Applied Mathematical Modelling 35 (2011) 1571–1580

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Formation of uniformly sized metal droplets from a capillary jet by electromagnetic force

S. Shimasaki *, S. Taniguchi

Graduate School of Environmental Studies, Tohoku University, Aoba-yama 6-6-02, Aoba-ku, Sendai 980-8579, Japan

ARTICLE INFO

Article history:
Received 14 September 2010
Accepted 21 September 2010
Available online 29 September 2010

Keywords:
Capillary jet
Breakup
Droplet formation
Metal particle
Electromagnetic force

ABSTRACT

A new method for producing uniformly sized metal droplets is proposed. In this method, an intermittent electromagnetic pinch force is applied to a capillary jet of liquid metal to generate fluctuations of equal interval on the surface of the jet. As the fluctuations grow, the liquid metal jet breaks into small droplets whose size depends on the frequency of the intermittent electromagnetic pinch force. The breakup of the capillary jet is numerically simulated by performing multiphase fluid flow analysis with surface tracking (volume of fluid method) and electromagnetic force analysis. The simulation results agree well with the results of model experiments. The jet breaks up into uniformly sized droplets when the frequency of the intermittent force equals the frequency that corresponds to the natural disturbance wavelength of the capillary jet.

1. Introduction

Capillary jet breakup and droplet formation are fundamental topics in fluid dynamics. For over a century, a great number of studies have investigated the mechanisms of these processes [1]. According to linear instability theory [2,3], capillary jet breakup is mainly governed by surface tension. Small perturbations of the optimal wavelength grow fastest and the droplet size is determined by the wavelength. Recently, many numerical simulations of capillary jet breakup have been performed that take advantage of the dramatic improvements in computational power and numerical techniques [4,5].

Droplet formation from a capillary jet is used in a broad range of industrial applications including ink jet printers, solder spheres, and fuel injection. Many techniques have been developed for metals to produce uniformly sized particles and small spheres [6–8]. Minemoto et al. proposed the jet-splitting method for fabricating uniformly sized spherical silicon particles with a diameter of 1 mm for spherical silicon solar cells [7]. This method employs a dropping furnace and a free-fall tower. In the dropping furnace, molten silicon is emitted from an orifice at the bottom of a crucible and forms a jet. This jet breaks up into droplets due to natural disturbance of the jet surface. The silicon droplets solidify in the free-fall tower and solid silicon particles collect at the bottom of the tower. However, it is difficult to fabricate uniformly sized silicon particles consistently by this method.

Our group has proposed a new method that increases the production rate and yield of silicon particles for spherical silicon solar cells [9,10]. In this method, an intermittent electromagnetic pinch force is applied to a molten metal jet. The electromagnetic force can be applied precisely to the jet and does not involve direct contact.

In the present study, model experiments are performed on capillary jet breakup and droplet formation by applying an electromagnetic force to a jet. Gallium is used as the liquid metal because it is very easy to handle due to its low melting

* Corresponding author.
E-mail address: shimasaki@mail.kankyo.tohoku.ac.jp (S. Shimasaki).

0307-904X/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.apm.2010.09.033

Nomenclature

A_0	initial perturbation amplitude
$\mathbf{B}$	magnetic flux density
d_0	nozzle diameter
f	frequency
$\mathbf{F}$	Lorentz force
$\mathbf{J}$	current density
k	turbulent energy
Oh	Ohnesorge number
p	pressure
r	radius
Re	Reynolds number
t	time
$\mathbf{v}$	velocity
v_0	mean axial velocity at nozzle exit
We	Weber number
z	distance from nozzle exit

Greek letter

α	volume fraction of fluid
γ	surface tension
ϵ	turbulent dissipation rate
κ	mean surface curvature
λ	wavelength
μ	viscosity
ρ	density
σ	electrical conductivity

Subscript

m	mixture
1	gas
2	liquid

point. The capillary jet breakup is numerically simulated; the simulation involves electromagnetic force analysis and multiphase flow analysis with surface tracking.

2. Experiments

Two experiments were performed: a single-pulse electromagnetic force experiment to confirm that a liquid metal jet can be broken up by applying an electromagnetic force and an intermittent electromagnetic force experiment to fabricate uniformly sized droplets from a capillary jet.

2.1. Single-pulse electromagnetic force

2.1.1. Experimental setup

Fig. 1 shows a schematic of the experimental setup. Molten gallium was heated and emitted from the nozzle with a mean axial jet velocity of 1.4 m/s. The circuit, which contains a fully charged capacitor, was shorted to apply a high instantaneous current to a single-turn coil through which the jet passes. The circuit capacitance could be set to 4.7, 10.0, or 14.7 mF; changing the capacitance altered the coil current. The experiment was performed in an argon atmosphere to prevent oxidation of the metal surface. Artem'ev and Kochetov [11] found that the breakup of a gallium jet was not affected by the surrounding gas when it had an oxygen concentration of less than 0.2–0.3%. Images of the jet surface were captured by a high-speed camera and the coil current was measured by a current probe. Fig. 2 shows the variation in the coil current with time. For a capacitance of 14.7 mF, a peak current of more than 7 kA was applied to the coil.

The mechanism for jet breakup induced by applying an electromagnetic force is as follows. The coil current induces a magnetic field around the coil and an eddy current in the liquid metal jet. The interaction between the magnetic field and the eddy current ($\mathbf{F} = \mathbf{J} \times \mathbf{B}$), generates a Lorentz force in the liquid metal. This force disturbs the fluid flow in the jet causing it to fluctuate; the liquid jet starts to breakup as the fluctuations grow in intensity.