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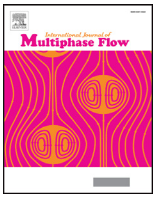

On the synergistic interrelation between supercavity formation through vaporous and ventilated routes

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ABSTRACT

A supercavity can be attained via two distinct routes: vaporous and ventilated supercavitation. A vaporous supercavity is one that is obtained by the coalescence of individual vapor bubbles formed by cavitation. On the other hand, a ventilated supercavity results from the coalescence of bubbles of non-condensable gas formed through gas injection at the rear part of the cavitator. A typical strategy of operation of a supercavitating underwater vehicle entails an interplay between these two modes viz. accelerating it to a high speed using ventilation, when a natural supercavity can be sustained. This fact necessitates a systematic study of the synergistic relationship between the process of supercavity formation under these two modes. Thus, in the current work, we have systematically carried out water tunnel experiments to study the effect of vaporous and ventilated modes of supercavitation on each other during supercavity formation. The results show a systematic dependence between the relevant parameters which include the formation natural cavitation number and the formation gas entrainment coefficient. Further, the effects of change in Froude number and blockage are also reported and discussed.

1. Introduction

Supercavitation, a limiting case of cavitation, occurs when the formed cavity is so large so as to entirely encompass the object which forms it. Owing to its potential application in the drag reduction of underwater vehicles, supercavitation research has gained a considerable momentum in the last decade and a significant amount of research has been conducted into different aspects of supercavitation, viz. natural supercavitation, artificial supercavitation, supercavity closures, supercavity closures, ventilation demand, supercavity control etc. (Savchenko and Savchenko, 2012; Rashidi et al., 2014). Most of these studies can be broadly categorized into studies on either natural or artificial supercavitation and have been widely discussed in the prior literature recently (Karn et al., 2015a; Serebryakov et al., 2015; Karn et al., 2016a,b; Lee et al., 2016; Cao et al., 2017; Karn and Rosiejka, 2017). A natural supercavity is a consequence of the cavitation induced by reduction in pressure at the cavitator because of high liquid velocity, whereas an artificial supercavity is formed by the coalescence of individual gas bubbles resulting from the injection of a non-condensable gas at the rear of the cavitator (Karn et al., 2016a).

There are essential similarities and differences between a vaporous and a ventilated supercavity, as reported by prior studies. One of the earliest studies in this area by Silberman and Song (1961) suggested that natural and artificial supercavities should have similar average characteristics viz. cavity length, as long as the cavitation number is the same. This has been supported by a number of other authors such as Semenenko (2001) and Zhang et al. (2007). Silberman and Song (1961) further proposed that this similarity might be exploited to generate cavities by ventilation. The benefit of obtaining supercavities through the ventilation route is that low sigma values ($\sigma < 0.1$) required for supercavity generation can be obtained at a much lower flow speed of few meters per second, which otherwise require a flow speed of over 50 m/s through a purely vaporous route (Epshtein, 1975). However, there are distinct dissimilarities between the two. As pointed out by Skidmore (2013), artificial supercavities differ from the natural supercavities in their method of gas exchange. According to Cox and Clayden (1956), supercavity rear is often a very turbulent region of flow where the contents of the cavity are entrained away. In a ventilated supercavity, the air entrainment out of the supercavity depends upon the rate of gas supply. But in the case of a natural supercavity, the loss of vapor from the rear portion is made up by the evaporation at the walls of the interface and thus there is an inexhaustible supply of vapor (Cox and Clayden, 1956;

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Spurk, 2002). The recent study by Karn et al. (2016a) related the gas entrainments with the supercavity closure modes and pointed out the differences in closure mechanisms for the natural and artificial cases. Their study suggested that there is an increasing tendency to form a re-entrant jet based closure in vaporous supercavities, while a myriad number of other closure mechanisms appear in ventilated supercavities.

Thus, a natural supercavity, characterized by a re-entrant jet, is essentially vaporous, whereas an artificial (or ventilated) supercavity which is primarily composed of gas, may lead to different kinds of closure mechanisms. In a natural supercavity, the cavity pressure is usually taken to be the water vapor pressure, provided the liquid does not contain any dissolved gases. However, it is noteworthy that even in the occurrence of a ventilated supercavity, there is some contribution of a ‘vaporous’ component that is caused by the vapor bubbles resulting from the cavitation of the liquid at the cavitator edges. Arguably, this vaporous component of supercavitation will diminish the ventilation requirements to establish an artificial supercavity. Similarly, prior reports have ascertained that the presence of a non-condensable gas inside a single cavitation bubble reduces the rate of collapse and increases the minimum bubble volume (Brennen, 2013). This factor again facilitates the coalescence of individual vapor bubbles into a vaporous supercavity. Thus, the mutual effect of both the modes of supercavitation on each other is evident. Understanding of the synergistic relationship between vaporous and ventilated supercavitation is important, especially because the operation of a supercavitating underwater vehicle is driven by an interplay between these two distinct modes of supercavitation. For instance, a typical operational strategy of a supercavitating vehicle entails accelerating the vehicle to a high speed employing a ventilated supercavity, till a point when a natural supercavity can be sustained (Karn et al., 2016b). The formation and sustenance of natural supercavitation in a vehicle (which is the desired mode of vehicle operation under cruising conditions) again depends upon two factors: the vehicle speed and the vehicle depth below the free surface, which in turn affects the hydrostatic pressure. The physical parameters involved in these studies are incoming velocity (U), ventilation flow rate at standard conditions ($\dot{Q}_{\mathrm{As}}$), ambient pressure (P_∞), cavity pressure (P_C) and cavitator diameter (d_C), and these are typically expressed in terms of non-dimensional parameters such as Froude number, $Fr = U/\sqrt{gd_c}$, vaporous cavitation number, $\sigma_v = (p_o - p_v)/0.5\rho U^2$ etc., where $g$and ρ denote gravitational acceleration and water density, respectively. In addition, for ventilated/combined supercavitation, gas entrainment coefficient, $C_{Qs} = \dot{Q}_{\mathrm{As}}/Ud_C^2$ should also be taken into consideration.

