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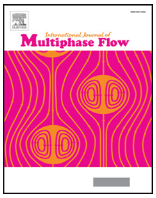

# An experimental study of cavity flow over a 2-D wall-mounted fence in a variable boundary layer

Luka Barbaca*, Bryce W. Pearce, Paul A. Brandner

*Australian Maritime College, University of Tasmania, Launceston, Tasmania, 7250, Australia*

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ABSTRACT

Ventilated and natural cavity flow over a 2-D wall-mounted fence immersed in a boundary layer is experimentally investigated in a cavitation tunnel. Cavity topology, upstream wall pressure distribution and the resulting hydrodynamic forces were determined as a function of ventilation rate, fence immersion in the oncoming boundary layer and free-stream conditions. Cavities exhibit a typical re-entrant jet behaviour, which is the primary mechanism of air/vapour entrainment into the main flow. Some entrainment is also observed via the turbulent break-up at the cavity surface, the intensity of which increases with deeper immersion of the fence within the wall boundary layer. A similar cavity topology, apart from some difference in the wake, is observed for ventilated and natural cavities at the same flow conditions. This similarity is also present in the relations between all other parameters investigated. It was found that with a decrease in cavitation number lift (i.e. force normal to the wall) increases and drag (i.e. force normal to the fence) decreases, resulting in an increased hydrodynamic efficiency of the wall/fence system. With an increase in fence immersion in the boundary layer, lift and drag both increase at the same rate, resulting in a constant lift-to-drag ratio.

## 1. Introduction

Efficient sea transport and drag reduction of marine vehicles are interrelated topics of interest to the maritime community. Various methods based on the use of gaseous layers/bubbles for reduction of the skin friction of the wetted part of a vessel have been extensively investigated since mid-last century. With reference to the extent of gaseous layer/bubble, these methods can be categorized into four groups: bubble drag reduction (BDR); gas layer/film drag reduction (GLDR); partial cavity drag reduction (PCDR) and supercavity drag reduction (SCDR) (Ceccio, 2010; Mäkiharju et al., 2013; Murai, 2014). Of particular interest for this study are the latter two, which involve creation and maintenance of large gaseous pockets covering a significant portion (i.e. partial cavity) or the whole body (i.e. supercavity). Additionally, partial cavity drag reduction techniques can be divided into those using the body designs with and without cavity lockers (also labelled as 'arrestors' or 'sloped beach') used to control the flow at the cavity closure (Kopriva et al., 2008; Mäkiharju et al., 2013).

The origin of the gaseous cavity can be twofold. A cavity can form naturally, i.e. due to the phase change of the water to vapour, or artificially by injecting an incondensable gas (typically air) into the wake of a cavitator. The latter process is commonly referred to as 'ventilation' and the resulting cavity termed a ventilated cavity. The main parameter used to characterize these cavitating flows, both natural and ventilated, is the cavitation number, $\sigma_c = (p_\infty - p_c)/0.5\rho U_\infty^2$, where $p_\infty$ is the reference free-stream pressure, $p_c$ is the pressure inside the cavity, $\rho$ is the liquid phase density and $U_\infty$ is the reference free-stream velocity. Past studies have shown that both natural and ventilated cavities present at the same flow conditions have a largely similar behaviour except for differences in the closure physics (May, 1975; Kunz et al., 1999). To form a cavity applicable for drag reduction in high-speed applications the $\sigma_c$ value usually has to be of the order of 0.1. For a naturally cavitating flow $p_c = p_v$ (where $p_v$ is vapour pressure) and achieving such a low $\sigma_c$ generally requires impractical operational speeds in excess of 90 knots (Kawakami and Arndt, 2011). In contrast, for the ventilated case $p_c$ is also controlled by the flux of injected air and sufficiently large cavities can be formed at lower, more practical, speeds making the technique applicable to a broad range of applications. Ventilation has also been investigated for drag reduction of low-speed ships (Butuzov et al., 1999) and lifting surfaces (Kopriva et al., 2008), where practicable cavities were achieved for somewhat different cavitation number values (i.e. negative $\sigma_c$ for slow ships and $\sigma_c \approx 1$ for lifting surfaces).

