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# Gas entrainment behaviors in the formation and collapse of a ventilated supercavity

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ABSTRACT

The present work reports some interesting gas entrainment behaviors in the formation and collapse of a ventilated supercavity under steady and unsteady flow conditions. Our experiments show that the gas entrainment required to establish a supercavity are much greater than the minimum gas entrainment required to sustain it, and these gas entrainment values depend on Froude (*Fr*) number, cavitator size and the flow unsteadiness. Specifically, the measurements of the formation gas entrainment coefficients under different *Fr* numbers indicate that it does not monotonically increase with *Fr* but displays increasing and decreasing trends in different regimes of *Fr*. On the other hand, the collapse air entrainment coefficient initially decreases with *Fr* and then approaches to a constant. Similar trends of formation and collapse gas entrainment coefficient are observed for different cavitator sizes. Moreover, the introduction of unsteady gusts causes a slight monotonic increase in the formation and collapse gas entrainment requirements. Our study points out the crucial factors to be considered in the estimation of gas storage requirements for a ventilated supercavitating vehicle.



## 1. Introduction

High speed underwater vehicles experience a tremendous amount of flow resistance when moving underwater due to skin friction drag [1–3]. Supercavitation is a special case of cavitation which can be employed to create a bubble of gas/vapor inside water that is large enough to encompass an object (or vehicle) travelling through the water. Supercavitating vehicles are a revolutionary step in the direction of underwater locomotion because it can lead to drag reduction of as high as 90%, facilitating a substantial increase in speed [4]. The phenomenon of supercavitation is generally characterized by non-dimensional parameters such as cavitation number, $\sigma = 2(P_\infty - P_c)/\rho U^2$ and Froude number ($Fr = U/\sqrt{gd_c}$) where $P_\infty$, $P_c$, $\rho$, $U$, $g$ and $d_c$ denote the ambient pressure, the internal cavity pressure, water density, flow velocity, gravitational acceleration and cavitator size, respectively. A supercavity is attained at small $\sigma$ ($\sigma < 0.1$) and this can be accomplished naturally or artificially. A natural supercavity refers to a large attached vapor cavity which is generated by a body travelling at very high speeds (>90 knots at a depth of 1 m in open waters) or at low ambient pressure [5]. On the other hand, an artificial or ventilated supercavity is generated by blowing non-condensable gas into the low pressure region near the nose of the vehicle. The non-condensable gas increases the cavity pressure, allowing for low $\sigma$ to be attained at much lower speeds. Ventilated supercavitation has numerous advantages over natural supercavitation viz. greater adaptability for vehicle maneuvering and control. Also, some of the typical negative effects encountered in natural cavitation viz. surface damage, buffeting and vibrations, etc. are absent in ventilated supercavitation [6]. A vehicle can be optimally ventilated in case of maneuvering, etc. to circumvent the possibility of cavity collapse at different stages of vehicle operation.

A typical design strategy of a supercavitating vehicle entails accelerating the vehicle to a high speed at which a natural supercavity can be sustained. The drastic drag reduction required to attain high speeds at the initial launch of the vehicle is achieved by ventilated supercavitation. Further, the operation of a ventilated supercavitating vehicle depends on its ability to supply sufficient gas to fill the cavity at different flow conditions and at different stages of vehicle motion. The ventilation requirements for a ventilated supercavity is characterized by the gas entrainment coefficient at the standard conditions, $C_Q = \dot{Q}/Ud_c^2$, where $\dot{Q}$ denotes

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**Nomenclature**

| | | | |
|---|---|---|---|
| $P_\infty$ | test-section pressure | $C_{Qf}$ | formation coefficient |
| $P_C$ | internal cavity pressure | $C_{Qc}$ | collapse coefficient |
| $\rho$ | density of water | $f$ | gust frequency (Hz) |
| $U$ | incoming liquid velocity | $\alpha$ | gust amplitude (deg) |
| $d$ | cavitator diameter | $St$ | Strouhal number |
| $\dot{Q}$ | gas ventilation rate | $D_T$ | water tunnel diameter |
| $\sigma$ | cavitation number | | |
| $Fr$ | Froude number | | |
| $C_Q$ | gas-entrainment coefficient | | |

the gas ventilation rate at standard conditions (i.e. at a temperature of 273 K and a pressure of 1 bar. Experimentally, $\dot{Q}$ is a direct reading from the mass flow controller). The determination of the gas storage requirements for a ventilated supercavitating vehicle requires information on gas supply rate to form and sustain a steady supercavity at different flow conditions. Thus, it is important to understand the gas entrainment behaviors relating to supercavity formation and collapse.

A number of prior studies have investigated the gas entrainment behavior of ventilated supercavity under a wide range of conditions [5–12]. Ventilation hysteresis is intricately related to the formation and collapse gas entrainments and previous studies on ventilation hysteresis have been reported [12]. Ventilation hysteresis refers to a phenomenon whereby the supercavity can be sustained at much lower values of gas entrainment than required to form it, as shown in Fig. 1.

