Journal of Magnetism and Magnetic Materials 201 (1999) 306–309

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Dynamic behavior of a magnetic fluid jet injected from a vibrating nozzle

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Received 20 May 1998; received in revised form 8 September 1998

Abstract

This paper describes an experimental study of the dynamic behavior of magnetic fluid jets which are injected from a vibrating nozzle into the atmosphere. It was found that an intact liquid jet can be made to bifurcate continuously into a pronged jet by vibrating the nozzle with certain combinations of frequency and acceleration. The effects of the magnetic fields on the drops produced by the jet breakup are also revealed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Magnetic fluids; Jet breakup; Fluid vibration

1. Introduction

The capillary instability of a circular jet is of fundamental interest and importance with respect to a variety of applications. Rayleigh first showed from a linearized stability analysis that only axisymmetrical surface disturbances with wavelengths greater than the circumference of the jet would grow. Liquid atomization is a process of breaking up a jet into droplets of diameter much smaller than the jet diameter. Many experimental and theoretical works have been done on the process of breaking up a jet into droplets [1]. In spite of many investigations, there is no study on the dynamic behavior and the breakup of magnetic fluid jet.

In this paper we present experimental results of the dynamic behavior of a magnetic fluid jet which is injected from a vibrating nozzle into the atmosphere.

2. Experimental apparatus and procedures

Fig. 1 shows a schematic diagram of the experimental apparatus. The experimental apparatus consisted of the liquid injection system, nozzle vibration system, and photograph system [2]. The liquid injection system allowed the test liquid to be injected vertically into stagnant air. The outlet inner diameter of the nozzle is 0.52 mm. The test liquid from the liquid reservoir is passed through the nozzle, and is collected in a flask directly below the nozzle. The jet was subjected to externally applied vibrations at a given frequency and acceleration

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PII: S0304-8853(99)00028-1

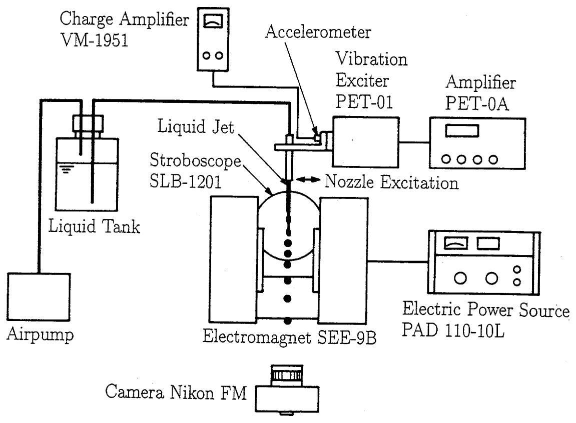

Fig. 1. Schematic diagram of the experimental apparatus.

using a small electrodynamic shaker. High speed photographic technic was also employed in order to understand the wave interaction on the surface of the jet. Test of magnetic fluid jets are conducted under the applied magnetic field by using the water-cooled electromagnet. The magnetic fluid used in this experiment was water-based ferricolloid W-35.

3. Experimental results and discussion

3.1. *Capillary instability of liquid jets*

Rayleigh analyzed the instability of a circular cylindrical jet of imcompressible inviscid fluid in air, and found that axisymmetric spatially harmonic disturbances of the radius r of the form:

$$r = 1 + \varepsilon \exp(\beta t - \mathrm{i}kx) \tag{1}$$

grow in time according to

$$\beta = \left(\frac{8\sigma}{\rho_\ell d_0^3}\right)^{1/2} \left[\frac{k(1-k^2)I_1(k)}{I_0(k)}\right]^{1/2} \tag{2}$$

in which ρ_ℓ, d_0, σ and I's are, respectively, the density, initial jet diameter, surface tension, and the modified Bessel functions [1]. Length and time variables have been nondimensionalized by radius $d_0/2$ and $d_0/2v_c$, where v_c is the capillary–wave velocity $(2\sigma/\rho_\ell d_0)^{1/2}$. This result predicts that disturbances are unstable or stable according to the wave number $k < 1$ or $k > 1$. Rayleigh found the wavelength of maximum instability to be [3]

$$\lambda = \frac{2\pi}{k} = 4.508 d_0. \tag{3}$$

For a given value of $k < 1$, this analysis would predict jet breakup when $\varepsilon \exp(\beta t) = 1$.

By vibrating the nozzle, there is the possibility of forcibly generating resonant waves on the surface of the liquid jet, i.e. the atomization process would be expedited. Since magnetic fluid droplets are very sensitive to magnetic fields, there is also the possibility of controlling the shape through applied magnetic fields.

