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Effect of low ambient air pressure on spray characteristics of water mist

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ABSTRACT

To investigate the effect of low ambient air pressure on the characteristics of water mist which was injected into a low pressure (<0.1 MPa) environment, the sizes and velocities of the water droplets were measured using Shadowgraph technique. A stainless steel vessel with a diameter of 600 mm and height of 800 mm was designed for simulating low ambient air pressure conditions using a vacuum pump. Ambient air pressures of 0.1, 0.08, 0.06, 0.04, 0.02 MPa, and working pressures of the water mist system of 1.0, 3.0, 4.0 MPa were considered. The results show that, under each certain pressure of water mist system, both of the Sauter mean diameter (d_{32}) and the arithmetic mean diameter (d_{10}) of water mist droplets decrease with decrease of the ambient air pressure from 0.10 to 0.02 MPa. An empirical formula has been developed to express the influence of ambient air pressure on Sauter mean diameter of water mist. In addition, the axial velocities of water mist droplets generated with working pressure of 3.0 MPa and 4.0 MPa decrease following a decrease in ambient air pressure, while there is no obvious variation to the tested results of the cases with 1.0 MPa working pressure.

1. Introduction

The transformation of bulk liquid into sprays and other physical dispersions of small droplets in a gaseous atmosphere is important in several industrial processes and has many practical applications in the spray combustion of liquid fuels and fire suppression with water mist/spray, etc.

Studies of the effect of ambient pressure or temperature on fuel spray combustion have received much attention in past years [1–7]. However, most of the studies focused on the effects of high ambient air pressures (>0.1 MPa). For instance, Hiroyasu et al. [8] studied the effects of high ambient pressure (3.0 MPa) and jet velocity on the breakup of high-velocity water jets under conditions similar to those encountered in diesel engines. Similar tests using diesel-type nozzles with water as the test fluid were also conducted by Arai et al. [9]. These studies reported that an increase in ambient pressure causes the breakup length to diminish and indicated that ambient pressures in the range of 0.1–3 MPa have a strong effect on breakup length and spray angle of the high speed jet. DeCorso [10] was among the first to investigate the effect of ambient air pressure on the spray characteristics of simplex swirl atomisers. That measured an increase in drop size when the ambient pressure was increased from 0.1 to 0.79 MPa and attributed this increase in drop size to increased coalescence of the spray drops as the ambient pressure increased. Lee and Reitz [11] investigated the effects of gas density and velocity on the breakup mechanisms of liquid drops injected into a transverse high-velocity gas flow at four spray chamber pressures (1, 3.7, 6.4 and 9.2 atm). Over a pressure range of 0.1–0.5 MPa, a marked rise in the Sauter mean diameter (d_{32}) was observed with an increase in ambient air pressure (P_a) ($d_{32} \propto P_a^{0.27}$). For a given nozzle, known as the pressure-swirl atomizers, many equations have been proposed for d_{32} via correlation of available experimental data where both ambient air and liquid properties were taken account [12–14].

As mentioned above, most of the studies focused on the effect of high ambient air pressure (0.1–3.0 MPa and even higher) on liquid fuel sprays. Although many studies have been conducted on water mist characterization and its effect on fire suppression [15–18], few work has been done on the effect of low ambient air pressures (<0.1 MPa) on spray characteristics, even though its effect on spray pattern, spray flux density and flow coefficients has been preliminarily documented [19,20]. The variation of ambient pressure will cause the variation of air density, the surface tension and viscosity of fluid. Most of the previous studies about the spray behaviour and atomization characteristics affected by ambient pressure mainly focused on fuel spray or high ambient pressure above

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Nomenclature

f	focal length of the objective (m)
f'	focal length of the image (m)
m_a	mass of air (kg)
M	magnification of the imaging system
n	refractive index of air
n_a	the amount of substance of air
n_0	refractive index of air in the reference state
n'	refractive index of air on the image side
P	pressure (Pa)
P_0	air pressure in the reference state (Pa)
ΔP_L	injection pressure differential across the nozzle (Pa)
Q	volumetric flow rate (m^3/s)
R	the ideal gas constant (m^3 Pa mol^{-1} K^{-1})
s	objective distance (m)
s'	image distance (m)
T	air temperature (K)
T_0	air temperature in the reference state (K)
y	objective height (m)
y'	image height (m)
ρ	density (kg/m^3)
ν	kinematic viscosity (m^2/s)
σ	surface tension (kg/s^2)

Subscripts

a	air
L	liquid

0.1 MPa. But the properties of water are different from those of fuel and the ambient pressure of water mist applications is mostly lower than the spray combustion field. So the study on the effect of low ambient air pressure on water mist droplet size and velocity is still essential.

