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An experimental study on the spray and thermal characteristics of R134a two-phase flashing spray

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ABSTRACT

Flashing spray of volatile liquids is a common phenomenon observed in many industrial applications such as fuel injection of engines, accidental release of flammable and toxic pressure-liquefied gases, failure of a vessel or pipe in the form of a small hole in chemical industry, and cryogenic spray cooling in laser dermatology, etc. In flashing spray, the volatile liquid is depressurized rapidly at the exit of a nozzle (or a hole in a vessel) and becomes superheated. Such superheated liquid (in the form of either a jet or droplets) will lead to explosive atomization with fine droplet and a short spray distance. This paper presents an experimental investigation to the spray and thermal characteristics of flashing spray using cryogen R134a. A photographic study of the spray is firstly conducted to visualize the spray formation and the dynamic characteristics of the spray. Afterwards, the spray characteristics are measured by the phase Doppler Particle Analyzer (PDPA). The distributions of the diameter reveals the dramatic dynamic variation of the liquid droplets due to explosive atomization of large droplets in the region near the exit of nozzle, while the self-similar velocity profiles are fitted by two empirical correlations to describe the non-dimensional axial and radial velocities, respectively. The temperature field within the spray is measured by a small thermocouple. The temperature measurements provide detailed quantitative information of both radial and axial temperature distributions of droplets within the spray. These experimental results provide deep understanding into the whole characteristics of two-phase flashing spray of volatile liquids.

1. Introduction

Flashing spray occurs when a high-pressure liquid is injected into low pressure environment to make the liquid superheated, characterized by explosive atomization of superheated liquid to generate fine droplets and accompanied by strong evaporation of these droplets, leading to extremely low droplets temperature. Flashing spray finds many industrial applications, for example, flash-spray internal combustion engine [1], distillation of salt water by flashing evaporation [2], cryogen spray cooling in laser treatment of dermatology [3,4], etc. The explosive flashing spray may also take place during the accidental release of flammable and toxic pressure-liquefied gases in chemical or nuclear industry, when failure of a vessel or pipe in the form of a small hole will result in formation of a flashing jet containing a mixture of liquid droplets and vapor [5]. Flashing spray is also relevant for the aerospace engineering, where high-pressure fluids expand into near vacuum during engine start-up will lead to high superheat state as well as flash atomization and vaporization [6].

With a low boiling point (−26.1 °C at the atmospheric pressure) and high volatility, R134a has been widely used for flashing spray in many industrial applications as a non-toxic and ozone-friendly refrigerant. One important case is the cryogen spray cooling that is successfully used in laser dermatology to prevent burning injury of skin during surgery [3,4]. Saturated R134a at room temperature in a storage tank is injected into the atmospheric environment through a special designed nozzle. Flashing atomization and strong evaporation will result in a low temperature spray which provides efficient cooling to skin [7–10]. Spray cooling with R134a also has been used in the metal foundries, cooling of microelectronics and chiller in air-conditioning systems to remove high heat fluxes [11–13]. In the field of industrial safety, Yildiz et al. [14,15] used R134a as model fluid to simulate the accidental release of pressured liquid.

The importance of these applications has motivated research on the flashing spray. Brown and York [16] firstly used the photograph technology to investigate the flashing spray pattern using water. After that, several other visualization studies were also performed

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Nomenclature

d	inner diameter of the nozzle (mm)
L	length of the nozzle (mm)
z	spray axial distance from the nozzle exit (mm)
Z	non-dimensional axial distance
R	spray radial distance from the centerline (mm)
D_{10}	droplet arithmetical mean diameter (μm)
D_{32}	droplet Sauter mean diameter (μm)
U	axial velocity (m/s)
V	radial velocity (m/s)
T	droplet temperature (°C)

Subscripts

max	maximum
min	minimum
s	saturated
MTD	minimum temperature distance
CSD	Cold Spray Distance
STL	Spray Thermal Length
STW	spray thermal width
SCW	spray cold width

using water. Miyatake et al. [17] and Peter et al. [18] studied the effect of the liquid superheat and the flow rate on the flashing spray. Reitz [19] and Park and Lee [20] investigated the mechanisms of the flashing sprays. Additionally, Allen [21,22] used the Malvern technique and LDV system to measure the droplet diameter and the axial velocity distributions of two-phase flashing propane jets. Yildiz et al. [14,15] and Aguilar et al. [23,24] conducted experiments to investigate the two-phase flashing R134a jets using the PDPA system.