The use of ventilated supercavities (SCDR) has been extensively studied in the context of axisymmetric underwater projectiles con-

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* Corresponding author.
*E-mail address:* luka.barbaca@utas.edu.au (L. Barbaca).

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figured with a nose-mounted disk cavitator. A large catalogue of published literature exists with a comprehensive review of the principles governing this flow discussed by Semenenko (2001) and more recently by Karn et al. (2016). The main emphasis with the PCDR technique has been with the application of what has been termed 'air lubrication' to a substantial portion of the wetted surface of a ship's hull. Generally, air is injected through a backward-facing step spanning the width of the hull bottom, with a sloped beach placed in the cavity closure region to ensure a smooth cavity reattachment and minimal air loss (Arndt et al., 2009; Matveev et al., 2009; Lay et al., 2010; Elbing et al., 2013). A decrease in drag in the range of 10–30% has been reported in full-scale studies of planning and semi-displacement hulls (Latorre, 1997; Butuzov et al., 1999) and the concept has been also applied commercially on full displacement hull forms (Mizokami et al., 2010). Recently, a study of a partial cavity detaching from a wall-mounted fence (i.e. a forward facing step) of limited span has been reported by Barbaca et al. (2017a). There has also been some interest in creating partial cavities by using transverse jets of air injected into the liquid cross-flow through discrete holes. Reports on cavities formed by jet injection via a single hole have been authored by Insel et al. (2010) and Mäkiharju et al. (2017) and via an array of holes by Lee (2015). The use of ventilation on low-drag partially cavitating foils with a smooth reattachment has been proposed by Kopriva et al. (2008). Apart from their use in hydrodynamics, ventilated cavities have been also utilized to prevent surface erosion on dam spillways (Chanson, 1989) and to attenuate pressure fluctuations in hydro turbines (Papillon et al., 2002).

Alternatively, air injection can be used on lifting surfaces to reduce the form drag. On a device referred to as 'base-ventilated' hydrofoil, air is injected through a blunt trailing edge, forming a supercavity in the wake of the hydrofoil. The pressure in the wake increases proportionally to the amount of injected air, leading to a decrease in the streamwise differential pressure across the foil and a reduction in the form drag (Lang and Daybell, 1961; Verron and Michel, 1984; Franc and Michel, 2004; Pearce and Brandner, 2015). A recent comprehensive review on ventilation of lifting bodies, both natural and artificial, has been authored by Young et al. (2017). A similar flow, observed in the case of a ship's transom mounted fence (also termed an 'interceptor'), can be considered as an 'infinite' (i.e. nominally zero cavitation number) ventilated cavity flow with atmospheric pressure in the wake of the fence (Brizzolara, 2003).

An aspect of partial and supercavity flow that has not had any comprehensive focus in the published literature is the effect of variable immersion of a cavitator in the oncoming wall boundary layer. Vigneau et al. (2001) investigated the effects of upstream wall boundary layer thickness on the development of a cavity resulting from an axisymmetric gas jet injected into a confined vertical water flow. Some numerical results on the flow around a transom mounted interceptor of a variable height immersed in a constant thickness boundary layer were reported by Molini and Brizzolara (2005) and a recent study investigating ventilated cavities detaching from a backward-facing step for a range of upstream boundary layer thicknesses has been authored by Pearce et al. (2015). The relatively sparse knowledge gained thus far for cavitating flow configurations is in contrast to the now quite well understood flow over wall-mounted fences immersed in a boundary layer in single-phase flow (see for example Good and Joubert, 1968; Fang and Wang, 1997).

