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Atomization of the Liquid Injected into the Air Current in Tubes (II)  
(Droplet Size and Droplet Size Distribution)  
by  
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(Received September 8, 1971)  

1. Introduction  
Injection of liquid into an air current in a tube for transportation or mixing has been applied widely in the fields of mechanical and chemical engineering. However, problems which always arise in such cases are atomization of liquid by means of air current, size of the liquid droplets which pass through and the condition of adherence to the tube wall. However, there are very few reports on these and particularly, information on investigation in low-speed air current cannot be found. In the previous paper, the authors made clear the condition of liquid adherence on tube wall, atomizing rate and characteristics of atomization when liquid is injected at right angles into a low-speed air current and in this paper, the effects of air current velocity, quantity of injected liquid, tube length and nozzle diameter on size of droplets which pass out of the tube end and droplet size distribution were investigated with an experiment using warm water having the same viscosity coefficient as that of gasoline.

2. Test Equipment and Method  
Fig. 1 shows the equipment. This is the same as that used in Report (I) and consequently, only the necessary parts will be explained here. Air blown in by means of the blower is sent to the measuring tube 20 by way of surge tank, control valve and rectifying tube. Brass tubes were used for tube 20 for measurement and glass tubes for observation, the inside diameter of these was 28.5 mm and 7 lengths from 100 mm to 700 mm in increments of 100 mm were used. The liquid was preheated in
Fig. 2 Shutter equipment and liquid droplet catching equipment

Fig. 3 Rotary disk

A tank, introduced into the head tank by way of control cock and injected into the air current from a nozzle attached to a holder. A part of the liquid which comes out of the nozzle adheres to the inside wall of the measuring tube, flows along the wall and flows out from the tube end while the balance flows out from the tube end in the form of suspended droplets. The end of the nozzle was fixed concentric with the measuring tube which is placed in a horizontal position and the injection flow rate was adjusted with a screw located below the head tank. The droplets which have been caught were investigated by placing a shutter apparatus and a droplet catching apparatus shown in Fig. 2 at the end of tube 20 and the droplet size and droplet size distribution were obtained. That is, a rotary disc 23 shown in Fig. 3 was placed in the passageway of the injection stream and the intermittent injection flow produced by the slit was blown on the oil for catching on glass plate 23, and photographed quickly with the photography apparatus 25. 21 is an injection current chopper and 24 is speed reduction device for changing the revolution of the disc. Special care was taken regarding exposure time and optical cleanliness when photographing the droplets which have been caught. The number of droplets measured differs in accordance with the average droplet size but this was 4~1000 droplets per sample and the magnification of the photo was 10 times in case of low wind velocity and large droplet size and 20 times in case of high wind velocity and small droplet size. Also, a rubber ring (15 mm diameter, 1~5 mm thick) shown in Fig. 2 was attached to the glass plate for droplet size measurement for maintaining the depth of the catching oil. Silicone oil was used for the catching oil.

The ranges of the experiment were nozzle flow quantity $Q_n = 0 \sim 1 \text{ cm}^3/\text{s}$, nozzle diameter $D_n = 0.7 \sim 1.5 \text{ mm}$, nozzle projection $l = (0 \sim 3/4)D_n$, and air current velocity $v_n = 0 \sim 35 \text{ m/s}$.

3. Calculation Equations for Average Droplet Size

Fig. 4 Method of showing average droplet size
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Preciously the efficiency of atomization was compared with a droplet number-diameter curve but the theoretical basis for this is inadequate and particularly, it is inconvenient for indicating efficiency numerically. Let us assume that droplets of different sizes shown in Fig. 4 (A) are averaged into droplets with uniform droplet size \( \bar{d} \) as shown in (B).

The average droplet size \( \bar{d} \) in case

1. Of the ordinary meaning in which the number of droplets in (A) and (B) are equal and the sum totals of diameter \( d \) are equal, that is,

\[
\bar{d} = \frac{\sum x \cdot d_n}{\sum d_n} \tag{1}
\]

where it is assumed that there are \( d \), droplets of \( x \) diameter in (A).

