Journal of Aerosol Science 61 (2013) 27–35

Contents lists available at SciVerse ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Effects of superheat on characteristics of flashing spray and snow particles produced by expanding liquid carbon dioxide

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ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form
17 February 2013
Accepted 4 March 2013
Available online 20 March 2013

Keywords:
Superheat
Flashing spray
Snow formation
Size distribution
CO_2

ABSTRACT

This research experimentally investigates influences of superheat on flashing spray characteristics and on the snow formation of liquid CO_2. Results show that liquid, two-phase flow or even three-phase flow can be found upon the release of liquid CO_2 from high pressure to atmospheric pressure. This is due to complicated phase transition processes that involve hydrodynamic instabilities and thermal non-equilibrium conditions. Results also show that the spray pattern transfers from jet spray to cone spray, and then to a bowl spray configuration with the increase of superheat. The drastic changes in spray angle and mass flow rate indicate onset conditions from external-flashing to internal-flashing atomization mode. This is due to bursts of bubbles inside the nozzle chamber that result in the choking of the two-phase flow. Moreover, a few microns of CO_2 snow size are measured in this research, which is consistent with records from literature on this topic. The narrower size distribution of snow particles and a critical spray angle resulting from two competing phenomena under internal-flashing atomization mode are also discussed in this research.

1. Introduction

Due to the fact that it is nontoxic, nonflammable and un-reactive under most conditions, and also the fact that it leaves no liquid waste characteristics, carbon dioxide (CO_2) is a leading candidate for more environmentally responsible replacement of organic and aqueous solvents in many microelectronic applications (Weibel & Ober, 2003; Wang et al., 1999; Yang et al., 2006; Jones et al., 2004). Most notably, CO_2 snow cleaning possesses unique organic and particle removal abilities and has become popular in recent years (Hoening, 1986; Sherman, 2007; Sherman et al., 1994; Liu et al., 2011; Yang et al., 2007; Char & Sheu, 2009; Lin et al., 2012; Shen et al., 2012).

The thermodynamics and the mechanisms of CO_2 snow formation can be described by the Joule–Thomson effect. The expansion of CO_2 from a high pressure cylinder to atmospheric pressure through a nozzle is ideally a constant enthalpy process, so the pressure decreases along a constant enthalpy line as the CO_2 passes through an orifice. During decrease in CO_2 pressure, liquid droplets nucleate and convert to solids at the interface between the liquid–gas and gas–solid regions, accompanied with rapid boiling of the liquid into gas and the formation of a lot of bubbles. The atomization conjunction of the bubble formation is called “flash-atomization” and is a kind of effective breakup mechanism of the liquid column due to a burst of bubbles. It usually exploits thermodynamic instability to breakup a liquid jet as the heated liquid is accelerated

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http://dx.doi.org/10.1016/j.jaerosci.2013.03.005

through an injection nozzle with a sudden pressure drop sufficiently below saturation pressure. Zeng and Lee (2001) developed an atomization model for sprays under flash boiling conditions and found sprays atomized by bubble growth result in smaller droplet size than those generated using aerodynamic force alone. Recently, the spray characteristics and particle size of CO_2 produced by flash-atomization have been getting more and more attention. Liu et al. (2010, 2012) and Hulsbosch-Dam et al. (2012) used the laser diffraction method and model validation to determine particle size distribution of the spray. Liquid droplets and solid particles with a size range of a few microns were obtained and validated.

The governing factors of occurrences of different spray patterns are very complicated in nature and have been determined to be a function of nozzle dimensions and internal surface roughness, inlet fluid temperature (Peter et al., 1994), flow rate, chamber pressure, bubble concentration at the nozzle exit and the properties of the flow media used. Vapor bubbles within the nozzle may cause a reduced mass flow by reducing the effective nozzle diameter or by reducing the overall fluid density (Reitz, 1990). According to where breakup occurs, Oza (1984) first defined the external flashing (breakup occurs outside the nozzle) and internal flashing (breakup occurs within the nozzle) regimes to emphasize the mechanism of the breakup of flash-boiling jets in the high degree of superheat regime. With increasing degrees of superheat, the breakup length becomes shorter, and the spray angle becomes larger (Senda et al., 1994); however, a critical spray angle exists due to the air entrainment as the superheat is further increased (Park & Lee, 1994).

