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Experimental study on the relation between internal flow and flashing spray characteristics of R134a using straight tube nozzles

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ABSTRACT

Internal flow, specifically nucleation, inside the nozzle has a significant effect on external spray characteristics. The relation between the internal flow pattern and spray characteristics of R134a flashing spray was investigated by using the transparent nozzle with length of 60 mm and inner diameter of 1.4 mm. In addition, the effect of inlet pressure on the spray characteristics, such as spray cone angle, droplet velocity, and temperature, were measured by using stainless-steel tube nozzles with length of 60 mm and diameter of 1.4, 1.2, and 1.0 mm. The high flow velocity, droplet velocity, low mass flow rate and decrease of superheat caused by the evaporation inside the nozzle lead to the decrease of spray cone angle, while the evaporation inside the nozzle contributes to the formation of fine droplets. Promoting the formation of stable bubbly flow inside the nozzle could be an effective way to acquire a small cone angle and fast drop of droplet temperature.

1. Introduction

Flashing sprays occur when a saturated liquid is released to a low-pressure environment by passing through a throttling valve or other throttling devices (for example, a narrow orifice). Following sudden depressurization, violent vapor nucleation and explosive atomization of the liquid emerge under superheated condition. Flashing sprays have been encountered in many industrial applications, including combustion engines [1], deep-stage separation technology of heavy oil [2], and distillation of salt water by flash evaporation [3], and as an airless and lower-pressure spray method it shows potential to be used in practical coating applications, especially in the automotive paint spray technology. It is energy-saving and safe, and droplet size can be possibly optimized by changing the superheat to achieve higher paint transfer efficiency [4,5]. The explosive flashing spray could also occur in the chemical or nuclear industry when the vessel or pipe cracks during the accidental release of flammable and toxic pressure-liquefied gases [6].

Owing to its practical importance, the phenomena and mechanism of flashing spray atomization have been widely studied since the work of Brown and York [7] in the early 1960s. Fine atomization can be achieved through a simple geometry nozzle with the flashing spray technique, and a straight tube nozzle has been adopted in most studies [7–10]. The working medium in flashing spray is frequently superheated when it is released through the nozzle in a low-pressure environment. The pressure could also be decreased below the vapor pressure within the nozzle because of friction or acceleration, in which evaporation would be triggered inside the nozzle. The two-phase flow pattern inside the nozzle, such as bubbly, slug, and annular flow, plays an essential role in the atomization [11].

Park and Lee [12] visualized the internal flow pattern and external spray pattern of hot water flashing spray using circular transparent nozzles with lengths of 108 and 20 mm. As the superheat degree increases, the internal flow regimes change from bubbly flow to slug flow, and then to annular flow, thereby extracting smaller and more uniform droplets. Gunther and Wirth [13] found that when the water temperature increased to 130 °C, nucleation appears inside the capillary nozzle and the spray pattern changes from jet to a fine spray, which means that the atomization is enhanced when bubbles appear inside the nozzle. Recently, Zhang et al. [14] performed flow visualization on the flashing spray of methanol using a transparent slit nozzle, and found that bubbles formed inside the nozzle and the spray pattern was dominated by superheat degree; the researchers suggested that the area fraction of superheated jet near the nozzle has a positive relation with the bubble number density inside the nozzle, which means that the breakup of superheated jet is directly related to the intensity of bubble formation inside the nozzle. Oza et al. [8,9] assumed that primary atomization could be completed inside the nozzle due to the two-phase flow caused by the evaporation within the nozzle; they defined the "internal-flashing mode" under the high super-

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Nomenclature

d	bubble diameter (mm)
D	nozzle inner diameter (mm)
D_{32}	droplet Sauter mean diameter (μm)
g_c	constant coefficient
k	coefficient
P	pressure (MPa)
R	bubble radius (m)
Re	Reynolds number
SD	standard deviation
T	temperature (°C)
V	velocity (m/s)
We_c	critical Weber number
z	axial distance (mm)
α	spray cone angle (°)
α^*	dimensionless spray cone angle
μ	dynamic viscosity (kg/m·s)
ρ	density (kg/m^3)
σ	surface tension force (N/m)

