International Journal of Multiphase Flow 61 (2014) 48–61

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Experimental and numerical investigations of mechanisms in fluidic spray control

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ARTICLE INFO

Article history:
Received 21 September 2013
Received in revised form 8 January 2014
Accepted 10 January 2014
Available online 30 January 2014

Keywords:
Spray control
Cavitation
Droplet measurement
Flow structure
Two-phase flow

ABSTRACT

A fluidic control method in an axisymmetric spray orifice is investigated experimentally and numerically. In this method, a nominally steady secondary flow is introduced through an annular slot placed near the vena contracta along the orifice wall to control the cavitation, and thus the spray, at pressures up to 550 kPa driving pressure difference. Images of cavitation, measurements of droplet sizes and discharge coefficients, and CFD modeling are combined to explore the flow physics leading to the production of small droplets. Experimental results suggest that the secondary flow is incapable of confining cavitation to the region upstream of the slot, and generally a larger secondary flow rate results in a lower discharge coefficient, and a larger fraction of small droplets. The homogeneous model-based CFD code of Chen and Heister was employed to model the internal flows, which indicated that a high pressure region upstream of the slot, large pressure fluctuations in the orifice, and long cavitation lengths are the favorable conditions for atomization. The CFD simulations, together with experimental measurements, correlate the orifice geometry and flow structures to droplet sizes. Understanding the relationship between flow structures and droplet sizes helps to design orifices in favor of production of small droplets.

1. Introduction

Spray control is important. For example, fuel sprays might be optimized for engine load or bio-fuel blends on a daily basis. Spray coating of contoured surfaces may have a spray that adapts to changes in contour, and hydro-entanglement of unwoven textiles may benefit from maximizing momentum flux with minimal droplet production. Recent research on the connection between small-scale internal flow cavitation and droplet sizes has demonstrated a promising approach for a new spray control method.

Compared to a plain orifice (Fig. 1(a)), an orifice with a small step placed at a strategic location (Fig. 1(b)) (where the flow reattaches to the orifice wall for a plain orifice at a pressure below that for hydraulic flip) can substantially increase the pressure for hydraulic flip, and produce a large fraction of tiny droplets (Ong, 2000; Ong et al., 2003).

The success of the small step motivated us to devise a circular orifice with an annular slot (through which a secondary flow is introduced to the orifice) placed at the strategic location (Figs. 1(c) and 2(a)), namely orifice 1, which is not the target in this paper.

Orific 1 is found to work exactly like a step orifice does (Tseng and Collicott, 2011) at certain secondary flow rate, wherein the advantages of a fluidic spray control orifice are demonstrated—the secondary flow is proved to be able to influence the cavitation distribution, spray and droplet size, and the strength of this control effect can be modulated. Since the location of the slot is merely based on the successful small steps (Ong, 2000; Ong et al., 2003) which were guesses at what would work well, the question—how the slot location will influence the cavitation distribution—has inspired us to devise another orifice, namely orifice 2, as shown in Fig. 2(b), where an annular slot is placed near the vena contracta. Unless specified, the results in this paper are all from orifice 2.

Historical research has demonstrated that orifice geometry may greatly affect droplet distribution in several ways. Hiroyasu et al. (1991) and Hiroyasu (2000) showed that cavitation and turbulence significantly influence atomization, which can be manipulated by installing a wire mesh over the inlet of the orifice and a gap at the middle of the orifice hole (Hiroyasu, 2000). The wire mesh transforms the jet from non-cavitating hydraulic-flipped flow to cavitating flow; a larger ratio of gap length to orifice length is capable of atomizing the jet more rapidly, and enabling a larger spray angle, where a higher degree of atomization has proven to be ascribed to a strong disturbance arising from cavitation in the nozzle (Tamaki et al., 1998, 2001; Hiroyasu, 2000). In Hiroyasu's

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.01.003
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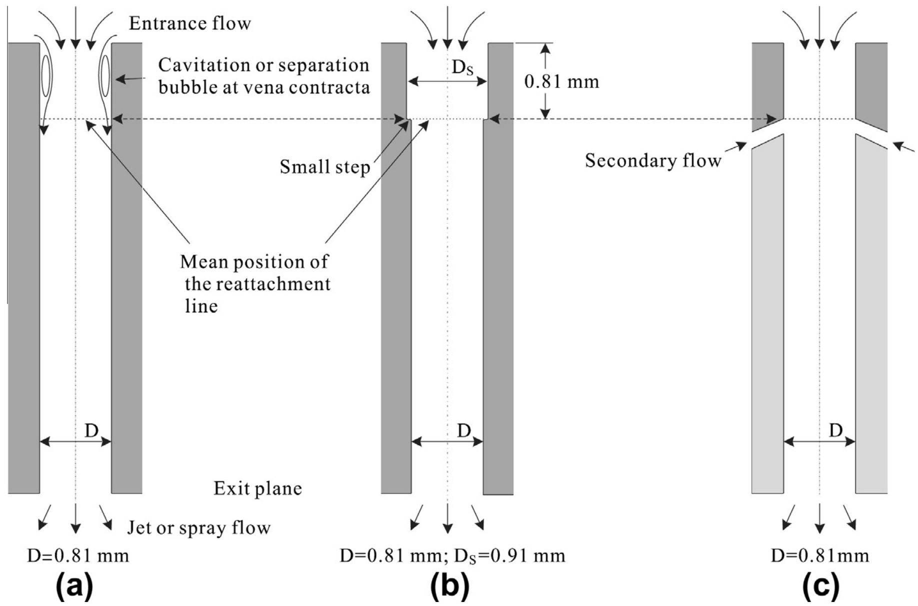

Fig. 1. Diagram of the (a) plain orifice, (b) step orifice, and (c) orifice 1.

