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Visualization studies of the spray from swirl injectors under elevated ambient pressure

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the results of a visualization study on spray formed by swirl injectors with different geometries under elevated ambient pressure. A spray test facility with an ambient pressure chamber was constructed, and sprays were recorded using a high-speed camera. The parameters of the spray characteristics, e.g. the spray cone angle and breakup length of liquid sheet, were measured, and the effects of the ambient pressure and injector geometrical parameters on the spray were obtained. Experimental results indicated that when other parameters in the swirl injector remained constant, the increase of ambient pressure caused a decrease in the spray cone angle and the breakup length of liquid sheets. However, the mass flow rates remained nearly constant. An increase in nozzle diameter increased the spray cone angle, and the variation of breakup length according to nozzle diameter was somewhat irregular. The increase in the diameter of the tangential inlet reduced the spray cone angle; the breakup length scarcely varied.

1. Introduction

The liquid swirl injector is a key component in the thrust chamber of a liquid rocket engine. Numerous studies have been conducted on swirl injectors to reveal the relationship between injector geometry and various flow parameters, such as discharge coefficient, spray cone angle, and liquid film thickness within the injector [1–7]. The breakup characteristics of swirl injectors were also studied extensively [8–12]. Recently, Vijay et al. [13] reviewed studies about swirl spray development in connection with the effect of nozzle geometry and injector operating conditions.

Most of the previous studies were limited to atmosphere pressure conditions. For liquid propellant rocket engines, atomization takes place in the combustion chamber, where pressure is very high. To investigate the spray characteristics of the injector in conditions closest to actual application, it is necessary to perform spray experiments in a high pressure environment.

The influence of ambient pressure on swirl injector fluid dynamics is reported less often than the effects of ambient pressure on spray from other types of injectors [14–16]. The influence of chamber ambient pressure on downstream spray angles and sheet distributions was examined by DeCorso and Kemeny [17] and Ortman and Lefebvre [18]. These studies measured spray features where the axial distances were greater than ten nozzle diameters from the nozzle tip. At such axial locations, spray was assumed to be affected by aerodynamic forces. Their results both showed a general reduction of spray angle with increasing chamber backpressure up to 0.80 MPa. However, it is more likely that the spray regime near the nozzle tip is linked to swirl injector hydraulics.

Sovani et al. [19] studied spray cone angles in high ambient density environments that simulate conditions inside the combustion chamber of a diesel engine. One interesting result of their experiment was that the cone angle first decreased when ambient pressure increased from 0.27 to 1.5 MPa; however it then increased as the ambient pressure rose from 1.5 to 5.5 MPa. They concluded that this occurred because the two-phase flow leaving the injector was under-expanded at low ambient pressures.

Kim et al. [20] measured spray angles and sheet breakup lengths near the nozzle tip under different Weber number and chamber-gas-to-liquid density ratios, at ambient pressures up to 4.0 MPa. They found that the spray angle was relatively insensitive to density ratio changes until the intact sheet began to disintegrate. Wang and Lefebvre [21] studied the effect of ambient pressure on mean diameter and diameter distribution of liquid droplets. Shim et al. [22] carried out both calculations and experiments on the spray characteristics of a hollow-cone spray from a high-pressure swirl injector at ambient pressures of 0.1 MPa, 0.5 MPa and 1.0 MPa. They used a hybrid breakup model to calculate the spray structure and compared it with experimental results.

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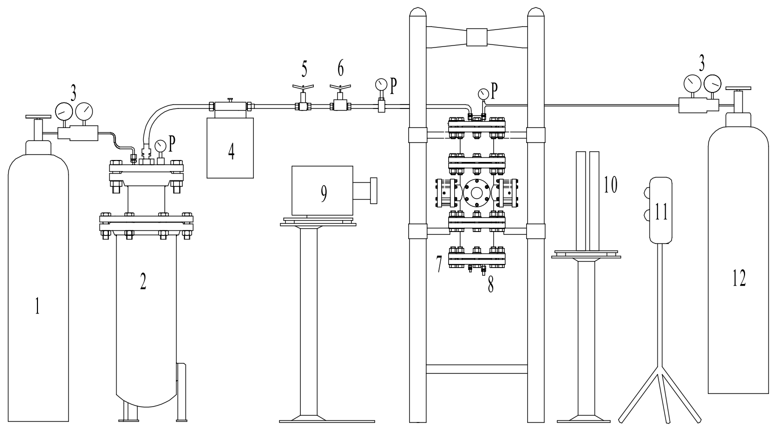

Fig. 1. Schematic of the experimental system: 1 – high pressure gas tank; 2 – high pressure water tank; 3 – pressure reducing valve; 4 – Coriolis mass flowmeter; 5 – cut-off valve; 6 – pressure regulator valve; 7 – ambient pressure chamber; 8 – vent valve; 9 – high speed camera; 10 – matte glass screen; 11 – light source; 12 – gas tank to pressurize the ambient pressure chamber.

