Visualization Study on Flash-Boiling Spray of Refrigerant R134a from an Expansion-Chamber Nozzle (Postprint)

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Abstract

Flash-boiling spray can achieve favorable atomization effects at relatively low pressures due to the special bubble bursting phenomenon. To investigate the flash-boiling spray mechanism of refrigerant R134a, this study employs high-speed cameras to conduct visual observations and quantitative comparisons of the internal flow patterns within straight-tube quartz glass nozzles and the external spray characteristics of nozzles with different expansion chambers. It is found that as spray pressure increases, refrigerant R134a exhibits various cavitation flow patterns inside the straight-tube nozzle, including symmetric cavitation, asymmetric cavitation, and slug-like cavitation, among which the symmetric cavitation flow pattern corresponds to essentially identical atomization cone angles. For expansion-chamber nozzles, the length-to-diameter ratio of the expansion chamber corresponding to the smaller spray cone angle is 1:22:1, and the optimal external spray cone angle stabilizes at approximately 70°.

Full Text

Visualization Study of R134a Flashing Spray from Expansion-Chamber Nozzles

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Abstract

Flashing spray achieves excellent atomization at relatively low pressures due to the unique phenomenon of bubble explosion. To investigate the flashing spray mechanism of refrigerant R134a, this study employs high-speed photography to visualize and quantitatively compare internal flow patterns within straight-tube quartz glass nozzles and external spray characteristics of various expansion-chamber nozzles. The results reveal that as injection pressure increases, R134a exhibits distinct cavitation flow regimes inside straight-tube nozzles, including symmetric cavitation, asymmetric cavitation, and slug-like cavitation. The spray cone angle remains essentially constant under the symmetric cavitation flow regime. For expansion-chamber nozzles, the optimal length-to-diameter ratio of the expansion chamber for achieving smaller spray cone angles ranges from 1:2 to 2:1, with the optimal external spray cone angle stabilizing at approximately 70°.

Keywords: Flashing spray; Expansion-chamber nozzle; Internal flow pattern; Spray cone angle
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1. Introduction

When high-pressure liquid or liquefied gas discharges from a nozzle and experiences a sudden pressure drop below the saturation pressure corresponding to its initial temperature, the subcooled liquid transforms into a highly unstable superheated liquid. Under minimal disturbance, this superheated liquid undergoes violent explosive boiling, breaking into fine droplets—a process known as flashing spray. This phenomenon has numerous industrial and daily life applications. For instance, violent flashing sprays caused by leaks in high-pressure liquid or liquefied gas storage containers and pipelines can lead to catastrophic accidents, as the leaked medium rapidly disperses uniformly in the air as fine droplets [1]. Other examples include fuel flashing sprays in gasoline direct injection engines and transient refrigerant flashing sprays in laser dermatology, which can cool and protect normal skin tissue while improving treatment outcomes [2, 3].

In practical processes, high-pressure liquids experience pressure losses while flowing through the nozzle before ejection, causing partial liquid superheat and boiling phase change that forms a gas-liquid two-phase flow. At the nozzle exit, the liquid becomes superheated and the gas phase rapidly expands and ruptures, producing excellent atomization. Therefore, flashing spray involves two critical processes: (1) phase-change boiling inside the nozzle to achieve internal two-phase flow, and (2) liquid atomization caused by bubble rupture at the nozzle exit.

Flashing spray characteristics depend heavily on the gas-liquid two-phase flow pattern inside the nozzle [5, 6]. Previous researchers have conducted visualization studies of initial cavitation flow patterns for superheated liquids within nozzles. Sou & Hosokawa [7] used water as the working fluid and observed three distinct flow patterns near straight-tube nozzle inlets at different Reynolds numbers: fluctuating jet (Re $\leq$ 64000), supercavitation jet (Re ~ 70000), and fully asymmetric jet (Re ~ 76000). Suh et al. [8] experimentally investigated actual diesel engine injection conditions using diesel fuel and observed similar phenomena near transparent straight-tube nozzle exits, though the Reynolds numbers corresponding to various flow patterns were lower. Many scholars have also improved nozzle structures: Bar-Kohany et al. [9] analyzed optimal nozzle structures for spray formation based on Sher et al.’ s [10] face-center theory, finding that forming gas-liquid two-phase flow inside the nozzle could improve spray performance. Consequently, they proposed a nozzle structure with an expansion chamber and conducted experiments using diesel fuel, demonstrating that this nozzle required lower injection pressure than straight-tube nozzles to achieve the same atomization effect.