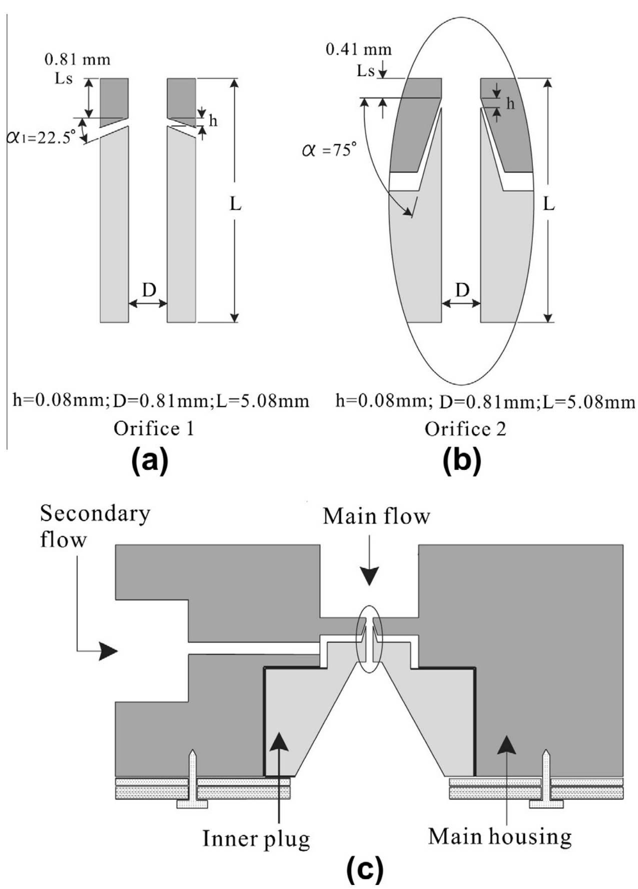

Fig. 2. Plane section views of the main housings and the inner plugs of orifice 1 and orifice 2, which form the annular plenum and the conical void terminating in the annular slot. The region circled in (c) corresponds to (b).

experiment, the orifice diameter is 0.3 mm, the gap length is 0.3 mm, and the ratios of gap to orifice length are between 5 and 41.

The spray has also been observed to be affected by different inlet geometries (Laoonual et al., 2001). Plain, counterbore, rounded, and beveled inlets of different angles result in different spray distributions, among which the beveled nozzle with a bevel angle of 60°, and the rounded nozzle having an inlet radius of curvature approximately the same as the orifice radius are shown to be capable of greatly increasing the pressure for hydraulic flip. This effect is an analogy to that of a small step placed at a strategic axial location (Ong, 2000). In their study, the nozzle diameter is 6 mm, the length-to-diameter ratio is either 5 or 10, and the pressures are up to 2 MPa.

In addition to straight orifices, orifices inclined at different angles (including 0°, 14°, 80°, 85°, and 90°) to the axis of the injector have also been investigated by some researchers (Ganippa et al., 2001; Li, 1999), wherein an asymmetric nozzle is found to be responsible for asymmetric cavitation distributions, and thus different degrees of atomization. The side with a higher degree of atomization has thicker cavitation on the same side upstream.

To simulate the actual geometry of a diesel engine injector, Li et al. (1998) and Li (1999) employ orifices angled at 14° with respect to the surface normal, and having diameters in the range of 0.206–0.397 mm. In their experiment, UCF-1 calibrating fluid was used as the working liquid, and the pressure was as high as 200 MPa. Some features of the asymmetric unsteady cavitation extending downstream from the inlet are also observed later by Ganippa et al. (2001).

Recent work at Purdue further demonstrated that either a small step (Ong, 2000; Ong et al., 2003) or a slot placed at a strategic axial location (Tseng and Collicott, 2011) changes the inlet cavitation, discharge coefficient, and droplet size distribution, and substantially increases the pressure for hydraulic flip. That one small change in the orifice can create such a wealth of changes in the flow indicates that a control mechanism likely exists to exploit further. Extending the investigation to explore the influence of the orifice geometry for a fluidic spray control orifice as well as the flow physics will assist in affording us in-depth knowledge of how cavitation may be more effectively manipulated.

2. Purpose

Although cavitation has long been known to affect fluid spray, the links between droplets and flow structures are poorly