Table 1
Geometry parameters of the model injector.

D_s/mm	18												
D_n/mm	0.6			1.0			1.5			2.0			1.0
Number of tangential inlets n	2			2			2			2			3
D_t/mm	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.5
$A = (D_s - D_t)D_n/nD_t^2$	5.1	2.2	1.2	8.5	3.7	2	12.8	5.5	3	17	7.3	4	2.4
Injector No.	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13

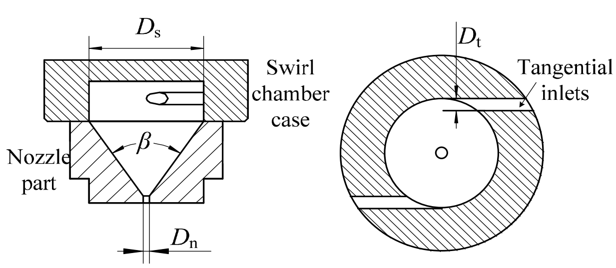

Fig. 2. Schematic of the swirl injector.

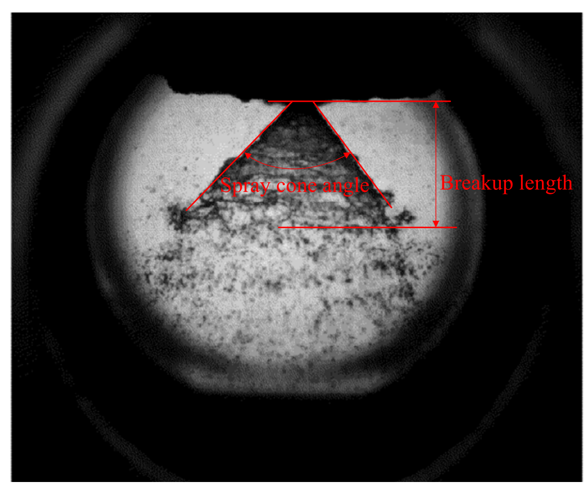

Fig. 3. Definitions of spray cone angle and breakup length.

Kenny et al. [23] measured the film thickness and spray angle near the injector nozzle using shadowgraphs. Recently, Fu [24] numerically investigated the internal flow of open-end swirl injectors under ambient pressures. The results showed that the variation of ambient pressure affects the liquid phase volumetric fraction within the gas–liquid shear layer. The spray angle near the wall remained constant, independent of the ambient pressure. Because the injector geometry used in the studies above was not the same, the conclusion is not universal. Moreover, none of these cited works focused on the effects of injector geometry on spray characteristics of swirl injectors under high ambient pressure.

For the design of swirl injectors used in liquid rocket engines, it is important to determine the appropriate flow characteristics, spray angle, and liquid sheet breakup length. However, although many experimental diagnostics have been performed on the spray features of swirl injectors, the effects of geometry parameters on swirl injector flow characteristics requires further study, especially for conditions of high ambient pressures. This paper reports experimental observations of the spray features for a series of pressure swirl injectors with different geometries under high ambient pressure. Flow structure and breakup characteristics of thin liquid sheets have been studied. The effect of injector geometry on the breakup and spray characteristics of the liquid sheet is predominantly discussed.

2. Experimental methods

For safety reasons, tap water was used to simulate actual propellants used in liquid rocket engines. The schematic of the experimental system is shown in Fig. 1; it consists of a water tank, pressure chamber, injector unit, pressure and flow measurement system and a high-speed camera. The pressure chamber is equipped with circular quartz windows, allowing a view of nearly 90 mm. The pressure chamber was filled with N_2, making it possible to vary the ambient gas pressure by adjusting the pressure reducing valve of the high gas tank 12 in Fig. 1. A pressurized supply system was adopted. High pressure gas forced the water flowing through the regulator valve to the injector, which was mounted in the pressure chamber. The pressure inside the water tank, the pressure chamber and the injector unit were monitored by pressure sensors. Mass flow rate was measured by a Coriolis mass flowmeter, whose measuring range is 0–5000 g/min and the precision is ±0.2%. The