3.2. *Effect of nozzle vibration*

The capillary instability of vertical jets of magnetic fluid was examined by imposing external mechanical vibrations. Fig. 2 shows some aspects of the magnetic fluid jets at various excitation frequencies. In Fig. 2, f_0 is the excitation frequency, and G_0 is the dimensionless excitation acceleration defined by the following equation:

$$G_0 = \frac{X_0 \omega^2}{g}, \tag{4}$$

where X_0 is the excitation amplitude, and ω is the angular frequency ($\omega = 2\pi f_0$). It can be seen that magnetic fluid jets are corrugated by external mechanical vibration. The wavelength λ_m of the nonaxisymmetric surface wave is given by liquid jet velocity U_ℓ and excitation frequency f_0:

$$\lambda_m = \frac{U_\ell}{f_0}. \tag{5}$$

The wavelength of capillary axisymmetric instability at $G_0 = 0$ is nearly in agreement with Eq. (3). The dominant wavelength on the liquid surface depends on the excitation acceleration G_0. Both λ and λ_m are recognized in a magnetic fluid jet at $f_0 = 40$ Hz in Fig. 2. Fig. 3 shows the observed wavelength of the nonaxisymmetric waves for magnetic liquid jets. A curved line shows Eq. (5). In Fig. 2, the dominant wavelength in the region of

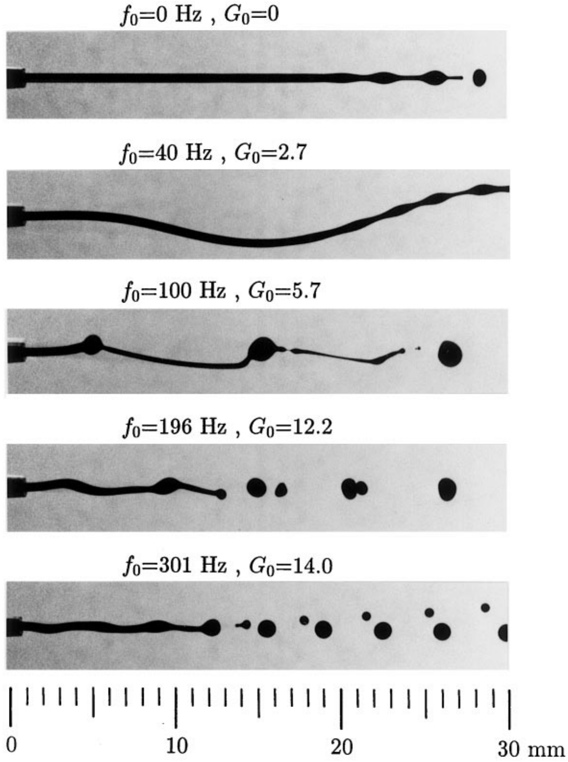

Fig. 2. Stroboscope photographs of magnetic fluid jets.

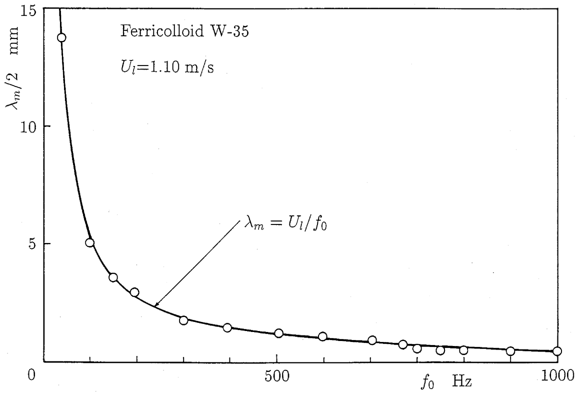

Fig. 3. Observed wavelength of the nonaxisymmetric waves.

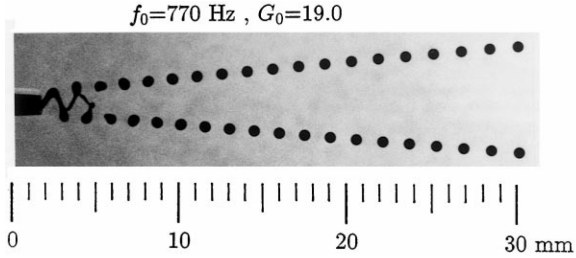

Fig. 4. Stroboscope photograph of the branching magnetic fluid jet.

$f_0 \geqslant 100$ Hz is λ_m, because the excitation acceleration is relatively high. As the excitation frequency of the nozzle increased slowly from zero at a certain excitation acceleration, the intact jet suddenly forked into branches. The experimental results showed that an intact liquid jet can be made to bifurcate continuously into a pronged jet by oscillating the nozzle at right angles to its axis with certain combinations of frequency and acceleration. It was found from stroboscope photographs, that the observed multiple-pronged jet was actually multiple streams of drops after the jet disintegration generated by the nozzle vibration. Fig. 4 shows the stroboscope photographs of magnetic fluid jet. The nozzle vibration produces uniform-size drops. The bifurcation area of the liquid jets was investigated on the excitation frequency-acceleration diagram. The experimental results showed that magnetic fluid jet can be made to bifurcate easily in the neighbourhood of

$$f_0 = \frac{U_0}{n\lambda}, \tag{6}$$

where n is the positive integers. Eq. (6) corresponds to the resonance of the nozzle–jet system. Especially beautiful bifurcation was obtained when $n = 2$.