2. The number of droplets are equal and the sum totals of the surface area are equal,

\[
\bar{d} = \left( \frac{\sum x^2 \cdot d_n}{\sum d_n} \right)^{1/2} \tag{2}
\]

3. The number of droplets are equal and the sum totals of the volume are equal,

\[
\bar{d} = \left( \frac{\sum x^3 \cdot d_n}{\sum d_n} \right)^{1/3} \tag{3}
\]

4. The sum totals of the diameters and sum totals of surface areas are equal,

\[
\bar{d} = \frac{\sum x \cdot d_n}{\sum x \cdot d_n} \tag{4}
\]

5. The sum totals of the diameters and the sum totals of volumes are equal,

\[
\bar{d} = \left( \frac{\sum x^3 \cdot d_n}{\sum d_n} \right)^{1/2} \tag{5}
\]

6. The sum totals of the surface areas and the sum totals of volume are equal,

\[
\bar{d} = \frac{\sum x^3 \cdot d_n}{\sum x^2 \cdot d_n} \tag{6}
\]

This equation is so-called Sauter's average diameter equations. The above 6 equations can be considered but as it can be assumed that the selection of the average droplet size \( \bar{d} \) depends on the objective; the efficiency of atomization generally depends on the large droplets in the injected quantity; although a large number of small droplets are present atomization becomes poor if some large droplets are mixed; and the number of droplets being equal in (A) and (B) is meaningless, it can be said that when the actual requirement of combustion is taken into consideration, Eq. (6) in which the surface areas and volume are taken as being equal is most rational. Eq. (4) and Eq. (5) lack theoretical meaning and in case of Eq. (1), it will mean that there will be no difference in \( d \) even if the value of large and small droplets are of the same rank and large droplets are present if the number of small droplets corresponds to that of the large droplets. The large droplets will have influence in the order of Eqs. (1), (2), (3) and (6). In this work, it was decided to obtain average droplet size \( \bar{d} \) from Eq. (6).

4. Results and Discussion

4.1 General Tendency of Change in Average Droplet Size

In case atomization is carried out by air current blown in from a nozzle at right angles to the injection current, the change in average droplet size due to air velocity \( v_a \) is not simple and can be divided into several portions having different trends. When the phenomenon was observed by means of stroboscope and instantaneous photos in order to make clear each portion, it was found that they can be divided into the 4 zones shown in Fig. 5 from the difference in the mode of suspension of the liquid droplets and characteristics such as rebound of suspended droplets. Also, the phenomenon such as that shown in Fig. 5 was called the peak phenomenon. Fig. 6 shows an example of photos
\( Q_n = 0.5 \text{ cm}^3/\text{s} \quad D_n = 0.70 \text{ mm} \)
\( \frac{L}{D_i} = 1/2 \quad L = 30 \text{ cm} \)
\( t = 0.45 \text{ sec} \quad \text{V}_a = 10 \text{ m/s} \)

(a)

\( \text{V}_a = 13 \text{ m/s} \)

(b)

\( \text{V}_a = 15 \text{ m/s} \)

(c)

\( \text{V}_a = 18 \text{ m/s} \)

(d)

\( \text{V}_a = 21 \text{ m/s} \)

(e)

\( \text{V}_a = 24 \text{ m/s} \)

(f)

\( \text{V}_a = 26 \text{ m/s} \)

(g)

\( \text{V}_a = 28 \text{ m/s} \)

(h)
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Fig. 6 Photos showing change in droplet size