However, it may not be always possible to extricate ventilated and natural modes of supercavitation from each other. It is possible to obtain a purely vaporous supercavity at high velocities without any ventilation, while a purely artificial supercavity can be attained by injecting non-condensable gas at low velocities, when the generation of vapor bubbles due to cavitation does not take place. Even at moderate velocities, the effect of vaporous cavity formation will be observed. This suggests that the usual nomenclature of a ‘ventilated supercavity’ in the literature may refer to a combined vaporous-ventilated supercavity, and not to a purely ventilated supercavity, at least for a range of operational conditions. Although it may not always be possible to obtain a purely ventilated supercavity under real conditions, it can be attained in specific experimental facilities at certain conditions, for instance by increasing the test-section pressure in a cavitation tunnel. in a typical high-speed cavitation tunnel (For e.g. see Fig. 1), the test-section pressures can be completely regulated to yield a purely natural supercavity (when the test-section pressure is lowered), a purely artificial supercavity (when the test-section pressure is increased) or a combined vaporous-ventilated supercavity. Moreover, it must be pointed out that although a large number of studies have been conducted to study the steady developed cavities of ventilated and vaporous type, a systematic study of the supercavity formation process per se has not hitherto received much attention.

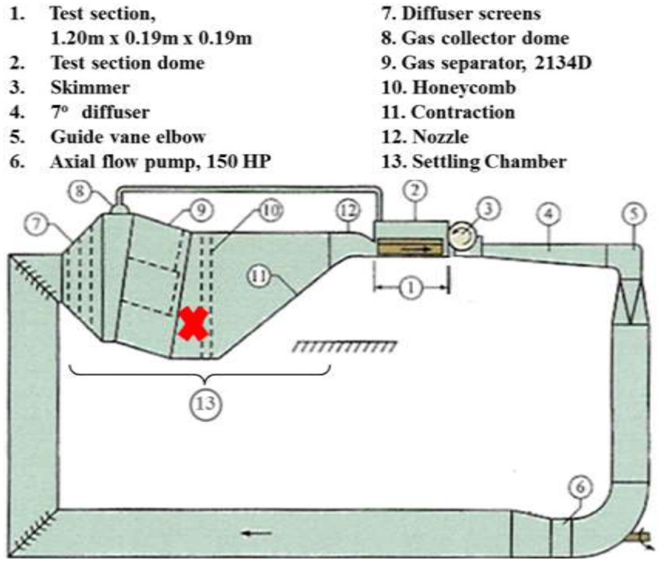

Fig. 1. Schematic of the test-section of the experimental facility along with the orientation of the two models in the test-section. The cross mark represents the location where temperature and dissolved oxygen concentration are measured in our experiments. Adapted from Karn et al. (2016a).

Thus, in the current study, we study the *formation process* of both the natural and artificial supercavity separately and also study the effect of one mode on the other. First, the formation of a natural supercavity and the effect of increasing amounts of ventilation on the σ_v requirements for supercavity formation (σ_{vf}) is explored. Next, C_{Qs} requirements for the formation of an artificial supercavity ($C_{Q\mathrm{sf}}$) are explored and then its variation with respect to increasing amount of suppression of natural supercavitation is investigated. This paper is structured as follows: Section 2 provides the details for the experimental facility and the setup. Subsequently in Section 3, we present results and discussion on the formation requirements for a supercavity under both modes, which is followed by a final conclusion in Section 4.

2. Experimental setup and methodology

Experiments were conducted to study the formation of supercavitation under natural and artificial modes under different flow conditions. The experiments were carried out in the high-speed water tunnel at the Saint Anthony Falls Laboratory. This water tunnel is a closed recirculating facility with horizontal test-section having a hydraulic diameter of 214 mm and dimensions of 1.20 m (Length) × 0.19 m (Width) × 0.19 m (Height) as shown in Fig. 1. This tunnel is specifically designed for experiments on natural and ventilated cavitation and is capable of operating at a maximum velocity of 20 m/s (Karn et al., 2015b,c,d, 2016c).

Backward Facing Model (Karn et al., 2015a, 2016a) or Free Closure Model (Karn and Rosiejka, 2017) was used in our experiments. In the backward facing model, a thin NACA0012 hydrofoil strut is placed upstream of the cavitator to avoid the interaction between the formed cavity and the strut body leading to a free closure as reported by Logvinovich (1973). Fig. 2 demonstrates how the BFM is being mounted in the test-section.

To minimize the disturbance to the flow, the thickness of the hydrofoil strut is limited to 5 mm, so that it can barely envelope the ventilation pipe running to the cavitator. The hydrofoil has a

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