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Characteristics of the breakup and fragmentation of an electrohydrodynamic melt jet

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ABSTRACT

In this study, the breakup of a melt jet into a viscous medium is investigated in the presence of an intense electric field. Fragmentation of the melt jet occurs due to both hydrodynamic and electrohydrodynamic (EHD) forces within two kinds of silicone oil of different viscosities. The size and shape characteristics of the produced particles have been studied using SEM images, and the particle size distributions were found to exhibit considerable variations when a voltage was applied and when both the viscosity and temperature of the base fluid were changed. The morphologies of the particles were also affected by the same parameters. For instance, by applying EHD force, significant enhancements in size reduction and increased roundness of the particles occurred. The breakup process of the melt jet was found to be dominant by hydrodynamic or electrohydrodynamic instabilities, depending on the situation. Governing mechanisms (instability) in the cases of pure hydrodynamic and electrohydrodynamic fragmentations are discussed.

1. Introduction

The disintegration of a liquid jet into droplets is a classic problem in fluid mechanics. Therefore, academic interest regarding liquid jet breakup and atomization can be dated back to as early as the 19th century, exemplified by the early works of Plateau (1873), Rayleigh (1879, 1945) and Chandrasekhar (1961). A rather recent comprehensive review of liquid jet breakup can be found in Lin and Reitz's work (1998).

The disintegration of liquid jets results in the formation of mono-dispersed droplets, which have numerous applications in droplet-on-demand processes, such as in ink-jet printers and microfluidic devices. In general, jet disintegrations and atomization into sprays have many instrumental applications in internal combustion engines, gas turbines, chemical reactors, oil–water separators, evaporative cooling systems, surface painting systems and powder production systems.

The spraying of a single melt jet leads to the production of metal particles in a controlled manner, which allows precise particle sizes and distributions to be achieved. Other methods, such as twin flow atomization (Metz et al., 2007) and centrifugal atomization (Eslamian, Rak, & Ashgriz, 2008), lead to the formation of poly-dispersed particles with different characteristics than those of the disintegration of the liquid jet. More information about spray-route powder production is available in an article by Eslamian and Ashgriz (2009).

The disintegration of a melt jet into water has also been used in nuclear science engineering. Dinh, Bui, Nourgaliev, Green, and Sehgal (1999) performed a systematic study of a jet breakup using various liquids to investigate the effects of the jet velocity, density ratio, melt and coolant viscosities, and heat transfer. In another study, Nishimura, Sugiyama, Kinoshita, Itagaki, and Ueda (2010) experimentally investigated the fragmentation of a molten copper jet penetrating in a sodium medium.

By applying electrostatic forces on an emerging jet from a nozzle in a well-controlled process, also known as electrohydrodynamic atomization (EHDA) or electrospray, the liquid jets with low flow rates (1–50 mg/h) (Jaworek, 2007; Gañan-Calvo, 1999) may be disintegrated into fine particles in various modes. For instance, in cone-jet mode, a thin jet emerges from the capillary, and it then breaks into charged particles. For a practical application, this process is used for producing metal particles known as liquid metal

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Nomenclature

A	area of the processed particle in the SEM images (m^2)
d	diameter (m)
p	perimeter of the processed particle in the SEM images (m)
Re	Reynolds number (–)
C_d	drag coefficient (–)
CR	roundness ratio of the processed particle in the SEM images = $4\pi A/p^2$ (–)
Oh	Ohnesorge number (–)
T	bulk temperature of fluid (°C)
u	velocity (m/s)
V	applied voltage between the nozzle and ring electrode (V)
We	Weber number (–)

Greek symbols

λ	dominant wavelength (m)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

0	initial state (before penetrating the oil)
a	ambient
j	melt jet
KH	Kelvin–Helmholtz
o	Surrounding oil
RT	Rayleigh–Taylor

ion sources (LMIS), and these nano-sized metal particles can be obtained at flow rates below 5×10^{-4} mg/s (Forbes, 2000). In a recent study, Shimasaki and Taniguchi (2011) proposed a new method for producing mono-sized metal particles by using intermittent electromagnetic pinch forces.