Although research on flashing spray characteristics in diesel engine nozzles has been conducted, current understanding of the flashing atomization mechanism remains insufficient, particularly regarding how internal flow affects atomization characteristics. This study utilizes the highly volatile, low-temperature medium R134a to investigate and observe cavitation flow patterns inside straight-tube nozzles and their relationship with external spray, while also examining spray characteristics of expansion-chamber nozzles with different length-to-diameter ratios.

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2. Experimental System and Test Methods

As shown in Figure 1 [Figure 1: see original paper], five quartz glass nozzles with different expansion-chamber length-to-diameter ratios were fabricated, along with a straight-tube nozzle for comparing internal flow patterns and their influence on external spray field characteristics. To enable accurate comparison, all other nozzle dimensions were fixed, with only the expansion-chamber length-to-diameter ratio varied (the straight-tube nozzle had no expansion chamber). Nozzle dimensions are listed in Table 1 .

The experimental system is illustrated in Figure 2 [Figure 2: see original paper]. Refrigerant R134a was stored in a temperature- and pressure-controlled tank, connected via high-pressure hoses to a manual valve and a fast-response solenoid valve (B2021SBTTO24DVC by Gems, USA, with opening and closing times less than 5 ms, enabling accurate control of transient sprays lasting tens of milliseconds). The nozzle exit was mounted on the solenoid valve. A high-speed camera (Phantom V611 by York, USA) was used to visualize internal flow and external spray morphology, operating at 10,000 fps with an exposure time of 25 s. Highpower LED continuous lighting was employed for high-speed photography, with illumination provided using a low-angle upward viewing method.

3. Experimental Results and Discussion

Pressure losses occurring across the solenoid valve and through the sudden contraction from the liquid pipe cross-section to the nozzle cross-section cause partial cavitation of superheated refrigerant R134a at the nozzle inlet. The type of cavitation varies with injection pressure. Figure 3 [Figure 3: see original paper] shows the cavitation flow patterns of R134a inside the straight-tube nozzle. At low injection pressures, only small amounts of symmetric cavitation appear near the nozzle inlet, similar to the low-Reynolds-number flow patterns captured by Sou [7] and Suh [8]. As injection pressure increases, the cavitation remains symmetric but the cavitation region expands significantly. When injection pressure reaches 1.3 MPa, asymmetry appears in the wall cavitation, and the flow pattern shows a tendency toward fully asymmetric flow. Due to R134a' s low saturation temperature at atmospheric pressure, the fully asymmetric flow pattern does not occur. After incipience of vaporization at the edges, gas diffuses toward the center. This central gas acts as a large vaporization nucleus, causing further vaporization of the central liquid. Under pressure gradients, large bubbles are broken into smaller ones. Through high-speed turbulent action, fine bubbles uniformly mix with unvaporized liquid inside the nozzle to form a slug-like flow. As injection pressure further increases, the location of the two-phase mixing slug moves further upstream and the vaporization range expands further.

To reveal how internal flow patterns affect external spray characteristics, injection pressure was increased from 0.8 MPa to 1.6 MPa to obtain external spray conditions for the straight-tube nozzle at different pressures, as shown in Figure 4 [Figure 4: see original paper]. The results show that as pressure increases (starting from near-saturation pressure), the spray cone angle increases dramatically in the initial stage. When pressure reaches 1.1 MPa, the spray shape becomes less sensitive to further pressure increases, and the spray enters a relatively stable injection region. Combined with Figure 3, this corresponds to the symmetric vaporization flow region inside the nozzle.