\[ v = 30 \text{ m/s} \]
\[ v = 32 \text{ m/s} \]
\[ v = 34 \text{ m/s} \]
showing the condition of change in droplet size. [Zone (1)] As $v_a$ is small, the extent of bending of the liquid flow due to side wind is small so that the entire quantity strike the tube and although a portion of the droplets rebounds, they drop to the bottom of the tube again and none of the droplets are blown through the tube end. [Zone (2)] As $v_a$ increases gradually, the extent of bending by side wind of the liquid flow accompanied by primary disintegration becomes large and at the same time its tip drops obliquely to the bottom of the tube over some portion of the axial direction and strikes the bottom. As a result of this, a portion goes into the liquid which is flowing at the bottom of the tube while another portion strikes the surface of the liquid and rebounds and only the droplets which rebound start to pass through the end of the tube at A point. Then, as $v_a$ increases, even the large droplets among the liquid droplets formed by this rebound begin to reach the tube end so that $\bar{d}$ increases rapidly and becomes the maximum at B point. Also, in case of small $L$, the liquid itself begins to pass through directly at this point so that this is a zone in which rebounded droplets and droplets produced by disintegration of the liquid flow coexist. [Zone (3)] As $v_a$ becomes larger, the bending of liquid flow becomes larger gradually and at the same time, droplets produced become smaller gradually. On the other hand, the number of droplets which strike the surface of the liquid flowing at the bottom of the tube becomes smaller gradually and although there are some droplets which rebound and pass through the end of the tube, such droplets are also small. [Zone (4)] As $v_a$ increases further, there will be no droplets which rebound and rather, a large number of droplets adhere to the tube wall.

Droplets which pass through are chiefly atomized particles of the liquid flow itself due to disintegration.

4.2 Effects of Various Factors on Average Droplet Size

Figs. 8~10 show the change in $\bar{d}$ when $L, D_n$ and $Q_n$, respectively, are varied. The effects of these factors on $\bar{d}$ are discussed from the above results on the basis of the above-mentioned basic characteristics.

(1) Effect of Tube Length

A point appears at a lower wind velocity side the smaller the $L$ and also the value of $\bar{d}$ is larger and variance is larger. Furthermore, the maximum value becomes 2000, its peak phenomenon is marked and C point is at a relatively low velocity side. As $L$ becomes larger, A point and C point shift to the high velocity side, the peak phenomenon is not as marked and the maximum value of $\bar{d}$ becomes smaller rapidly. As a general tendency, $\bar{d}$ becomes smaller as $L$ becomes larger. However, as this $\bar{d}$ is much smaller than the average diameter of all droplets produced from liquid particles, it can be said that such an air current tube acts as a filter for large droplets.

(2) Effect of Nozzle Diameter

In a range of small $L$ and low wind velocity, $v_a$ is larger the smaller the $D_n$ and consequently, droplets of the liquid flow which are bent and drop to the bottom of the tube by side wind and re-
bound, and droplets which pass through are large. Consequently, \( v_a \) becomes smaller as \( D_a \) becomes larger and as a result, droplets which rebound also becomes smaller and the diameter also becomes smaller. As \( v_a \) becomes larger, \( \bar{d} \) becomes smaller the larger the \( D_a \) for small \( L \). As shown in Fig. 7, the negative pressure produced at the back side becomes large and consequently the liquid flow is bent downward strongly. As a result of this, the chance for liquid flow to be disintegrated by the side wind increases and this accelerates atomization further. However, in case of such atomization by negative pressure, the droplets which have been atomized once adhere to the tube wall as the tube becomes longer and consequently, the difference in \( \bar{d} \) due to \( D_a \) disappears. As a general tendency, A
point appears at the low velocity side as $D_a$ becomes smaller and shifts to the high velocity side as $D_a$ becomes larger. Also, the effect of $D_a$ is not as marked as that due to $L$.

(3) Effect of Injection Liquid Quantity

When $v_a$ is large the larger the $Q_n$ while $v_a$ is still small and droplets which rebound appear faster the smaller the $D_a$, probably due to strong rebound by striking the tube wall. (Fig. 11). However, a part of the liquid flow itself becomes atomized flow easily the larger the $Q_n$ with increase in $v_a$ (Fig. 12) and also $d$ becomes smaller as the droplets produced become smaller with increase in bending. As a general tendency, A point appears at the low velocity side the larger the $Q_n$ and also its peak phenomenon is marked but the difference in $d$ due to $Q_n$ does not become marked as the velocity increases.

5. Effect of Liquid Temperature on Droplet Diameter

In atomization of liquid, it was previously considered that, when water was used as the liquid, the effect of water temperature on liquid droplet diameter was very small and consequently, most people used water in experiments without taking into consideration water temperature.

