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Experiment and simulation on air layer drag reduction of high-speed underwater axisymmetric projectile

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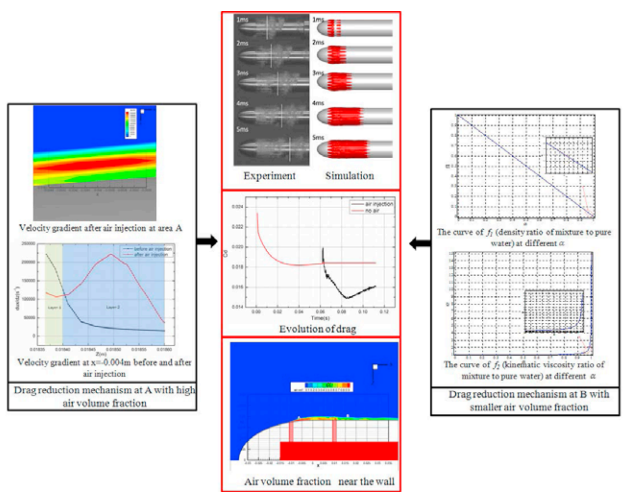
HIGHLIGHTS

- Experiment and simulation are both taken on axisymmetric body.
- Mechanism of drag reduction is analyzed.
- Unsteady evolution of drag is investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

Injection of air could lead to creation of a bubbly mixture or air layer near the surface that can significantly adjust the flow within the turbulent boundary layer. In this paper, stress wave propagation techniques and Split Hopkinson Pressure Bar (SHPB) are used in underwater launching experiment. Simulation with volume of fluid (VOF) method and modified renormalization group (RNG) k-ε model is also performed to study the physical process of drag reduction of axisymmetric body. Comparison between numerical and experimental air layer length shows good correlation. Results indicate that air layer has good effect on drag reduction. Friction drag reduction mechanism is analyzed from two aspects due to different air volume fraction α. At area with high α, fluid is heterogeneous and layered. Drag reduction is from decrease of velocity gradient and dynamic viscosity at the wall. At area with small α, the mixture is homogeneous. Empirical equation of turbulent boundary layer shear stress is applied to describe drag reduction mechanism. The unsteady evolution of drag with injection of air is also studied at last.

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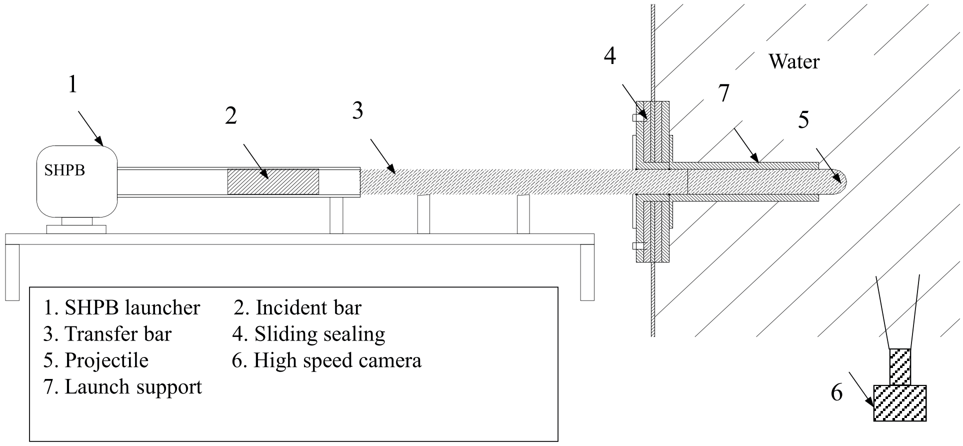

Fig. 1. Underwater launching system.

1. Introduction

Skin-friction drag constitutes a significant portion of the total resistance for nearly all transportation systems moving in a fluid [1]. Turbulent boundary layer skin friction in liquid flows may be reduced when bubbles or air layer is formed near the surface. The lubrication of external liquid flow with a bubbly mixture or air layer has been the goal of engineers for many years. This phenomenon was first detected by McCormick and Bhattacharyya [2], who found that viscous drag reduction of a fully-submerged body of revolution is obtained by creating hydrogen gas on the hull.

