4. Conclusion

The author measured the thermal conductivity by using a revolving ring. This method has the following advantages:

1. We need not measure the heat quantity in heating and dissipating.
2. The value of coefficient of heat-transfer which is included in the analytical equation of temperature distribution is not changeable with the temperature variation.
3. The method based on experiments of two peripheral velocities saves us the trouble to use a standard material and the thermal conductivity can be obtained directly from the experimental results.

The method leaves much to be improved in its details, but it can be considered available for the measurement of the thermal conductivity of any metal.

In closing the author wishes to express his hearty gratitude to Prof. T. Kato and Prof. M. Tsuyama for their kind guidance.

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Atomization of Liquid by Means of a Rotating Nozzle
(On the Disintegration Modes and Droplet Sizes) *

By Tosio Kurabayashi **

In order to clarify the fundamental characteristics of liquid atomization by means of a rotating nozzle, the behaviours of a water jet were observed by high speed photography, and on the other hand investigations of the variation of sizes of droplets produced from the jet were made, varying the atomization conditions with the nozzle diameter from 0.4 to 1.2 mm, the rotating diameter from 10 to 20 cm and the flow rate from 0.1 to 6 cm³/sec. It was found that the modes of disintegration were divided into five typical forms, and that each of them showed its own characteristic in the variation of droplet sizes. Detailed considerations are made on them. Finally the maximum diameter of the droplets was compared with the mean diameter.

1. Introduction

For the centrifugal atomizer two methods are available: one is a rotating cup or disk, and the other is a rotating nozzle. On the former there has been done a considerable amount of research work, but, on the latter, little information has been published to date.

The liquid jet issuing from a rotating nozzle is characterized by the following:

(a) High pressure is easily produced in the liquid by the effect of centrifugal force, which sometimes renders the pressure pump unnecessary.
(b) Since every part of the jet can be in contact with the ambient fresh air, evaporation or combustion is promoted.
(c) Good atomization may be maintained.

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throughout a wide range of operation.

As the first step to a systematical study of this atomization, observations of jet appearances and investigations of droplet sizes with some atomization conditions varied are made in this paper.

2. Experimental apparatus

In the present experiments, vessels with one hole on their side walls were used as shown in Fig. 1. Fig. 2 shows the schematic diagram of the apparatus for taking photographs of behaviours of the jet.

In order to determine the degree of spray fineness, liquid particles which are caught into a layer of oil covering the slide glass, were photographed and counted.

The experiments were carried out with water using the nozzle diameter $D_n=0.4-1.2$ mm, the rotating diameter $D_r=10, 16.8$ and $20$ cm and the flow rate $q=0.1-6$ cm$^3$/sec. The length of the nozzle was $9$ mm.

3. Relations between modes of atomization and droplet sizes

After leaving the nozzle, every part of liquid travels with a relative velocity $v=\sqrt{v_0^2+v_p^2}$ into the ambient air, where $v_0$ is the discharge velocity of liquid from the nozzle and $v_p$ is the peripheral one. Hence this velocity $v$ may have an important bearing on the process of atomization.

Fig. 3 represents a series of typical forms of liquid jets with the relative velocity gradually increased. From an inspection of these photographs the modes of atomization can be divided into the following five main types:

(1) Dripping
(2) Smooth jet
(3) Wavy jet
(4) Partially sprayed jet
(5) Spray

This classification is, however, based not only on the appearances of jets, but also, as shown below, on their own characteristics of disintegration mechanisms and the sizes of droplets produced from the jets.

Figs. 4 and 5 represent the Sauter mean diameter $d$ plotted against the relative velocity $v$ for various values of the flow rate $q$. In these figures the values of $d$ do not decrease monotonously with increasing values of $v$, but they form several stages with different characteristics.

From the photographs of the jets, it is found that the stage marked by 1 in these figures corresponds to the dripping, the one marked by 2 to the smooth jet, the one marked by 3 to the wavy jet, the one marked by 4 to the partially sprayed jet and the one marked by 5 to the spray. Hence it is important to know to which stage the type of a jet belongs when we discuss about the size of droplets.

The detailed characteristic of every stage is considered in the following sections.

3-1 Dripping

Before a droplet is flung away, the liquid spreads itself over a certain extent of the surface around the nozzle. If this area remains constant, sizes of droplets should be proportional to the value of $v^{-2/3}$. In practice, however, this area changes with the speed of rotation, so that it can not be determined precisely. It is, therefore, difficult to give any general formula for sizes of droplets.

3-2 Smooth jet

When the speed of rotation exceeds a certain value, the liquid begins to form a transparent cylindrical column with a smooth surface. This transition is also unstable by the same reason mentioned in dripping.

As shown in Fig. 3 (b) to (d), the appearance
Fig. 3 Typical modes of atomization
of the smooth jet is like that discharged from a fixed nozzle, and liquid particles are torn off from the tip of the column through rotationally symmetrical oscillation. Sometimes the length of a continuous jet is shortened with an increase of speed, as shown in Fig. 3 (d), because the liquid column becomes finer and unstable.

The decrease of $d$ in this region becomes suddenly heavy. This may be due to the fact that the speed of rotation makes a relatively smaller contribution to the thickness of a liquid column which has close relation to the droplet sizes.

### 3-3 Wavy jet

With further increase in speed of rotation, irregular deformations are caused on the surface by the disturbances in the liquid and the action of air forces. The effect of the former, however, may be small as compared with the latter, because, for instance, the Reynolds number $Re=\frac{(D_s u_0)}{\nu}$ for Fig. 3 (f) is 1,400 which belongs to the region of laminar flow, where $\nu$ is the kinematic viscosity of the water.

