AN EXPERIMENTAL STUDY OF THE BREAKUP OF A JET OF VISCOUS LIQUID IN A GAS FLOW

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Breakup of one jet in another jet incident at right angles is of interest in relation to the production of staple silicate fiber (glass and slag cotton). The problem has been examined theoretically for an ideal fluid [1] by the method of small perturbations applied to the growth of tangential waves that split the jet into longitudinal filaments. The critical values of the Weber number were calculated for the neutral oscillations corresponding to the stability limit.

It is of interest to examine by experiment a jet of viscous liquid, especially the relation of filament diameter to the properties of the liquid and to the parameters of the gas jet.

The experiments were done with melts of a resin based on abietic acid $H_{19}C_{29}COOH$ and of blast-furnace slag, which behave as Newtonian liquids whose viscosity μ, surface tension σ, and density ρ_2 are dependent on the temperature T.

Use of melts instead of ordinary liquids provided evidence on jet breakup directly from the shape of the particles. Calculations indicate that most of the melt fragments cool to the solid state in 10^{-4} to 10^{-5} sec, which stabilizes their form, which can thus be used to characterize the breakup quantitatively.

The average density of the slag melt was 2.5 times that of the resin melt, while the surface tension was higher by a factor of 10-13, and the viscosities were similar. The required temperatures were produced in laboratory electric furnaces and were monitored to 1° C with Pt/Pt-Rh and copper-constantan thermocouples. The required diameter in the melt jet was produced by adjustment of nozzle diameter and melt viscosity (temperature). The resin jets had diameters in the range 0.6-2 mm, and the slag jets 2-8 mm. The viscosities at the instant of encounter ranged from 0.008 to 0.7 kg-sec/m^2. The air jets were produced by nozzles with diameters of 3 and 5 mm with lengths of 30 mm, the excess pressure in the reservoir ranging from $2 \cdot 10^3$ to $4.5 \cdot 10^4$ kg/m^2, which corresponded to calculated velocities at the end of the nozzle between 400 and 506 m/sec. In certain instances the excess pressure was $15 \cdot 10^4$ kg/m^2, in which case the calculated velocity was 587 m/sec. The experiments were carried out as follows.

The liquid jet emerged from a nozzle at the bottom of a vessel 50-100 mm high and within 7-15 mm encountered the free horizontal air jet at the middle third of the initial part of the jet, and in any case fell into the constant-velocity core. The flow speed of the melt jet was low (up to 0.5 m/sec) relative to the gas jet and was not taken into account.

On meeting the air jet, the melt jet broke up, and the resulting particles were thrown into a collecting box after solidifying in the suspended state. The products were fibers, spheres, toroids, droplets, and irregular particles, the precise composition being dependent on the properties of the melt and on the air speed.

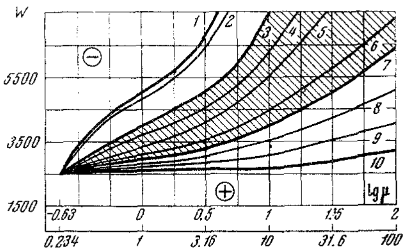

Fig. 1

The fiber diameter was measured with a microscope at ×300, the mean diameter being reckoned as the arithmetic mean of 100 measurements. Mean diameters have been published [2, 3] for glass wool made in this way and calculated in this fashion in accordance with GOST 4640-61 (slag cotton). The maximum deviation of the diameter from the mean was 400-500%, but at least 80% of the fibers differed from the mean by not more than ±30%. The proportion of nonfibrous inclusions by weight was determined by sieving, while the sizes were determined with sieves and under the microscope.