Merkle et al. [3–5] did much research on microbubble drag reduction through both experiment and simulation. In their research, integrated skin friction reduction of greater than 80% is observed. The volumetric gas flow required for this maximum is nominally equal to the volume flow of liquid in the boundary layer. In their simulation, a well-tested boundary-layer code employing a simple mixing length model for the turbulence is used. The order of magnitude and trends of the experimental skin-friction reduction are reproduced quite well by this simple model. Elbing et al. [1,6–8] did a set of experiments to investigate the phenomena of skin-friction drag reduction in a turbulent boundary layer (TBL) at large scales and high Reynolds numbers. Two distinct drag-reduction phenomena were investigated: bubble drag reduction (BDR) and air-layer drag reduction (ALDR). Results from the BDR experiments indicate that significant drag reduction (> 25%) is limited to the first few meters downstream of injection. Once ALDR was established, friction drag reduction in excess of 80% was observed. They also found the critical air flux required to establish ALDR. Xu et al. [9] report a series of numerical simulation of small bubbles seeded in a turbulent channel flow at average volume fraction of up to 8%. These results show that even for relatively large bubbles, an initial transient drag reduction can occur as bubbles disperse into the flow. Relatively small spherical bubbles will produce a sustained level of drag reduction over time. Sanders et al. [10] studied the bubble friction drag reduction in high-Reynolds-number (210 million) flat-plate turbulent boundary layer. Buoyancy pushed the air bubbles to the plate surface where they coalesced to form a nearly continuous gas film that persisted to the end of the plate with near 100% skin friction drag reduction.

Drag reduction is also an important phenomenon in cavitation. Wang [11,12] et al. and Ji [13] studied ventilated cavitation. They analyzed the flow field and drag reduction in cavitation. Ceccio [14] reviewed the use of partial cavity, super cavities and gas-injection for drag reduction of axisymmetric objects moving within a liquid. At issue are the conditions under which a stable gas or bubbly layer can be formed through the injection of gas at the surface, the amount of drag reduction that can be achieved, the required volume flux, and the possible increase in form (or other components) of drag resulting from the gas injection that might outweigh the benefits of the gas-induced skin-friction drag reduction.

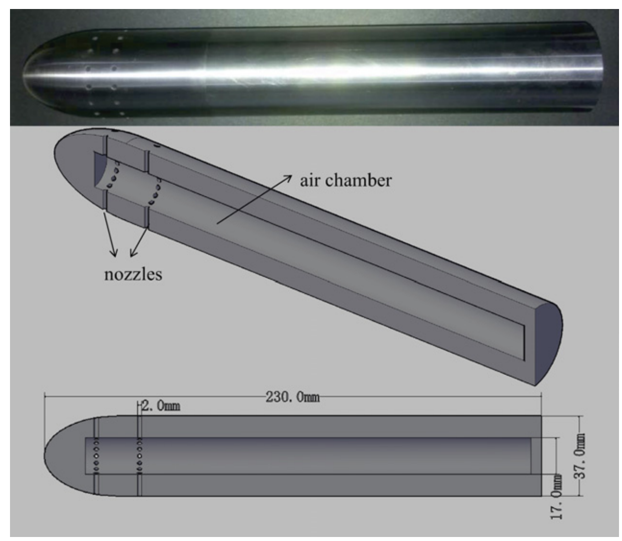

Fig. 2. Experimental model.

Much development on drag reduction of underwater vehicle has been achieved and this technique has been in application in some countries. But this phenomenon is still an open issue. In present paper, air layer drag reduction of streamlined axisymmetric body is studied by both experiment and numerical simulation. Through analysis of result, mechanism of air layer drag reduction and unsteady evolution of drag are detected.

2. Experiment

2.1. Experiment setup

Stress wave propagation techniques and SHPB are used in the experiment, as shown in Fig. 1. The scaled underwater launch system mainly consists of three parts, launching system, water tank and high-speed camera. The launching system converted from SHPB is used to accelerate the incident bar.

One-dimensional stress wave theory is employed here to analysis the process of the energy transmission in the system. Details can be got in Ref. [15]. By the stress wave generated from SHPB, the experimental system can accelerate model transiently to 30 m/s in less than 200 μs with slight disturbance of water during