thermal machine, because during the mixing process, the high-temperature gas bubbles transfer their thermal energy to the liquid phase rapidly [19], but thermal energy cannot be used to accelerate the water, which is an incompressible fluid. Therefore, any attempt to improve the