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Re-entrant jet mechanism for periodic cavitation shedding in a cylindrical orifice

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ABSTRACT

Periodic shedding of cloud cavitation is a common form of cavitation instability. The motion of a re-entrant liquid jet is central to this process but the mechanism which drives the phenomenon remains unclear, particularly for cavitation in cylindrical orifices. The current work describes an experimental investigation of the re-entrant jet mechanism for periodic cloud shedding in a large-scale (8.25 mm) cylindrical acrylic orifice. Refractive index matching and high-speed visualisation reveal in detail the motion of the re-entrant jet and indicate a complex mechanism causing the instability. Unabated optical access to the near-wall region of the orifice revealed a constant presence of liquid throughout the shedding cycle. The mechanism causing the periodic shedding was shown to be a combination of a traveling wave style deformation of the cavity interface and a translational pulse, each with distinctly different velocities.

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1. Introduction

Partial cavitation is inherently unsteady in nature and causes significant oscillations in cavity length (Callenaere et al., 2001). Cloud cavitation is one form of cavitation instability often observed for partial cavitation, in which large sections of the cavity are regularly shed from the main cavity and appear as cloud like structures in the cavity wake (Knapp, 1955). This periodic shedding of bubble clouds is common for cavitation on external bodies such as hydrofoils (Laberteaux and Ceccio, 2001, Ito et al., 2009), but also occurs for internal flows such as venturis and orifices (Stutz and Reboud, 1997, Stanley et al., 2011, De Giorgi et al., 2013). Central to the process is the motion of a liquid jet beneath the fixed cavity in the direction counter to the main flow, referred to as the “re-entrant” jet.

A number of studies have explored the influence of the re-entrant jet on the cloud cavitation instability, both numerically (Furness and Hutton, 1975, Barre et al., 2009) and experimentally (Lush and Skipp, 1986, Gopalan and Katz, 2000, Sato et al., 2013). Typically it is thought the re-entrant jet is created by the flow expanding in the closure region behind the cavity, impinging with the wall and establishing a local stagnation point (Callenaere et al., 2001). On the upstream side of the stagnation point conservation of momentum forces the fluid to flow beneath the fixed cavity. The jet progresses and when it reaches the vicinity of the leading edge it “pinches-off” the fixed cavity allowing it to be shed and form a vapour cloud (Wade and Acosta, 1966, Le et al., 1993). As the cloud is shed a new fixed cavity forms at the leading edge and begins to grow. As the separated cloud is convected downstream it coalesces and forms a rolling vortex due to the momentum of the free-stream. The velocity of the cloud was measured by Kubota et al. (1989) using LDA and a selective sampling method. Results showed the cloud consisted of a large number of small bubbles, and was convected with a lower velocity than the bulk flow with concentrated vorticity at its core. As the cloud is convected downstream it eventually collapses in the relatively high pressure behind the flow reattachment region.

A number of attempts have been made to measure the velocity of the re-entrant jet. Pham et al. (1999) used surface mounted electrical impedance probes to measure the velocity of the re-entrant jet beneath the cavity. The jet velocity was found to be of the same order of magnitude as the free-stream, however it decreased as it progressed beneath the cavity towards the leading edge. Despite these measurements, the authors visualised perturbations on the surface of the jet which they conjectured were the result of the impact of the re-entrant jet with the cavity interface. The shedding periodicity corresponded well to the propagation of these perturbations. Similarly, Sakoda et al. (2001) measured the jet velocity

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from visualisation and found it decayed as it progressed. Elucidating the motion of the liquid jet has proven difficult and often the re-entrant jet velocity has been inferred from the deformation of the cavity interface. In this way Le et al. (1993) found the velocity of perturbations travelling against the direction of flow were close to the magnitude of the free-stream, however the motion was difficult to interpret.

The injection of ink has been used to aid with visualising the re-entrant jet motion (Joussellin et al., 1991, Le et al., 1993, Kawanami et al., 1997). The cyclic nature of the jet became clear as coloured water could be seen near the leading edge at some instants of the period and only near the shed cloud in the wake at others.

Experimentally, gaining visual access to the flow beneath the cavity is difficult, particularly for cavitating orifice flow. This has contributed to the insufficient clarification of the re-entrant jet mechanism. Visualisation of periodic cloud shedding in large scale cylindrical orifices (Sato and Saito, 2002, Sugimoto and Sato, 2009) indicated the shedding cycle was similar to that described above. The velocity of the re-entrant jet, interpreted from the motion of the cavity "marching" towards the nozzle entrance, was found to be approximately equal in magnitude to the free-stream flow. However, the images used for this interpretation were likely to have been affected by the refraction of the light passing through the cylindrical nozzle, obscuring access to the liquid motion adjacent to the wall. Lack of spatial resolution near the wall region may also have influenced the conclusions of Gopalan and Katz, 2000, who observed there to be no flow beneath the cavity for certain conditions.

