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Technical Notes

Demonstration of a Fluidic Spray Control Orifice

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I. Introduction

FUEL sprays are vital components of many propulsion systems. Papers scattered sparsely through recent decades highlight how internal-flow structures, including cavitation, affect sprays. Recent research observing and predicting small-scale internal-flow cavitation has produced promising initial demonstrations of a new spray control method. Experiments have shown the following:

1) Unsteady cavitation is almost always present at, and downstream of, the inlet of the spray hole from 30 kPa [1] to 210 MPa [2].

2) Changes in the internal flow either perturb the spray [3] or cause substantial changes in the droplet size distribution in the spray [4–6].

3) A simple modification to the hole [7–10] changes the discharge coefficient [7–9], the cavitation [7,8], the spray patterns [10], and the distribution of drop sizes [7,8].

This Note reports on the demonstration of a miniature fluidic device designed to manipulate the internal cavitating flow, and therefore, droplet sizes. Unlike the step in the orifice wall [7,8], the fluidic device can be turned on and off and the magnitude can be modulated.

There are likely a variety of needs for spray control in propulsion. For example, production methods using sprays may benefit from increased tolerance to daily variations in material properties of a biofuel or temperature and humidity of the ambient air. Or, fuel injectors might be made to adapt to changes in engine load, altitude, or other operating conditions.

Reported here are the first internal-flow fluidic spray control results known to the authors. The geometry is based on knowledge gained from the initial operation of the unique step-orifice flow and should not be considered optimally designed. Similarities and discrepancies between the fluidic-control and the step-orifice results indicate that the intrinsically unsteady cavitating flow can be manipulated to the advantage of the spray user and that there likely remains room for substantial improvement in performance.

II Purpose

It has long been recognized that an orifice that is a straight circular hole with a nominally sharp inlet and a uniform diameter throughout the length (herein labeled a *plain orifice* and sketched in Fig. 1a) will produce a liquid jet that breaks into droplets. Recent work [8] demonstrated that a small upstream-facing step placed (Fig. 1b) at a location where the liquid flow reattaches to the wall downstream of a vena contracta can result in production of small droplets and substantially increase the pressure for hydraulic flip. To further probe the impact that the small step has on the spray, Collicott et al. [11] experimented with orifices of varying step sizes and concluded that controlling the spray by altering the step size is feasible in that droplet sizes change with different steps. Thus, the prior work shows that small changes in the geometry of the hole can create substantial changes in a spray. It is the ability to turn this control authority on and off that is sought in the present research.

III. Experiment

The flow rig for this experiment delivers pressurized water flow to the spray orifice. It consists of a compressed air supply of up to 1 MPa, optically accessible orifice, flash lamp, camera, pressure transducer, in-line flow meter for the secondary flow, and a Sympatec laser diffraction particle-sizer. This system is used to image cavitation and to measure pressure, flow rate, and droplet sizes. The water in the reservoir is split into the main and secondary flows, which are controlled by needle valves and then delivered to the orifice. A pressure transducer, sampled at 300 Hz and accurate to 0.03% measures the plenum pressure. The cavitation images are 2 μs backlit images recorded on a 1024×1024 square-pixel charge-coupled device.

Performance of one type of fluidic-control orifice, shown in Fig. 1c, is reported here. The orifice has an annular plenum and annular injection slot for the flow that controls the droplet production. These volumes are formed between the surfaces of the main housing and the inner plug, as shown in Fig. 2. The orifices in this work were machined from transparent acrylic and appear to have inlet bluntness approximately 5% of the orifice radius. The dimensions of the orifice are based on the successful step orifices [8], which were themselves simply guesses at what would work well.

Droplet size distributions are measured with a Sympatec Helos laser diffraction particle-sizer. The graphical presentations include a volume cumulative distribution curve (left scale and the curve that rises to the upper right) as well as volume density distributions (right scale, the curve that is zero at the right side) defined as the ratio of a class, that is, the mass fraction for a range particle sizes, to the width of that range.

Measurements of the total flow rate, which is the sum of the main flow and the secondary flow, are made by timed collection of the efflux. Such measurements were repeated thrice. Discharge coefficient C_d is calculated from measured quantities: driving pressure difference ΔP, velocity scale in the orifice $V = \sqrt{2\Delta P/\rho}$, orifice exit area A, water density ρ, and measured total mass flow rate $\dot{m}$:

$$C_d = \dot{m}/(\rho A V) \tag{1}$$

The percentage of secondary flow is the ratio of secondary to total mass flow rate. Primary and secondary flows are controlled by needle valves and measured by rotameters. Timed collection of the efflux also measures total flow. Backpressure in all cases is atmospheric pressure.