3.3. *Effects of applied magnetic fields*

Some tests are conducted under the applied magnetic fields by using a water-cooled electromagnet as shown in Fig. 1. The direction of the applied magnetic fields is parallel to the vibrated direction. Fig. 5 shows a stroboscopic photograph of magnetic fluid jet under applied magnetic fields. In Fig. 5, I is the electric current corresponding to the magnetic field strength. It can be seen that the surface disturbance on fluid jet has a step-like shape in the applied fields. The swell portion of the jet is distorted into square-like shape, and the neck

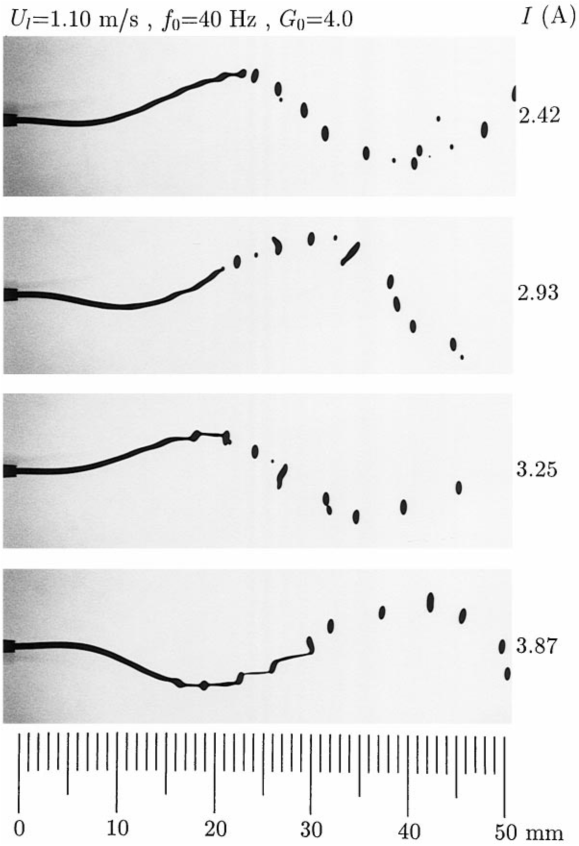

Fig. 5. Stroboscope photographs of magnetic jets under magnetic fields.

portion of the jet is elongated by applying a field. Magnetic liquid droplets are also elongated in the applied fields. The drop shape can be obtained by a minimization of energy. This problem was considered theoretically by the authors in the previous paper [4]. The drop elongation increases with the magnetic field strength. The magnetized drops interact with each other and they coalesce when they form a line in the direction of the magnetic field. However, the coalescence does not occur when the bifurcation angle is wider. In such case, vertical drops interact with each other, that is, they repulse each other. Fig. 6 shows that fact. The distance S_d, between vertical drops increases with the magnetic field strength. The falling velocity of drops is accelerated because the magnetic force acts on the drops in addition to the gravity.

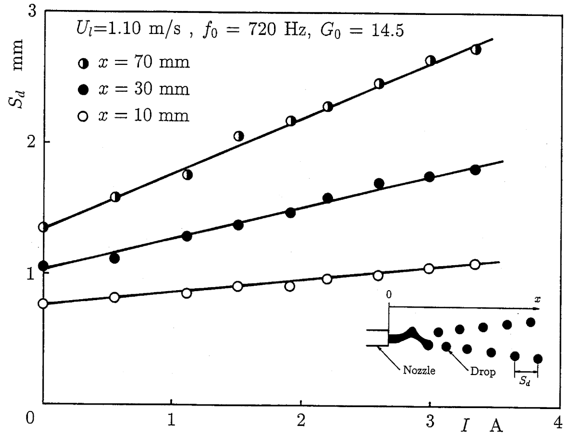

Fig. 6. Variation of the distance S_d by magnetic fields.

4. Conclusions

1. An intact magnetic fluid jet can be made to bifurcate continuously into a pronged jet by vibrating the nozzle sinusoidally in a lateral direction to its axis with certain combination of frequency and acceleration. The observed pronged jet is actually composed of streams of drops produced by the jet breakup generated by the nozzle oscillation.
2. The bifurcation of the magnetic fluid jets occurs easily in the neighbourhood of the resonance range of the nozzle-jet system. Especially beautiful bifurcation occurs when $\lambda_m \approx 2\lambda$.
3. The surface disturbance on magnetic fluid jet shows a step-like shape in the applied fields. The neck portion of the jet is elongated in the applied fields. The liquid drops which disintegrate from the magnetic jet are also elongated, and the magnetized drops interact with each other.

References

[1] D.B. Bogy, Annu. Rev. Fluid Mech. 11 (1979) 228.
[2] S. Sudo, T. Ikohagi, K. Katagiri, Proc. Int. Conf. Fluid Eng. 1 (1997) 269.
[3] H. Lamb, Hydrodynamics, Dover, New York, 1945, p. 1.
[4] S. Sudo, H. Hashimoto, A. Ikeda, JSME Int. J. 32 (1989) 47.