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Experimental investigation of ventilated partial cavitating flows with special emphasis on flow pattern regime and unsteady shedding behavior around an axisymmetric body at different angles of attack

Taotao Liu, Biao Huang *, Guoyu Wang, Mindi Zhang

School of Mechanical and Vechicular Engineering, Beijing Institute of Technology, 5 South Zhongguancun Street, Beijing 100081, China

A R T I C L E I N F O

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A B S T R A C T

The objective of this paper is mainly to investigate the ventilated partial cavitating flow structure at different angles of attack with experimental methods. A high-speed camera technique is used to record cavity evolution patterns. The numerical simulation is performed by CFX Solver with a free surface model and filter-based turbulence model. Three flow pattern maps are constructed to depict the flow pattern and structures at different angles of attack α, i.e. the range of Froude number *Fr* and gas entrainment coefficient C_Q. The maps show that the angle of attack α has a significant effect on ventilated cavitating flow structures. With the increasing value of α, the asymmetry of ventilated cavity becomes obvious and the angle between the axis of the body and the closure line θ is decreased. The value of the included angle θ is found to vary with *Fr* number and C_Q. The cavity break-off may be mainly determined by the momentum and the direction of re-entrant jet flow.

1. Introduction

Cavitation usually appears in the low pressure region (Brenen, 1995; Blake and Gibson, 1987; Wu et al., 2015, 2016; Wang et al., 2017a,b; Ji et al., 2013, 2017) around the shoulder of the underwater projectiles during the launching process. Cavitation on the projectile can lead to many problems such as pressure pulsation, sudden change in loads and vibration (Joseph, 1995; Arndt, 2002; Wang et al., 2015; Hu et al., 2015; Long et al., 2017). For this reason, the researchers try their best to minimize the undesired effects and maximize the advantage of cavitation (Abraham et al., 2003; Amromin and Mizine, 2003; Sanders et al., 2006; Elbing et al., 2008; Ceccio, 2010; Wu et al., 2014; Wang et al., 2018). Artificial gas injection, which can form a continuous cavity covering the object surface (Semenenko, 2001; Stinebring et al., 2006), is an effective method to reduce friction drag and increase speed for high speed underwater vehicles (Brenen, 1995; Amromin et al., 2006, 2011).

Ventilated cavitation around hydrofoils and axisymmetric bodies have been widely studied (Franc and Michel, 2005; Chen and Lu, 2005; Arndt et al., 2009; Wosnik and Arndt, 2013; Karn et al., 2015; Karn and Arndt, 2015). In the experimental study, Wosnik et al. (2003) carried out to investigate some aspects of the flow physics of a supercavitating vehicle in a high-speed water tunnel. The digital strobe photography images were taken to describe cavity shape and re-entrant jet interaction qualitatively. Also, ventilation gas requirements from foamy cavity of the ventilated partial cavitating flows to continuous clear cavity were studied at different inflow velocities. Kopriva et al. (2005, 2008) performed an experimental study of test body drag reduction by ventilated partial cavitation in steady and unsteady flows. They found that the ventilated cavitation on the OK-2003 test body was effective in reducing drag and sharply increasing the lift to drag ratio. Kawakami and Arndt (2011) investigated various aspects of ventilated supercavities formed behind a shap-edged disk utilizing several different configurations. Results regarding two distinct types of re-entrant jet were presented. The first type, observed in ventilated partial cavitating flows, was characterized by an opaque cavity periodically shedding air from the cavity in the form of unstable, toroidal vortices. The second type was observed in the transition from the re-entrant to two vortex tubes closure mechanisms, which was characterized by a mostly transparent supercavity with a small region of water recirculation at the closure of the cavity. Karn et al. (2016a,b,c) conducted an experimental investigation into the physics of supercavity closure in detail. They found that there were four stable states of a ventilated supercavity, which include three stable closure modes (e.g., re-entrant jet, twin vortex and quad vortex), and foamy cavity. The foamy cavity referred to the state before the clear supercavity is formed, when the cavity consists of bubbles and foam without a clear gas-water interface. In addition, five unstable closure modes were

* Corresponding author.
E-mail address: huangbiao@bit.edu.cn (B. Huang).

