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The spray characteristics of an open-end swirl injector at ambient pressure

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ABSTRACT

To study the spray characteristics of an open-end swirl injector under ambient pressure, cold flow tests were conducted using a high-speed shadowgraph system. The effects of geometrical parameters (including tangential inlet diameter and injector length) and operating parameters (including injection pressure drop) under high ambient pressure were systematically investigated. The experimental results indicate that spray is suppressed by ambient pressure. With increased ambient pressure, the discharge coefficient increased while the spray cone angle, spray width and breakup length decreased. Under a low injection pressure drop of 0.1 MPa, the maximum deviations of the discharge coefficient and spray cone angle under 5 ambient pressure conditions were 22.6% and 31.2%, respectively. Under a high injection pressure drop of 0.7 MPa, the maximum deviations under 5 ambient pressure conditions were 1% and 18.1%, respectively. A critical pressure value was found at which the spray structure converts from a wide hollow cone to a narrow contracting bell. Increasing the tangential inlet diameter (D_p) or the ratio of the injector length to the injector orifice diameter (L/D) would eventually decrease the swirling intensity. Therefore, the discharge coefficient increases while the spray cone angle decreases. Comprehensively considering the effects of geometrical and operating parameters, empirical formulas for the discharge coefficient and spray cone angle are proposed for engineering applications.

1. Introduction

The distribution of swirl injector after primary breakup is uniformed, which contributes to improve the combustion efficiency. Therefore, swirl injectors are widely used in liquid rocket engines, internal combustion engines and aircraft engines [1]. In the past few decades, the effects of geometrical parameters and operating parameters on the atomization quality of swirl injectors have been widely investigated [2–9]. A large number of works have also been conducted on the breakup mechanism of swirl injectors [10–14]. However, most of these studies were conducted in atmospheric environment, whereas an engine combustion chamber is under ambient pressure in practical use, and the effects caused by the density difference between atmospheric pressure and ambient pressure are significant. Therefore, the results and empirical equations of atmospheric pressure are difficult to apply to practical conditions.

De Corso and Kemeny [15] were the first to study the effect of ambient pressure on the spray angle of a swirl injector. At a given injection pressure drop, the spray angle decreased significantly with increased ambient pressure, and the spray structure converted from a hollow cone to a bell. Kim et al. [16] conducted a series of experiments to study the effects of the recess ratio, the momentum flux ratio and gas injection on the spray patterns of gas-centered swirl injectors. Shim et al. [17] conducted numerical and experimental study of the spray characteristics of a high-pressure swirl injector at ambient pressures of 0.1 MPa, 0.5 MPa and 1.0 MPa. As the ambient pressure increased, the droplet diameters increased while the spray penetration, spray width and axial velocity decreased. Chen and Yang [18] applied theory and numerical simulations to investigate the effect on flow dynamics of ambient pressures within the range of 0.1 to 4.83 MPa, finding that a higher ambient pressure caused a thicker liquid film and a narrower spray cone angle. Chryssakis et al. [19] adopted the Linearized Instability Sheet Atomization model to simulate the primary and secondary atomization of a high-pressure swirl injector in a Direct-Injection Spark-Ignition engine. These researchers combined a series of optical measurements to validate the model accuracy, including Mie scattering, laser-induced fluorescence, particle image velocimetry and laser droplet size analyzer. Li et al. [20] measured the spray penetration, spray

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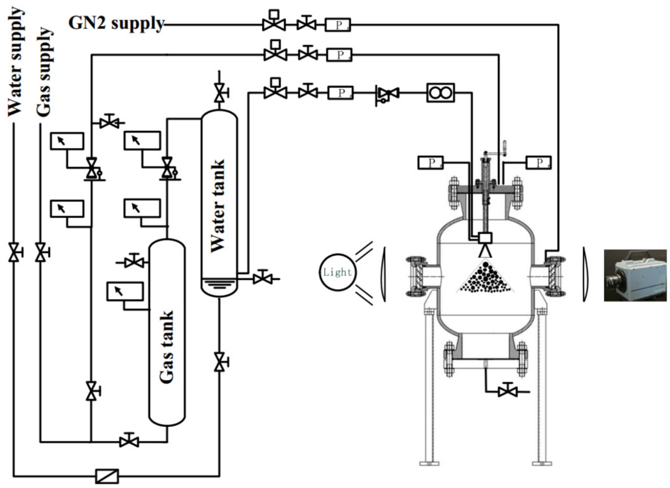

Fig. 1. Measurement system of an open-end swirl injector.

angle, and velocity of a swirl-type gasoline direct injection injector under different ambient pressures. These researchers found a critical point at which the spray behavior and structure would transform. Using a high-speed camera, Fu and Yang [21] studied the effect of the tangential orifice diameter and injector outlet diameter on the spray characteristics, including mass flow rate, spray cone angle and breakup length, of an open-end swirl injector under ambient pressure. Kim et al. [22] measured the spray angle and breakup length at different Weber numbers and ambient gas densities, and the laws governing the spray angle before and after the sheet breakup was found to be different. After considering the attenuation of sheet thickness in the linear instability theory, two empirical correlations of the spreading angles were proposed before and after the sheet break up. Kenny et al. [23] studied the fluid mechanism of a swirl injector under ambient pressures ranging from 0.10 to 4.81 MPa, observing that the discharge coefficient increased with the increasing chamber backpressure.