The break-up of the wavy jet occurs at irregular portions on it and the difference between main and successive drops disappears.

In this region the value of $d$ depends on such factors as the discharge velocity $u_0$(m/sec), the rotating diameter of the nozzle $D_r$(cm), the

![Fig. 4 Variation of mean diameter against the resultant velocity](image1)

![Fig. 5 Variation of mean diameter against the resultant velocity](image2)

![Fig. 6 Mean diameter against $\kappa$ in the region of wavy jet](image3)

![Fig. 7 Chain-like deformation producing uniform drops](image4)
diameter of the nozzle \( D_a \) (mm) and the resultant velocity \( \nu \) (m/sec), and the plotting of \( \ddot{d} \) against the term \( \kappa = \sqrt{D_a} (v_0 \sqrt{D_r})^{0.4}/\nu \) makes a straight line as shown in Fig. 6. Then an empirical formula is derived for water as

\[
\ddot{d} = 4.300 \sqrt{D_a} (v_0 \sqrt{D_r})^{0.4}/\nu
\]

Fig. 7 shows a particular jet with fine and regular deformations. An inspection of this figure reveals that the successive deformations are displaced by 90 degree in the form of chains, from the tip of which uniform drops are produced regularly.

3.4 Partially sprayed jet

As the speed is further increased, the crests of the roughened surface are pulled out to form ligaments by the negative pressure due to the high speed air stream and the big knobs begin to form bag-like thin membranes (Fig. 8).

Disruption resulting from these deformations is a secondary one, compared with the simple tearing-off of a liquid thread at the lower speed. It takes place, in the beginning, locally on the jet, and with increasing speed, gradually spreads itself, finally covering the whole jet. Hence we call the jet locally accompanied by such secondary disruption a partially sprayed jet, and when the whole jet is covered we call it a spray.

In this region, as the influences of the factors such as the vibration of the apparatus, the shape of the nozzle and the roughness of the nozzle surface on the drop formation, are quite indeterminable, it is difficult to derive a general formula for the variation of \( \ddot{d} \). We can only see that, with

\[D_r = 16.8 \text{ cm}, \quad D_a = 0.6 \text{ mm}, \quad \nu = 2 \text{ cm}^3/\text{sec}, \quad n = 2400 \text{ r.p.m.,} \quad v = 22.0 \text{ m/sec}\]

Fig. 8 Partially sprayed jet accompanied by ligament and filmy deformation

\[D_r = 16.8 \text{ cm}, \quad D_a = 0.6 \text{ mm}, \quad \nu = 2 \text{ cm}^3/\text{sec}, \quad n = 2750 \text{ r.p.m.}, \quad v = 25.6 \text{ m/sec}\]

Fig. 9 Spray

\[D_r = 16.8 \text{ cm}, \quad D_a = 0.6 \text{ mm}, \quad \nu = 4 \text{ cm}^3/\text{sec}, \quad n = 6000 \text{ r.p.m.,} \quad v = 54.7 \text{ m/sec}\]

Fig. 10 Longitudinal disruption of a liquid column

Fig. 11 Process of longitudinal disruption

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increasing flow rate \( q \), the value of \( \bar{d} \) increases, and that the transition point to the spray shifts towards the velocity of higher value.

3.5 Spray

In regard to the spray, the energy of its relative velocity to the surrounding air becomes large enough to smash the liquid jet immediately after leaving the nozzle, so that it cannot form a compact continuous thread.

In the transition from a partially sprayed jet to a spray there is no distinct, critical point as shown in Fig. 3 (a).

Fig. 9 shows another photograph of the spray.

In this region the contribution of variables such as \( D_r \), \( D_n \) and \( q \) to the droplet sizes becomes negligibly small. This may be due to non-existence of a compact liquid column. Then the expression for \( \bar{d} (\mu) \) against the resultant velocity \( v \) (m/sec) is simply obtained for water as

\[
\bar{d} = 1.26 \times 10^{1.13} v^{0.13}
\]

As the speed of rotation \( n \) (r.p.m.) is relatively high in the case of spray, the value of \( v \) becomes nearly equal to the peripheral velocity of the nozzle \( v_p \). Hence Eq. (2) may be written as follows:

\[
\bar{d} = 7.9 \times 10^{1.13} (D_r \cdot n)^{0.13}
\]

where \( D_r \) (cm) is a rotating diameter of the nozzle.

The longitudinal disruption of a liquid column sometimes takes place as shown in Fig. 10. Fig. 11 indicates the developing procedure of this phenomenon schematically.

4. Maximum droplet diameter

Fig. 12 shows one of the diagrams representing the relationship between the maximum diameter \( d_{\text{max}} \) and the mean diameter \( \bar{d} \) (shown by dotted or chain lines). An inspection of this figure gives the following relation in a range of relatively high speeds:

\[
d_{\text{max}} \approx 2\bar{d}
\]

5. Conclusions

The results attained may be summarized as follows:

1. Atomization of a liquid issuing from a rotating nozzle goes successively through the following five typical modes: (1) dripping, (2) smooth jet, (3) wavy jet, (4) partially sprayed jet and (5) spray.

2. Each mode has its own characteristic in variation of droplet sizes, say S.M.D. \( \bar{d} \), against the resultant velocity \( v \) (Figs. 4 and 5).

3. Formulae for \( \bar{d} \) are derived, in the case of water, as Eq. (1) for the region of wavy jet and as Eq. (2) or (2)' for the spray.

4. Variations of the maximum diameter \( d_{\text{max}} \) have almost the same tendencies as those of \( \bar{d} \) and the following relation is found,

\[
d_{\text{max}} \approx 2\bar{d}
\]

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