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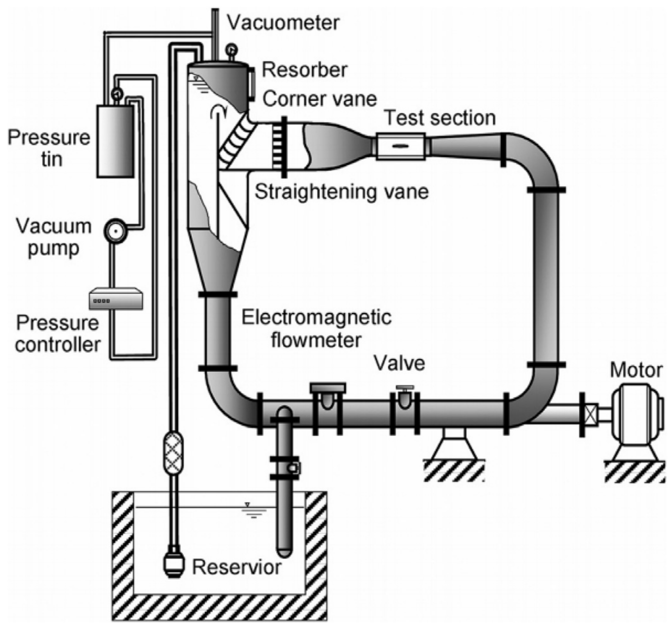

Fig. 1. Schematic of the water tunnel.

observed. Recently, Liu et al. (2017) investigated the ventilated partial cavitating flow pattern in detail with a high speed camera in a closed-loop cavitation tunnel. Four relatively stable states and three unstable flow patterns of a ventilated cavity was observed and they found that the *Fr* number and gas entrainment coefficients play a significant role on the globe ventilated multiphase structures. Karn and Rosiejka (2017) investigated the air entrainment characteristics in the formation of a ventilated supercavity from the foamy cavity and collapse to the foamy cavity from a supercavity in steady and unsteady flow conditions. Results shown that the gas entrainment required to establish a supercavity was much greater than the minimum gas entrainment required to sustain it. Further, these gas entrainment values depended on Froude number, cavitator size and the flow unsteadiness.

Meanwhile, during the underwater moving process of high speed vehicle, the ventilated cavitating body is usually required to work with angle of attack. The asymmetry of ventilated cavity due to angle of attack significantly affect the hydrodynamic performance. Xie and He (1999) performed an experimental study of ventilated cavitation for slender body at small angles of attack to examine the shape of cavity, the base pressure and the steady hydrodynamics forces and moments. Xiang et al. (2012) used a Eulerian-Eulerian two-fluid model integrated with the Multiple-Size-Group model to investigate the effect of attack angle on the bubbly flow and the drag reduction efficient of partially ventilated cavity. Zou et al. (2013) investigated the shedding of the ventilated supercavity with velocity disturbance. They established the models of gravity and angle of attack effects on suprecavity in uniform flows, respectively. Chen et al. (2015) numerically investigated the influence of angle of attack on

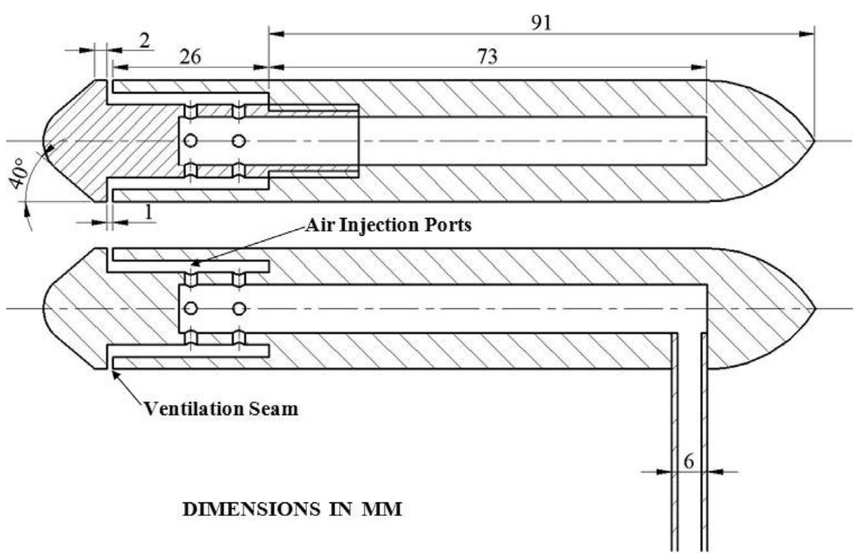

Fig. 2. Vertical and horizontal cross sections of test body (side view and top view).

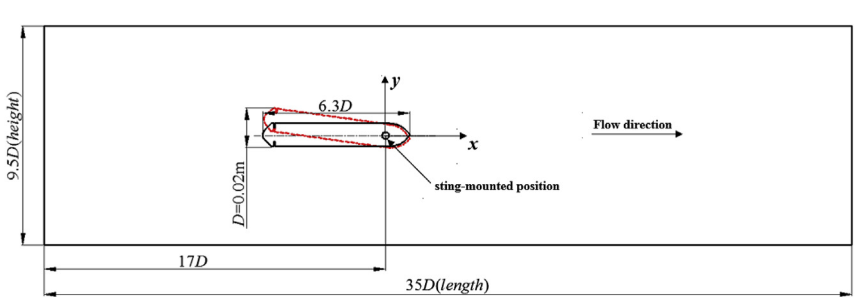

Fig. 3. Sketch of the test body's position in the test section.