However, few of these researches investigated the spray characteristics of an open-end swirl injector under high ambient pressure. Moreover, the study of the evolving spray formation process in relation to time under high ambient pressure is crucial, and such work is rarely seen in the current literature. Among the influential parameters, the injector length and tangential inlet diameter have not been fully considered; these parameters are related to combustion instability [24] and swirling strength, respectively.

Therefore, the main objectives of the present study are to systematically investigate the influence of operating parameters (injection pressure drop and ambient pressure) and geometrical parameters (tangential inlet diameter and injector length) on the spray evolution process and spray characteristics, such as discharge coefficient and spray cone angle. A high-speed shadowgraph was adopted to capture the spray image on a high ambient pressure test apparatus designed for this purpose. Comprehensively considering the effects of these operating and geometrical parameters, empirical formulas for the discharge coefficient and spray cone angle are proposed as references for engineering applications. And the predicted values are compared with experimental results.

2. Experimental methods

2.1. Experimental setup

A spray test rig with an ambient pressure chamber was developed as shown in Fig. 1. The spray test rig consisted of a liquid supply system, a gas supply system, a chamber, an injector unit, a data acquisition system and an optical measurement system.

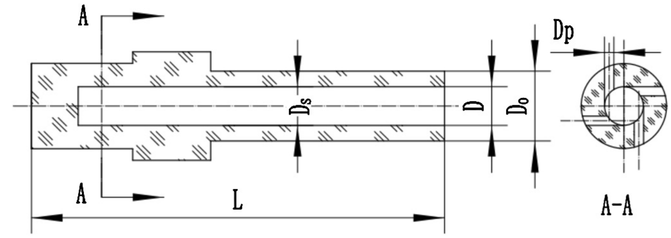

Fig. 2. Sketch of an open-end swirl injector.

Table 1
Geometric parameters of injectors.

ID	D_p (mm)	D (mm)	L/D	K
1	0.8	5	10	0.957
2	1.0	5	10	0.157
3	1.4	5	10	0.342
4	1.2	5	10	0.238
5	1.2	5	8	0.238
6	1.2	5	13.4	0.238
7	1.2	5	14.4	0.238
8	1.2	5	15.4	0.238

Distilled water and air were used as the liquid propellant and pressurized gas, respectively. The inner diameter and total height of the chamber were 580 mm and 2000 mm, respectively, and the design pressure was 5 MPa. Four observation windows with effective diameters of 120 mm were uniformly distributed around the circumference of the chamber. In order to improve the optical effect, a gaseous nitrogen purging system was used to prevent the droplets from accumulating on the observation windows. A vertical displacement device was installed at the top of the chamber to adjust the position of the injector, which could be adjusted to a maximum range of 180 mm. Thus, the injectors could be maintained at a similar position at the bottom of the chamber, and the maximum injector length difference was up to 34 mm.

Pressure sensors with an accuracy of ±0.5% were used to monitor the pressure of the chamber, injector, gas supply system and liquid system. The mass flow rate of the distilled water was monitored by a liquid turbine flowmeter, with a measuring range of 0.15–1.5 m^3/h and an accuracy of ±1%. For safety, the chamber was equipped with a relief valve, the opening pressure of which was set at 5 MPa. In addition, both a solenoid valve and a hand valve were used in the gas and liquid supply system. During the experiment, the solenoid valve was open all the time, closing only at the end of the experiment or in an emergency condition. A high-speed camera (Fastcam SA5) was used for the optical measurements. The exposure time was set to be 2.7 μs with a corresponding image of 1024 × 1024 pixels. The shooting frequency was 1000 frames/s.

The process of regulating the ambient pressure to the expected value was as follows. First, the ambient was filled with pressurized gas to achieve an ambient pressure near the expected pressure value. Second, the depressurization valve was turned down while the gas valve closed. The solenoid valve of the liquid supply system opened, and the injection pressure adjusted to the required value. In the end, the depressurization valve was adjusted to dynamically balance the chamber between import and export.

When the ambient pressure fluctuation remained below 0.005 MPa over a period of 30 s, the pressure was regarded as stable, and the average pressure value in the 30 s interval was regarded as the actual value. The mass flow rate was acquired similarly. A schematic of the open-end swirl injector is shown in Fig. 2, and its specific geometric parameters are presented in Table 1. The nozzle constant K is defined as:

$$K = A_p/(D_s - D_p)D \qquad (1)$$