The object of this paper is to investigate the effect of low ambient pressure on water mist characteristics, so the droplet sizes and velocities of water mist ejected into the environment at ambient pressures of 0.1, 0.08, 0.06, 0.04 and 0.02 MPa were measured and analysed. The results should be helpful for optimising the water mist fire suppression systems and valuable for considering the effect of low ambient air pressure on spray combustion in some high-altitude areas, known as Tibet of China, where the ambient air pressures of many areas are lower than 0.06 MPa.

2. Experimental description

2.1. Experimental apparatus

As shown in Fig. 1, the experimental apparatus includes three parts: a stainless steel vessel, a LaVision Particle-Master Shadow system and a water mist system. A KAWAKE JP-140V vacuum pump was connected to the vessel for generating low air pressure inside the vessel. Two glass windows with 150 mm diameter were aligned approximately 612 mm under the nozzle cap for convenient of using shadowgraph technology. Only one cap (with one orifice and 30° cone angle) of the water mist nozzle was placed at the centre of the vessel top to avoid wall effect and dense sprays because the dimensions of the vessel are not large enough to consider a practical used water mist nozzle. In fact, even under general pressure conditions, water mist nozzle is usually characterized with one of its caps as described in some standard codes, such as GBT 26785-2011 of China, to avoid over-attenuation of light by dense spray. In addition, a barrel like plastic shield was lied flat between the two glass windows to reduce the droplets number along the laser light, and at its top centre (just under the nozzle cap), opened a square aperture with 40 mm side. Thus only some of the droplets which were ejected inside the shield through the aperture could be measured. The imaging sample area was about 5 mm × 5 mm. Nominally, about 5–30 droplets were collected and analysed, the cases with less than 5 droplets were neglected.

The LaVision Particle-Master Shadow system features a double-pulsed 532 nm Nd-YAG laser, a programmable timing unit (PTU), a LaVision diffuser with a 120 mm output aperture, a mirror-based long distance microscope (LDM) that has 560 mm to 1520 mm working range and 70 mm back focal length, a CMOS camera and a LaVision computer with DaVis 8.0 software. The laser pulse energy was adjusted to 100 mJ (maximum is 200 mJ) to avoid damage to the CMOS camera by incidence of high optical density. The pulse width (5–10 ns) and the interval between pulses were programmed by the DaVis software according to the desired application. A LaVision diffuser was used for strobe background illumination for shadowgraph imaging. Table 1 presents information regarding the *f* numbers and the field of view (FOV) of the system for a chosen working distance.

A self-contained water mist system was used to generate water droplets. Only one cap of a nine-cap water mist nozzle was used for experimental tests to avoid wall effects and dense sprays. Fig. 2 presents an image of the cap and the nozzle. The diameter of the cap orifice and its *K*-factor were 0.6 mm and 0.12 L/min/MPa$^{0.5}$, respectively. The droplets were imaged at the centre of the vessel and approximately 400 mm away from the cap orifice.

2.2. Experimental methodology

Water mist droplet sizes and velocities were measured using shadowgraphy technique. This technique is based on high-resolution imaging with pulsed backlight illumination. The technique is independent of the shape and opacity of the particles and allows for the investigation of particles as small as 5 μm using an appropriate imaging system and light illuminating source. The details of the basic principles of shadowgraphy can be seen elsewhere [21–24]. A double-pulse laser combined with a double-frame camera were used by LaVision Particle-Master Shadow system, which allows the system to evaluate the velocities of individual particles.

Since the calibration and focus adjustment are difficult to perform after the air pressure inside the vessel was previously pumped to a low level (less than 0.1 MPa), so the Particle-Master Shadow system was calibrated and focused prior to data collection under normal ambient air pressure conditions. The calibration plate was put inside the vessel and adjusted for well calibrating through an operating window which was sealed after the calibration, while the two glass windows were well assembled during the calibrating, because the droplet image size should be reduced due to its large refractive index of 1.57 if they were not considered in calibration. Measurements at normal air pressure of 0.1 MPa were performed immediately following the calibration, then conducted other tests by reducing the air pressure inside the vessel and adjusting the working pressure of the water mist system, respectively. In each test, an average value of the droplet size and velocity was determined based on at least three measurements.