Generally, producing fine particles of a narrow size distribution and shape is desired. However, the size and shape of particles is a result of the breakup process. In addition, various parameters, such as the physical properties of the melt and the solidification conditions, affect the droplet formation characteristics, specifically the morphologies and sizes of the resultant particles.

The breakup and stability of a charged liquid jet have been investigated in several reports (Reneker & Yarin, 2008; Zhang, Liu, Yang, Hou, & Chan, 2009). Additionally, Son and Ohba (1998) performed an experimental observation and proposed an analytical model for two major modes of jet instabilities called as varicose and kink instabilities. While more recently, Riahi (2009, 2011) investigated the spatial stability of an electrically driven jet under various circumstances. In a previous study by our group (Esmaielzadeh Kandjani et al., 2010), a novel method was introduced for producing powder by both natural and electrostatic breakups of a penetrating melt jet into a viscous medium. However, this method cannot be categorized as an electrospray method due to the high flow rates used ($\sim$1 g/s) and because the melt jet is not driven by electrostatic force but rather broken up by electrostatic force.

The aim of the current study is to study the electrohydrodynamic-assisted fragmentation process of a melt jet and determine the effects of various parameters, such as the applied voltage and the viscosity and temperature of the viscous medium.

2. Methods and materials

2.1. Materials

The melt was formed using high-quality solder (a mixture of 40% Sn and 60% Pb) according to a procedure by Esmaielzadeh Kandjani et al. (2010). High-quality, pure silicone oil (Wacker) was used as the base fluid into which the melt jet impinged. Two kinds of silicone oil with different viscosities were selected for this purpose. The physical properties of the working fluids are listed in Table 1.

2.2. Experimental apparatus

The experimental setup, as shown in Fig. 1, consists of a crucible holding the melt at the desired temperature and an oil container. The melt crucible and nozzle were made of stainless steel, and inert gas was connected to the melt chamber with a controllable pressure valve. The temperature of the crucible and the pressure of the gas were controlled, and a high-voltage device was used for applying a voltage difference of up to +12 kV across the nozzle and the ground electrode, which was submerged in the oil. In this work, a circular pressure nozzle with an inner diameter of 250 μm was used as the high-voltage electrode, and a copper ring of 25 mm was used as the ground electrode.

2.3. Procedure

First, the applied voltage and the oil and melt temperatures were set to the desired values. Using inner gas pressure, the melt was forced out of the nozzle as a liquid jet. The nozzle was fixed above the oil chamber so the particles would push the oil into the viscous medium, and after which, the particles would break into fragments. Each experiment was conducted using two applied voltages (0 and 12 kV) and two oil temperatures (50 °C and 150 °C), which hereafter are referred to as “the low oil temperature” and “the high oil temperature”, respectively. Each experiment required approximately 30 s to produce enough powder for analysis. Additionally, the proper operation of the system was examined by capturing the scenes using a high-speed camera (Casio Exilim EXF1) and by weighing the powders produced to verify the constant flow rates. Once the experiments were complete, each powder was washed and dried. Further, morphology and structure analyses were conducted using SEM (Philips XL30) images; more than 150 individual particles were analyzed for each sample, and equivalent diameters, shapes and roundness ratios of each particle were obtained using an image process program developed in MATLAB.

3. Results and discussion

When a liquid is injected into another liquid, disintegration of the jet occurs because of the growing instabilities along the jet stream. In this study, the jets traveled a small distance in the air (10 mm), struck the liquid interface and then penetrated the silicone oil. This process ended with natural jet breakup, which left behind droplets and ligaments that solidified to form a wide range of sizes and shapes. By applying electrostatic force to the jet, the breakup process was significantly altered; therefore, the resulting droplets and particles were different. The amplitude and direction of the applied electrostatic force on the jet depended on the geometry and arrangement of the electrodes as well as the voltage difference and physical properties of the fluids. Here, the nozzle was connected to a high-voltage electric potential, and a ring was used as the ground electrode (see Fig. 1). The application of the electrostatic force triggers the disintegration of the jet in earlier stages compared to the natural jet breakup; this process is described in