Despite this knowledge the exact motion of the liquid which constitutes the re-entrant jet and indeed the driving force behind the establishment of the jet has been a point of some conjecture. The collapse of a shed bubble cloud is known to create pressure pulses in the vicinity of the guiding body, often orders of magnitude greater than the pressure in the mean flow (Reisman and Brennen, 1996, Reisman et al., 1998). Aside from being the cause of noise (McKenney and Brennen, 1994) it has been suggested that these pressure pulses may contribute to the motion of the re-entrant jet and the cloud cavitation instability (Leroux, 2004, Leroux et al., 2005). Instantaneous pressure measurements across the span of a hydrofoil suggested that shock wave phenomena could also be responsible for the cavity destabilization. However experiments suggest the correlation between pressure pulses generated by the cloud collapse and the re-entrant jet motion was not systematic, but rather dependent on flow conditions (Coutier-Delgosha et al., 2007).

Other studies (Callenaere et al., 2001, Laberteaux and Ceccio, 2001) have suggested the adverse pressure gradient in the cavity wake has a strong influence on the development of the re-entrant jet. Two parameters were identified as important for the re-entrant jet instability: (1) the strength of the adverse pressure gradient in the region of closure and (2) the cavity thickness compared to the re-entrant jet thickness. Extended cavities collapse in regions of relatively flat pressure gradient which reduces the thickness and strength of the re-entrant jet pulse. Thin cavities for which the thickness of the jet was comparable to the cavity thickness produced strong interactions between the liquid jet and the interface, which lead to regular shedding of smaller clouds.

Phenomenological models of the re-entrant jet mechanism presented in the literature generally represent the liquid jet as a coherent jet progressing from the closure region and "filling" the cavity void (Le et al., 1993, Callenaere et al., 2001, Franc, 2006) as indicated in Fig. 1. Following the shedding process, the growing cavity is described as remaining attached to the wall, i.e. there is no liquid layer separating the cavity from the body to which it is attached.

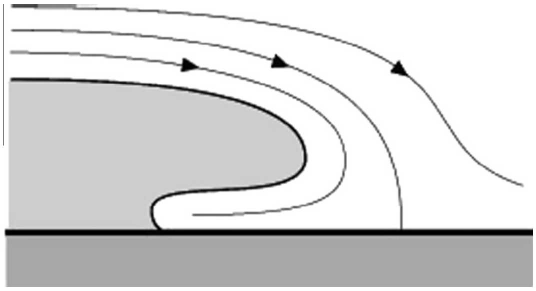

Fig. 1. Classical model of the re-entrant jet mechanism, as presented by Callenaere et al. (2001).

In this paper we challenge the current phenomenological models by investigating the mechanism of the re-entrant jet motion and its role in the periodic cloud shedding within a large scale cylindrical orifice. High speed visualisation has been used to investigate the behaviour of the cavity and the re-entrant jet at high temporal and spatial resolution. Results indicate the continued presence of a liquid sublayer separating the cavity from the nozzle wall. Observations of the surface of the cavity and bubbles within the liquid sublayer have been used to demonstrate a complex motion of the re-entrant jet and the mechanism by which it results in the periodic shedding of cloud cavitation within orifices.

2. Experimental setup

2.1. General description

A comprehensive description of the experimental facility used for the current work can be found in Stanley et al. (2011). Fig. 2 shows a schematic of the experimental rig. Flow through an 8.25 mm diameter cylindrical orifice is generated by a double acting hydraulic cylinder. Refractive index matching between the acrylic (PMMA) nozzle and the liquid was achieved using a 63% w/w aqueous solution of sodium iodide as the test fluid, providing unrestricted optical access to the wall region of the nozzle. The nozzle had an L/D ratio of 4.85 and a nominally sharp entrance (Fig. 3(a)). To avoid the introduction of disturbances to the flow from control valves, the nozzle injected vertically into a 120 L optical access pressure vessel. A 1 m length of supply pipe before the entrance to the nozzle was used to ensure the secondary flow introduced by the pipe-bend had no influence on the symmetry of the flow through the nozzle. This was further aided by a supply pipe to nozzle contraction ration of 6.25. Piston velocity, and hence Reynolds number, defined here as $Re = V_n D_n / \nu$, where the subscript n denotes parameters of the nozzle, was controlled by an analogue voltage signal sent to a proportional control valve on the hydraulic cylinder manifold. For a set piston velocity (Re) the cavitation number, defined here as $K = (P_1 - P_v)/(P_1 - P_2)$, could be independently controlled by adjusting the gas pressure within the pressure vessel. Experimental uncertainties in the measurement of Re and K were determined to be 3.9% and 4.3% respectively. Here P_1 is the injection pressure, P_2 the ambient gas pressure and P_v is the vapour pressure (typical value 1.048 kPa, uncertainty 1.2%). P_1 was measured using a static pressure tapping in the supply pipe 162 mm upstream from the nozzle contraction. P_2 was measured using a pressure sensor mounting in the top of the pressure vessel. Both sensors (Honeywell 24PCGFM6G) had estimated uncertainties of less than 2.2%.

High-speed visualisation was used to capture the temporal behaviour of the cavity within the nozzle and investigate the re-entrant jet motion and its role in the periodic cloud shedding. Acquisition of high-speed images using a Phantom V7.3 camera

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