As the above figure shows, a foamy cavity shows a reduction in $\sigma$ (or an increase in length) when $C_Q$ is increased. This process continues until $C_Q$ equals $C_{Qf}$ (formation gas entrainment coefficient) and a supercavity is established, after which no further reduction in $\sigma$ is possible upon change in $C_Q$. Moreover, the supercavity is maintained even as $C_Q$ drops down to very low values. Eventually, when $C_Q$ drops below $C_{Qc}$ (collapse gas entrainment coefficient), the supercavity transitions back into a foamy cavity. Recently, Karn et al. [13] discussed the phenomenon of ventilation hysteresis, particularly focusing on the transition of closure modes of a supercavity and relating ventilation hysteresis to the internal flows of a supercavity. However, the gas entrainment rate at the formation and collapse of a supercavity has not yet been examined in detail.

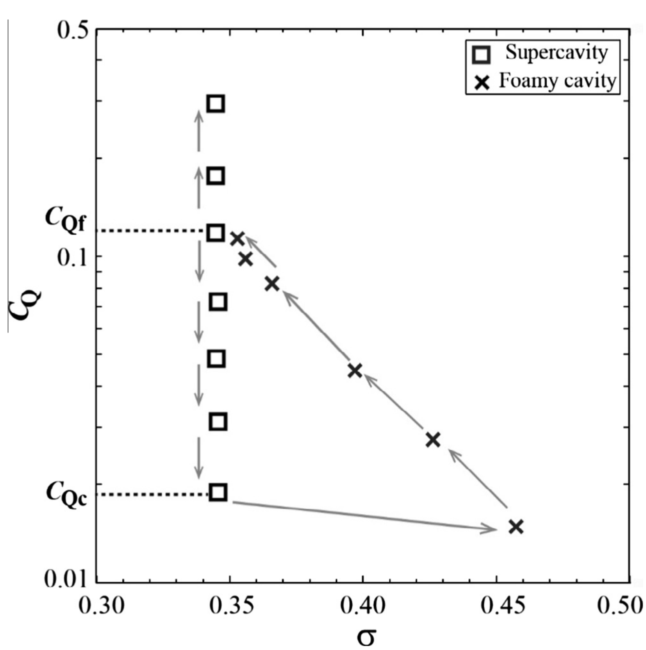


**Fig. 1.** A typical ventilation hysteresis curve observed in our experiments for a cavitator of 30 mm in diameter.

In this study, we focus our attention on gas entrainment during formation and collapse under steady and unsteady flow conditions, and study the effect of cavitator size on these behaviors. The current paper is structured as follows: Section 2 provides the details of experimental methods. In Section 3, experimental observations on formation and collapse gas entrainments are reported for steady states along with the effect of cavitator size on these behaviors. Subsequently, we present the behavior of gas entrainments for unsteady states which is followed by a summary and discussion in Section 4.

## 2. Experimental setup and procedures

Experiments are conducted to measure ventilation flow rates and formation and collapse processes of a ventilated supercavity under different flow conditions. The experiments are carried out in the high-speed water tunnel at the Saint Anthony Falls Laboratory. This water tunnel is a closed recirculating facility with a horizontal test-section of 1.20 m (Length) × 0.19 m (Width) × 0.19 m (Height). This tunnel is specifically designed for cavitation and gas ventilation studies and is capable of operating at a maximum velocity of 20 m/s. Flow unsteadiness can be introduced in the test-section by means of a gust generator as reported in previous studies [14–16]. Fig. 2a below shows a schematic of the experimental setup. The gust generator consists of two oscillating slender hydrofoils, which are placed 180 mm upstream of the cavitator. These hydrofoils oscillate in phase to generate uniform gusts. The motion is activated by a pivot arm that is linked to a flywheel through a connecting arm, which extracts the periodic motion from the motor. The eccentric flywheel allows the generation of gusts of varying amplitudes, represented by angle $\alpha$ as shown in the figure. Time-varying velocity amplitudes of the periodic gust flows are measured with Laser Doppler Velocimetry as described by Lee et al. [16] and it shows that the frequency of the periodic gust flow in the test-section is equal to the oscillation frequency of the gust generator at each flow condition.

A disk cavitator with its back surface facing the incoming flow and mounted downstream of a hydrofoil-shaped strut (referred to as 'backward facing model' in [5,13,14]), is employed in the current experiments. Fig. 2b illustrates the general placement of backward-facing model within the test section. As it shows, to avoid the interaction between the formed cavity and the strut body, a hydrofoil strut is placed upstream of the cavitator leading to a free closure as reported by Logvinovich [17]. The hydrofoil strut is just thick enough to envelope the ventilation pipe running to the cavitator. The maximum thickness of the hydrofoil, and the external diameter of the ventilation pipe equal 5 mm. High speed videos of the supercavity show that the slender streamlined hydro-