IV. Experimental Results

The droplet distributions are the results of both primary and secondary atomization. Primary atomization is where cavitation plays an important role in that the cavitation collapse appears to shed subdiameter-length-scale unsteadiness that elevates the subdiameter-length-scale unsteadiness [12] and modifies velocity profiles at the

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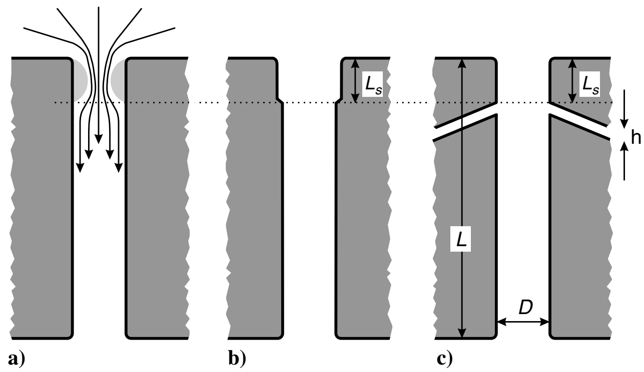

Fig. 1 Geometry of the plain, step [7], and fluidic-control orifices; $D = 0.81$ mm, $L = 5.08$ mm, $L_s = 0.81$ mm, $h = 0.08$ mm, and the injection slot is tilted up 22.5° for the fluidic orifice.

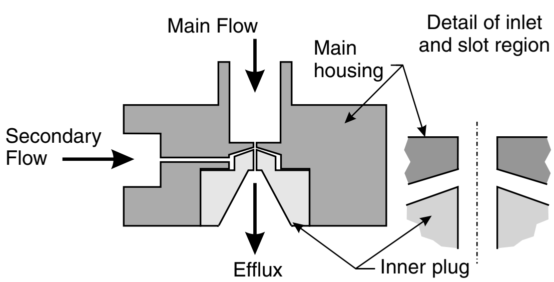

Fig. 2 Plane section view of the main housing and the inner plug forming the annular plenum and the conical void that terminates in the annular injection slot.

orifice exit [13], thus enhancing atomization [5]. Secondary atomization ensues shortly after the completion of the primary atomization, as the Weber numbers are much greater than 100, so the droplets can experience both shear [14,15] and catastrophic breakup [14].

Figure 3 shows a no-flow image and an image and droplet production for the orifice with zero secondary flow, $\Delta P = 550$ kPa, and atmospheric backpressure. The left-hand image shows the orifice with no flow, and thus the additional dark regions in the right-hand image are where two-phase boundaries in the internal flow refract light out of the imaging system aperture. The flow appears to be in the hydraulic flip state with some 3-D structure. The plot on the right side of Fig. 3 presents the corresponding droplet size distributions. Two measurement results (labeled curves no. 1 and no. 2) are plotted to provide an indication of the repeatability.

Numerous secondary flows have been explored and their effects have been quantified [16], but in this Note only 4% secondary flow is presented. At 4% secondary flow, Fig. 4 shows that partially cavitated flow exists at $\Delta P = 550$ kPa. The mechanism causing this change in structure is thought to be that proposed for operation of the small step in an orifice [8]; i.e., a region of increased static pressure upstream of the slot is formed to turn the secondary flow downstream. This elevated pressure need not be much greater than vapor pressure to cause significant collapse of the cavitation from the inlet. As expected, disappearance of the hydraulic flip leads to production of more numerous small droplets (Fig. 4), which conforms to Ong et al.'s [7,8] step-flow results. Higher secondary-flow rates of 15 and 20% are found to be capable of confining the cavitation to the vicinity of the orifice inlet, and the production of small droplets is still strong [16].

Discharge coefficient measurements are presented in Fig. 5. The minimum ΔP for hydraulic flip to occur at 0% secondary flow is 380 kPa. For the 1 and 2% cases, a bistable state changing between hydraulic flip and partially cavitating flow appears to exist and C_d lies between 0.72 and 0.82. The exact value presumably depends on the

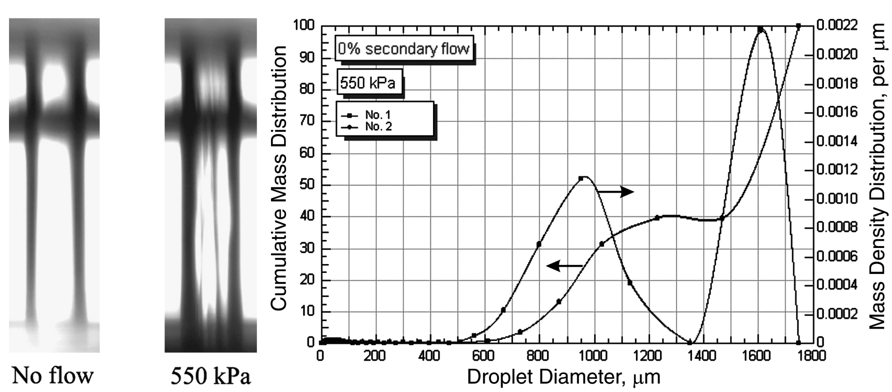

Fig. 3 Flow visualization and droplet size distributions for no secondary flow and $\Delta P = 550$ kPa; 35 cm downstream.