There are only a few reports on the thermal characteristics of R134a sprays [23–25]. Aguilar and his co-workers [23,24] found an exponential decay of the average temperature of steady state R134a droplets along the spray distance by using a large thermocouple with a bead diameter of approximately 0.3 mm. Yildiz et al. [25] also used thermocouples to measure the centerline droplets temperature of R134a sprays from nozzles of 1–3 mm. Their data shows similar variation as reported by Aguilar et al. [23,24]. Miyatake et al. [17] proposed an empirical correlation for the variation of spray temperature for superheated water spray. In a review article, Polanco et al. [5] mentioned a minimum spray temperature along the centerline of the flashing spray and defined a "minimum temperature distance". They reported a dimensionless minimum temperature distance of 150–170 (normalized by the nozzle diameters) for propane spray, similar to that by Yildiz et al. [25] for R134a spray.

Although above studies provided some useful information on the flashing spray, the results have not given a comprehensive investigation on the R134a two-phase flashing spray. It is apparent that more accurate experiments are required to provide a better insight into the mechanisms of the R134a flashing spray. The motivation of present work is aimed at conducting a full experimental study on both spray and thermal characteristics of the R134a two-phase flashing spray. The flashing spray pattern and the distribution of droplet diameter, velocity and temperature have been investigated by high-speed camera, PDPA and thermocouple. Empirical correlations based on the experiment results have been proposed to describe the droplets spray and thermal behaviors. These data should shed important light to the spray development and would be useful for future spray design.

2. Experiment system and procedures

2.1. Spray system

Fig. 1a shows a schematic of the experimental system for flashing spray study. The system consists of a commercial pressure vessel for storage of R134a (Dupont), a three-dimensional translational electric positioner (WN105TA300M by Beijing Winner Optics Instruments Co., China) with resolution of 8 μm, a solenoid electric valve (B2021SBTTO24DVC by Gems, US) which can open or close within 5 ms, and a specially-designed nozzle installed on the positioner. The nozzle is made of a stainless steel tube of length of 63.5 mm and inner diameter of 0.81 mm, which resembles that of commercial nozzles used for cryogen spray cooling in conjunction with dermatological laser treatments. A standard high-pressure hose connects the cryogen vessel to the valve, while the nozzle was fit tightly into the opening of the solenoid valve. The internal structure of the solenoid valve includes four 90° bends and two sudden contraction sections, as shown in Fig. 1b. A micro-scale flowmeter (931-06xx by Gems, US) is located in the middle of the high-pressure hose to monitor the flow rate of the spray. The experimental rig and PDPA system were shown in Fig. 1c and d.

2.2. Imaging system

A high-speed video camera (MotionXtra HG-100, US) with shutter speed of 997 μs is used to take photographs of the spray. A PLS-SXE300 Xe lamp with high power provides illumination for the high-speed camera at far distance for large view, while a white lamp with low power near the nozzle for close view. The camera and the lamps are positioned in the same horizontal plane, with the camera viewing perpendicularly to the spray axis. All photos are taken at the speed of 1000 fps and the same resolution of 1504 × 1128 pixels. The camera is placed either 1900 or 500 mm from the spray axis. At a far distance, the camera can catch the view of the entire spray; while at a close distance, the camera can take a photo of the spray near the nozzle exit. The two distances give the fields of view of about 190 × 140 and 50 × 37.5 mm^2, respectively.

2.3. PDPA measurement system

A Phase Doppler Particle Analyzer (PDPA by TSI, US) is used to simultaneously measure the velocity and diameter distribution of the droplets in the spray of R134a. The PDPA generates four interfacing laser beams with a power of 0.8 W of two wavelengths, 514.5 nm (channel one) and 488 nm (channel two). Two beams focus on a probe volume, typically smaller than 1 mm^3. When droplets go through the probe volume, these beams are interfaced and a Doppler signal with a frequency shift proportional to the droplet velocity is generated. The diameter and axial and the radial velocity of droplets can be measured simultaneously. The phase difference between the signals collected by adjacent detectors is proportional to the droplet diameter. Before taking the measurements, the optimum values of the PDPA parameters have to be selected including the diameter range (0–1000 μm), velocity range (0–100 m/s) and the laser power. For each measurement, the spray duration lasts 10 s. Repeatability tests have been conducted to evaluate the confidence on the experimental results. It has been shown that the dispersion did not exceed ±3% in the droplet mean velocities (U and V) and ±7% in the droplet mean diameters (3% in