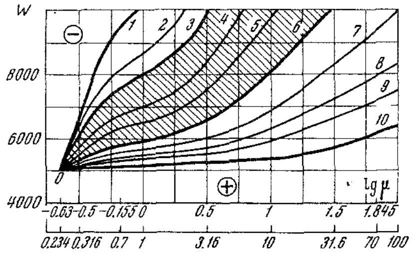

Fig. 2

The jet splits up in three ways: 1) into small drops and flakes, 2) into fibers, 3) into large irregular particles. The precise behavior is dependent on the ratio of air-jet diameter d and melt diameter d_2, as well as on the distance to the point where the melt met the air jet. If d/d_2 exceeded a certain value, this ratio ceased to have any appreciable effect. In general, this ratio may be expressed via the ratio of the mass flow rates G_1/G_2; if this exceeds 1.3, the mode of breakup is not dependent on the ratio. The results given below correspond to this condition.

The distance of the melt from the air nozzle affected the mode of breakup only if this distance exceeded 2/3 of the initial length of the air jet, when fewer fibers were formed, and droplets predominated. The results below relate to entry at the middle third of that part.

The following equation describes the breakup:

$$W = \frac{16.65 \cdot 10^3 d_2}{\sigma} + \frac{2\pi \cdot 10^{-3}}{\sqrt{\sigma^3}} \frac{d_2}{d^\circ} [1 + 2.2 (\lg 100\mu)^{1.7}],$$

$$\left(W = \frac{\rho_1 v_1^2 d_2}{\sigma}\right), \tag{1}$$

in which W is Weber's criterion, ρ_1 is the density of the air, v_1 is the calculated air speed at the exit from the nozzle, d° is the diameter of the fibers, and μ is the dynamic viscosity of the liquid. All quantities are expressed in the MKS system.

As for breakup of a drop in a gas flow [4], there are critical conditions. If

$$\frac{d_2}{d^\circ} = \frac{(\sigma W - 16.65 \cdot 10^3 d_2)\sqrt{\sigma}}{2\pi \cdot 10^{-3} [1 + 2.2 (\lg 100\mu)^{1.7}]} \geqslant$$

$$\geqslant 10^3 (0.15 \cdot 10^{-3} + d_2) \left(\frac{2\pi\sigma}{E}\right)^{1/2}, \tag{2}$$

a spray is formed.

If d_2/d° lies within the limits

$$10^3 (0.15 \cdot 10^{-3} + d_2) \left(\frac{2\pi\sigma^2}{E^2}\right)^{1/4} \leqslant \frac{d_2}{d^\circ} =$$

$$= \frac{(\sigma W - 16.65 \cdot 10^3 d_2)\sqrt{\sigma}}{2\pi \cdot 10^{-3} [1 + 2.2 (\lg 100\mu)^{1.7}]} \leqslant$$

$$\leqslant 10^3 (0.15 \cdot 10^{-3} + d_2) \left(\frac{2\pi\sigma}{E}\right)^{1/2}, \tag{3}$$

we have the region of transition from spray to fibers.

If d_2/d° lies within the limits

$$10^3(0.15\cdot 10^{-3}+d_2)\left(\frac{40\pi\sigma^{3/2}}{E}\right)^{1/3}\leqslant$$

$$\leqslant\frac{d_2}{d^\circ}\leqslant 10^3(0.15\cdot 10^{-3}+d_2)\left(\frac{2\pi\sigma^2}{E^2}\right)^{1/4}, \tag{4}$$

the liquid breaks up mainly into fibers, which under isothermal conditions (viscosity remaining constant at the initial value) then break up into droplets.

If d_2/d° lies within the limits

$$10^3(0.15\cdot 10^{-3}+d_2)\left(\frac{20\pi\sigma}{E^{1/3}}\right)^{1/2}\leqslant$$

$$\leqslant\frac{d_2}{d^\circ}\leqslant 10^3(0.15\cdot 10^{-3}+d_2)\left(\frac{40\pi\sigma^{3/2}}{E}\right)^{1/3}, \tag{5}$$

we have the region of transition from fibers to a stable jet or brittle fracture. The jet is stable if

$$d_2/d^\circ\geqslant 10^3(0.15\cdot 10^{-3}+d_2)\sqrt{20\pi\sigma/E^{1/3}}, \tag{6}$$

in which $E(\approx 10^{-6})$ is the energy needed to produce a new surface.