To analyze external spray characteristics and droplet diffusion after traveling a certain distance, the spray cone angle definition by Laura Juslin et al. [11] was adopted: the angle α formed by connecting the nozzle exit to two spray edge points at a certain distance (15 mm). The spray cone angles for the straight-tube nozzle at different pressures are shown in Figure 5 [Figure 5: see original paper], indicating that when injection pressure is below 1.1 MPa, the spray cone angle changes dramatically with pressure, but when pressure exceeds 1.1 MPa, the cone angle changes relatively slowly—similar to the Diesel spray experimental results of F. Payri et al. [12].

To further explore how nozzle structure affects spray characteristics, external spray features of expansion-chamber nozzles were compared. Figure 6 [Figure

6: see original paper] shows the effect of expansion-chamber structure on spray cone angle at different injection pressures, while Figure 7 [Figure 7: see original paper] displays spray morphology characteristics of expansion-chamber nozzles at various injection pressures.

As shown in Figures 6 and 7, the spray cone angles of nozzles 1, 2, and 6 change dramatically under different pressures. For nozzle 6, the excessive length-to-diameter ratio of the expansion chamber has a counterproductive effect, causing excessive vaporization of liquid and exhibiting oscillation characteristics similar to the straight-tube nozzle. In contrast, nozzles 3, 4, and 5 show small spray cone angles only near R134a' s saturation pressure; when operating in the high-pressure spray region deviating from saturation pressure, pressure increases do not significantly affect the spray cone angle. Comparing expansion-chamber nozzles with the straight-tube nozzle reveals that the expansion chamber enables effective vaporization of subcooled liquid inside the nozzle, forming a fully developed gas-liquid two-phase flow when re-entering the small nozzle section. This allows premature release of superheat, significantly reducing the spray cone angle. Therefore, nozzle structure (primarily the expansion-chamber length-to-diameter ratio) is the most critical factor affecting spray characteristics. For different injection pressures, an optimal length-to-diameter ratio range of 1:2 to 2:1 exists for the expansion chamber. When injection pressure operates far from saturation pressure, spray cone angle varies little with pressure and length-to-diameter ratio within this range, and the optimal external spray cone angle stabilizes at approximately 70°. This conclusion has strong practical value for applications requiring precise spray control.

Combining Figures 4 and 7, an insufficiently broken-up liquid region (darker area with large liquid fragments where superheat has not been fully released) can be observed in the central portion of R134a flashing sprays near the nozzle exit for all nozzle types. This region is significantly larger for the straight-tube nozzle and increases with injection pressure, while decreasing with increasing expansion-chamber length-to-diameter ratio. This further demonstrates that the gas-liquid two-phase flow generated by phase change inside expansion-chamber nozzles facilitates premature release of superheat in flashing sprays, reducing the insufficiently broken-up region in the spray field at the nozzle exit and improving atomization quality.

4. Conclusions

This study investigated internal flow patterns in straight-tube nozzles for R134a flashing spray using high-speed photography and analyzed external atomization morphology of various expansion-chamber nozzles, yielding the following conclusions:

1) During cavitation of refrigerant inside straight-tube nozzles, three flow types emerge with increasing pressure: symmetric cavitation flow, asymmetric cavitation (as a critical cavitation form), and slug cavitation.

2) Different flow types correspond to significantly different spray cone angles, while the same flow type produces essentially identical spray cone angles.
3) Analysis of external spray cone angle characteristics reveals that expansion-chamber nozzles have an optimal expansion-chamber length-to-diameter ratio range of 1:2 to 2:1. Expansion-chamber nozzles produce smaller spray cone angles than straight-tube nozzles, with the optimal external spray cone angle stabilizing at approximately 70°. Within the optimal length-to-diameter ratio range, when injection pressure operates far from saturation pressure, the spray cone angle shows little variation with pressure and expansion-chamber length-to-diameter ratio.

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Note: Figure translations are in progress. See original paper for figures.