In this study both ventilated and naturally cavitating flow over a 2-D wall-mounted fence is experimentally investigated in a cavitation tunnel. The effect that variable immersion of the fence in the oncoming boundary layer has on the cavity topology, upstream wall pressure distribution and hydrodynamic forces are examined. Additionally, the flow parameters are investigated with respect to the flux of injected air and variable free-stream velocity and pressure.

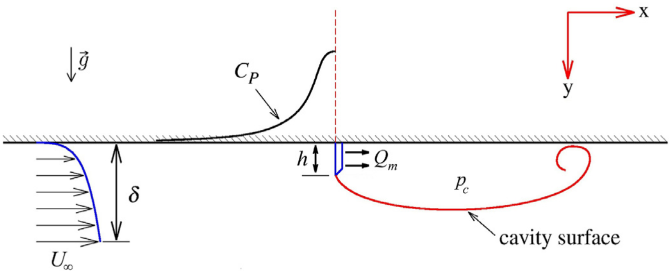

**Fig. 1.** Sketch of a wall mounted fence immersed in the oncoming wall boundary layer with a cavity detaching from the sharp fence tip. For a ventilated cavity, air is supplied from the downstream face of the fence with mass flow rate $Q_m$. The notional pressure distribution on the upstream wall is shown. The origin of the coordinate system is at the upstream fence face/wall junction.

This study represents a continuation of a research programme on the cavity flow over a wall-mounted fence at the Australian Maritime College (AMC) Cavitation Research Laboratory (CRL), which has up to date resulted in several publications reporting on both the numerical (Pearce and Brandner, 2014; Barbaca et al., 2017b) and experimental results (Barbaca et al., 2017a). This project is a part of a larger research program based on a novel concept, initially proposed by Elms (1999), utilizing a retractable fence attached to the trailing edge of a base-ventilated hydrofoil for generation of bi-directional lift with a rapid response. Some results on this wider topic are reported by Pearce and Brandner (2012) and Pearce and Brandner (2015).

The present results contribute to the basic understanding of this canonical cavitating flow, and also provide valuable data for the practical application of wall-mounted fences in a drag reduction context (i.e. PCDR or SCDR), or as an interceptor type device with a minimal drag penalty. The studied geometry is well suited for experiment and computation and a comparison of the experimental data with CFD (Computational Fluid Dynamics) results from Barbaca et al. (2017b) is provided. The experimental data for a 2-D wall-mounted fence is compared with the experimental results for a 3-D wall-mounted fence presented in Barbaca et al. (2017a) and some new results obtained with the 3-D setup.

## 2. Experimental setup and modelling

A schematic representation of cavity flow over a wall-mounted fence is shown in Fig. 1. A fence, of height $h$, is immersed in the upstream wall boundary layer of thickness $\delta$. The latter is defined as the distance from the wall where the local mean velocity, $U$, is 99% of the free-stream velocity $U_\infty$. In the case of a ventilated cavity, air is supplied to the wake region of the resulting bluff-body flow through a manifold on the downstream face of the fence with a mass flow rate $Q_m$ (Fig. 1). Alternatively, for $Q_m = 0$, a natural cavity may be formed due to phase change when the pressure in the wake of the fence, $p = p_c$, reduces to the vapour pressure, $p_v$ (Fig. 1). Irrespective of its origin, the cavity detaches from the sharp fence tip and exhibits a re-entrant jet closure. The resulting notional pressure signature on the wall upstream of the fence is indicated.

As already mentioned, the cavitation number, $\sigma_c$, is the fundamental dimensionless parameter characterizing cavitating flows. In the case of ventilated cavities, for constant free-stream conditions (i.e. free-stream pressure, $p_\infty$, and free-stream velocity, $U_\infty$), $p_c$ and hence $\sigma_c$ is determined by the air injection rate. This parameter is presented in non-dimensionalised form as a volumetric flow rate coefficient, $C_{Qv} = Q_m/\rho_{air}U_\infty S$, where $Q_m$ is the air

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