Figure 1 illustrates the breakup of a slag melt in relation to W and μ (Poise) for d_2 = 6 mm and σ = 0.045 kg/m.

Figure 2 shows the same relations for a resin melt at d_2 = 1.2 mm and σ = 0.004 kg/m.

The symbol (−) indicates the spraying region, while the symbol (+) indicates the stability region. Each curve corresponds to a certain fiber diameter, which for curves 1–10 of Fig. 1 are (in μm) as follows: 1.85, 2.0, 3.1, 4.0, 5.0, 8.0, 10, 15, 25, 61; similarly, in Fig. 2, they are 5.63, 8, 10, 15, 20, 32, 50, 75, 100, and 200.

Curves 1 satisfy the condition of (2), the spraying region lying to the left. The region between curves 1 and 3 corresponds to condition (3). Between curves 3 and 7 (Fig. 1) or 6 (Fig. 2) we have the region corresponding to (4), and fibers are produced most stably in this region.

The zone of preferential fiber production becomes wider as μ increases and largely vanishes for μ = 0.00234 kg-sec/m^2, so such a liquid breaks up into drops without forming fibers, or else the latter exist for less than the solidification time.

Between curves 7 (Fig. 1) or 6 (Fig. 2) and curve 10 we have region (5), where thick fibers or large drops are formed. Below curve 10 we have the stable region described by (6).

Figures 1 and 2 do not show the experimental points, as these would unduly confuse the figure. Over 300 separate runs were compared with (1) in conjunction with (3)–(5); the maximum deviations were ±12%, which were satisfactory.

Condition (2) gives the minimum fiber size that can be produced in this way as

$$d^\circ_{\min}=\frac{2\pi\cdot 10^{-3}d_2[1+2.2(\lg 100\mu)^{1.7}]}{(\sigma W-16.65\cdot 10^3 d_0)\sqrt{\sigma}}\geqslant$$

$$\geqslant\frac{d_2}{10^3(0.15\cdot 10^{-3}+d_2)}\left(\frac{E}{2\pi\sigma}\right)^{1/2}. \tag{7}$$

The mean minimum diameter is thus dependent only on σ and d_2. Calculations from (7) agree well with the results for resin and slag (discrepancy not exceeding 8%). Only spray was produced in repeated attempts to obtain smaller diameters by increasing the gas speed or reducing the viscosity of the liquid.

The mean fiber diameter can be deduced from (1), but the equation is inconvenient for practical purposes in the production of staple slag cotton.

The speed at the exit from the nozzle is dependent on the pressure, so some simplification is possible by expressing the fiber diameter in terms of the pressure. If (3)–(5) are met, d° is given by

$$d^\circ=\frac{d_2}{0.15\cdot 10^{-3}+d_2}\left[1+0.1\left(\frac{G_2}{G_1}\right)^5\right]\left(\frac{\mu E}{\sigma P}\right)^{1/2}, \tag{8}$$

in which P is the excess air pressure. This shows that G_1/G_2 ceases to have any appreciable effect if its value exceeds 1.3. Results from (8) differ from those from (1) by not more than ±5%, which arises from the simplifications in transforming (1). Experimental values deviate from those given by (8) by not more than ±17%. Calculations from (8) agree well with published results for silicate melts [2,3], and again the discrepancies do not exceed ±17%.

Equations (1) and (8) do not involve the density of the liquid, although this varied by a factor 2.5 with the present materials (120 to 280 kg-sec^2/m^4).

There is a marked effect from the speed of the liquid when it meets the air jet; speeds greater than 1.5–2.0 m/sec cause fiber production to cease, and the jet breaks up mainly into drops. It has been shown [5] by high-speed photography that filaments can be formed in the breakup of liquid jets.

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