Subscripts

crit	critical value
d	droplet
in	nozzle inlet
max	maximum
min	minimum
sat	saturation
v	vapor

heat degree to distinguish the flashing spray model of "external flashing," which means that no breakup occurs within the nozzle when the superheat degree is low. With the increase in the superheat degree, the spray pattern of liquid CO_2 shifted from jet to cone spray, and then to a bowl spray. Lin et al. [15] attributed this drastic change in spray angle to the onset conditions from external-flashing to internal-flashing atomization mode. However, the experiment on flashing spray with heated water passing through a short tube orifice completed by Reitz [10] demonstrated that an intact liquid core still existed around the nozzle exit under high degrees of superheat, and the steady jet expelled smaller droplets upon leaving the nozzle. The experiment indicates that the breakup of jet did not occur inside the nozzle, which cast doubt on the flashing atomization theory proposed by Oza et al. [8,9]. Using convergent nozzles, Kurschat et al. [16] and Vieira et al. [17] also documented the existence of a metastable liquid core under high superheat degrees. Although opinions vary on whether the primary atomization could appear inside the nozzle, the two-phase internal flow inside the nozzle is acknowledged to have a significant effect on the spray characteristics [11].

The nucleation inside the nozzle and the enhancement of flashing spray atomization were achieved by increasing the liquid temperature in almost all of the flashing spray experiments. Both the evaporation inside the nozzle and micro-explosion of droplets outside the nozzle [18] could be enhanced in these experiments. However, increasing the degree of superheat is not always straightforward. By contrast, changing the injection pressure is another effective way to adjust the flow pattern inside the nozzle, thereby enabling the analysis of the relationship between the internal flow and external spray.

Several current studies on the internal flow of flashing spray mainly focused on the superheated water and fuels. Minimal knowledge is available on low-boiling-point cryogens such as R134a, R404A, and R407C. Flashing spray by these cryogens may be suitable for intense cooling because low temperature can be simply achieved as a result of evaporation. A good example of cryogen spray is R134a spray cooling, which has been widely used in dermatologic laser surgery to protect the epidermis from undesirable thermal damage [19]. Much effort has been devoted to investigate the influence of various parameters on cryogen spray cooling, such as the spurt duration [20], spray distance [21,22], spray angle [23], cryogen film thickness [24], back pressure [22,25], mass flow [26], nozzle structure [27], and different cryogens [27,28]. In addition, the spray characteristics of cryogen were investigated [29]. However, few current visualization experiments for the internal flow inside the nozzle of R134a flashing spray have been conducted, except those by Zhou et al. [30] and Ju et al. [31,32], who used expansion-chambered nozzles in their studies.

Zhou et al. found that the spray cone angle was smaller when a straight nozzle was used, thereby providing a different perspective from the general viewpoint that the expansion chamber contributes to the increase of spray cone angle [11]. Ju et al. found that the spray angle was diluted by the mixture flow with high gas/liquid void fraction inside the nozzle, and a lower degree of superheat caused by evaporation contributed to the decrease of the spray cone angle. More detailed studies should be performed to investigate the effect of evaporation within the nozzle on cryogen spray characteristics, especially when straight tube nozzles are used.

Thus, the motivation for this work is to investigate the flashing spray characteristics of R134a to understand the relation between the internal flow and external spray characteristics. A transparent straight nozzle was designed, and the internal flows and external spray patterns were recorded by a high-speed CCD camera. The two-phase flow pattern inside the nozzle is controlled by adjusting the inlet pressure instead of the liquid temperature. The spray characteristics including the spray droplets velocity, diameter, and temperature were investigated by using the stainless-steel nozzle under different inlet pressures.

2. Experimental setup and methodology

2.1. Spray system

A schematic of the experimental system to visualize the flashing spray is illustrated in Fig. 1. Non-toxic commercial cryogen R134a (Dupont, USA) stored in a vacuum flask was released to a pressure stabilizer. Driven by high-pressure nitrogen, cryogen flowed into the nozzle for atomization through the hose tube and a solenoid valve (ZC51-8B-6.3, Dun Ming, China), which was fixed on a 3 D positioner with resolution of 8 μm (WN105TA300M by Beijing Winner Optics Instruments Co., China). A pressure sensor with accuracy of ±0.1% (0–5 MPa, MIK-P300, MEACON, China) was located near the nozzle inlet to measure the static pressure when the valve was triggered. All signals were acquired by a DAQ board (NI: M-6251, USA), which was also used to synchronize the valve and high-speed camera.

2.2. Imaging system

As shown in Fig. 1(a), a high-speed camera (FASTCAM SA-Z, Photron, Japan) was used to capture the internal flow and external