Owing to its complexity and the fact that it is not easy to observe, mechanisms responsible for internal-flashing and external-flashing are not clear in the literature on this topic, especially in regard to the application of CO_2 to produce snow particles that involve vapor, liquid and solid phases. Moreover, the mechanism of bubble formation, growth and burst, especially the inter-relationships between the distinctive processes that determine the spray quality are not well understood. In this research, liquid CO_2 with different degrees of superheat is investigated to discuss the characteristics of flashing spray and snow particles for more evidence and a deeper understanding of CO_2 flashing spray and snow formation.

2. Experimental setup

The schematic diagram of the experimental setup is shown in Fig. 1. The experimental facility consists of a high pressure tank, a cooler, an exhaust valve and a test chamber. The liquid CO_2 is supplied from a high pressure tank with a temperature of 25 ± 2 °C and a 57 bar pressure. It flows through a cooler and cools down to a specific temperature while its pressure is maintained, and finally it forms a spray inside the test chamber through a nozzle. The nozzle is made up of stainless steel with a 250 μm diameter orifice. The test chamber is 250 mm × 250 mm × 600 mm in size with quartz optical windows for visualization and for optical diagnostics. A gas nitrogen injection system is also used to ensure a dry environment and to prevent water mist interference.

The instrumentation consists of a digital high-speed camera (IDT, Inc) coupled with a 4× magnification optical microscope, a particle size analyzer (Spraytec, Malvern Instruments, Inc) based on laser diffraction method, a CO_2 turbine flowmeter and T-type thermocouples with a NI 9213 controller. In this research, the frame rate and exposure duration of the high-speed camera are set at 100 fps and 5 ms, respectively. A DC light with a light diffusion plate is used to ensure uniform light sources, and a turbine flow meter is set in the upstream channel before the cooler to measure the mass flow rate of the liquid CO_2 without the interference of a complicated two-phase flow.

The size distribution of the liquid and solid particles is measured in-situ with a particle size analyzer detected at 40 mm downstream of the spray flow from the nozzle orifice. A significant volume of low temperature CO_2 gas in conjunction with injected ambient temperature nitrogen gas in the measuring region will cause a beam steering effect. This results in the defocus of the laser beam and leads to a high scattering signal on the first/outer ring of the 31 ring detector. This signal in the first/outer ring is not from particle scattering and is interpreted as coarse particles that should be removed. In this research, a limited range of particle diameter below 50 μm suggested by Liu et al. (2012) is set to eliminate the error signal

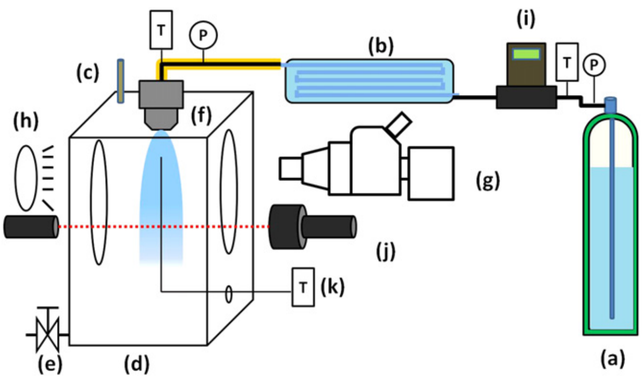

Fig. 1. Experimental setup (a) high pressure tank, (b) cooler, (c) injection inlet of gas nitrogen, (d) test chamber, (e) exhaust valve, (f) nozzle, (g) high-speed camera with microscope, (h) DC light, (i) mass flow-meter, (j) particle size analyzer, and (k) thermal couple.