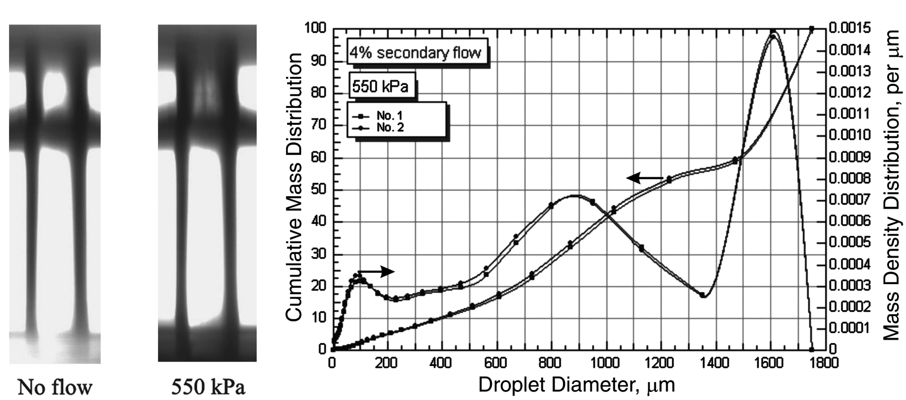

Fig. 4 Flow visualization and droplet size distributions for 4% secondary flow and $\Delta P = 550$ kPa; 35 cm downstream.

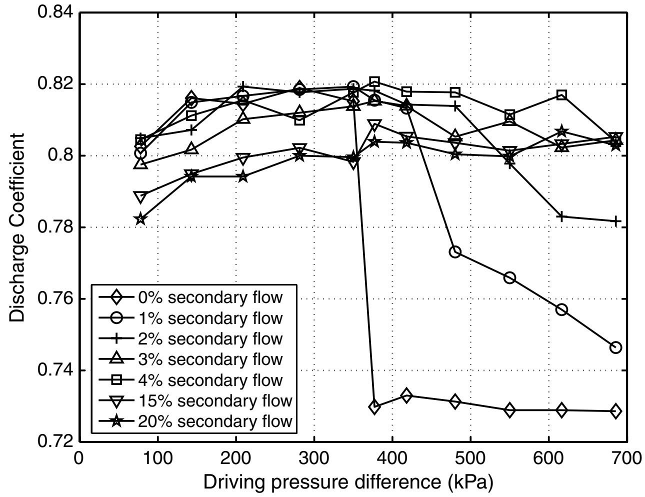

Fig. 5 Measured discharge coefficient versus driving pressure difference for seven secondary-flow rates.

relative durations that the flow exists in the two states. For secondary flows of 3% and above, it is remarkable that C_d is approximately 0.8, even for ΔP values that cause hydraulic flip for the plain hole. The right-hand image in Fig. 4 confirms that even a 4% secondary flow can prevent the onset of hydraulic flip.

V. Discussion

Small droplet production is seen to be affected by at least ΔP, cavitation length, and the unsteadiness of the cavitating flow. Of course, changing the backpressure should have a strong effect too. Hydraulic flip being excluded, a larger ΔP is observed to produce more smaller droplets as the jet interacts more violently with the ambient air.

For the orifice discussed in this Note, the presumed creation of elevated pressure upstream of the slot confines the downstream extent of the cavitation created at the orifice inlet and, at the same time, increases the unsteadiness of cavitating flow caused by a higher characteristic frequency in the periodic growth–collapse of cavitation regions. This then enhances production of small droplets, as in Hiroyasu [5].

At $\Delta P = 550$ kPa the small droplet production by this orifice design increases as the secondary-flow rate increases from 0 to 2%. This is accounted for by the flow regime alternating between hydraulic flip and partially cavitated states. The greatest impact of cavitation in this orifice is found at 4% secondary flow. Although the effect of cavitation weakens substantially at 15% secondary flow, a stronger effect of cavitation is enabled in the 20% case [16]. This suggests that multiple flow processes are important in the control method.

VI. Conclusions

Fluidic control is shown to be capable of the same type of spray control as the step; it can create substantially smaller droplets and increase the ΔP that causes hydraulic flip. Understanding how the secondary flow creates these flow features will be important to creating functional designs. Cavitation is the sole visible internal-flow process and thus the target of flow visualization. The internal flow is a highly unsteady, nonequilibrium two-phase flow with separation and reattachment features. Although the results available do not provide knowledge of how small droplets are affected by secondary atomization, a number of researchers provide evidence of the link between internal-flow structures and droplet sizes.

A fluidic-control orifice is found to work like the step orifice at some secondary-flow rates. Flow visualization shows that the secondary flow restricts cavitation to the regions upstream of the slot. This creates shorter cavitation lengths that lead to higher-frequency fluctuations of the internal flow and then small droplets. Production of small droplets in this orifice is found to be a maximum near 4% secondary flow.

Manipulating the production of subdiameter-length-scale unsteadiness within the orifice appears to be important in controlling a spray. That is, studying liquid jet or spray instabilities is only part of the task of developing spray innovations because such instabilities process the disturbances from upstream.

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