The author measured the water temperature from 1～70°C at intervals of 10°C under the following condition in order to investigate the effect of water temperature on liquid droplet size (Fig. 13). That is, $d$ was measured 3 times each at the various temperatures in order to assure accuracy with $Q_n$, $D_a$ and $v_a$ maintained constant. Measurements above 70°C were not carried out because accurate $d$ values cannot be obtained due to evaporation of liquid. The measurement results are shown in Fig. 14. It was found from this experiment that the effect of water temperature on liquid droplet size was that it became smaller at both the low temperature and high temperature sides and the maximum was observed in the vicinity of 40°C. Also, the difference in $d$ due to temperature difference was approximately 150μ in this example.
Fig. 13. Change in droplet size due to liquid temperature

(a) $Q_n=0.5 \text{ cm}^3/\text{s}$, $d_n=0.70 \text{ mm}$

(b) $l/D_i=1/2$, $U_{in}=30 \text{ m/s}$

(c) $t=0.45 \text{ sec}$, $t_w=1^\circ \text{C}$

(d) $t_w=1^\circ \text{C}$

(e) $t_w=10^\circ \text{C}$

(f) $t_w=20^\circ \text{C}$

(g) $t_w=30^\circ \text{C}$

(h) $t_w=40^\circ \text{C}$

(i) $t_w=50^\circ \text{C}$

(j) $t_w=60^\circ \text{C}$

(k) $t_w=70^\circ \text{C}$
6. Correspondence of Atomizing Rate and Average Droplet Size

The average droplet diameter $d$ of the droplet group which blows out of the tube end was made to correspond to the atomizing rate $\gamma$ of the previous paper to investigate the relation between changes in these and the results are shown in Fig. 15. It was found from this that a close correlation between change in $\gamma$ and change in $d$ is not particularly observed.

![Graph showing the relation between atomizing rate and average droplet size.](image)

Fig. 15 Corresponding atomizing rate $\gamma$ and average droplet size $d$

7. Maximum Droplet Diameter

Droplet size distribution is the most accurate method for showing non-uniformity of droplets but a simple method for obtaining a general idea is to obtain the maximum droplet diameter $d_{\text{max}}$ of a droplet group. Also, the maximum droplet size is important as one of the atomization characteristics because, for example, in case of liquid fuel atomization, it is closely related with the time required until it burns completely, formation of soot, combustion rate and combustion efficiency. In this work, the largest droplets caught during droplet size measurement were used and these were compared with $d$ at the various zones. An Example of a comparison of the results is shown in Fig. 16. It can be seen from this that the relation between $d_{\text{max}}$ and $d$ is influenced by $v_a$ and is not affected by other factors such as $L$, $D_a$ and $Q_a$. Also, the change of both indicates almost the same tendency and the following simple relation exists for the entire range of $v_a$

$$d_{\text{max}} = (1.5 \sim 2)d$$  \hspace{1cm} (7)

The approximate value of $d$ whose calculation is rather trouble-some can be estimated for them
above equation by measuring $d_{\text{max}}$.

8. Droplet Size Distribution

Fig. 17 shows an example of change in droplet size distribution when $D_{n}$ is changed gradually with $Q_{n}$, $L$ and $v_{n}$ maintained constant, and Fig. 18 when $L$ is changed gradually with $Q_{n}$, $D_{n}$ and $v_{n}$ maintained constant. The ordinate shows in percent the droplet size frequency counted at 50/$\mu$ intervals and this becomes equal to the percent of rate of change in number of droplets $\Delta n/\Sigma x$ when this is taken as the number of droplets present in the change in droplet size $\Delta x$. Therefore, the curve which is obtained shows the distribution curve $f(x)$ with respect to 100 droplets.

$$f(x) = \frac{dn}{dx}$$

(8)

It can be seen from these figures that with the exception of the first peak which is composed of fine droplets, a second peak composed of medium size droplets and large droplets does not appear and the droplet size distribution becomes a relatively simple form. Furthermore, formulation of droplet size distribution can be considered from the above. Nukiyama and Tanasawa proposed the following equation for atomization of liquid by parallel air current,
Fig. 18 Change in droplet size distribution by change in nozzle diameter

\[ \frac{dn}{dx} = ax^a \exp(-bx^b) \] .................................................... (9)

and when expressed logarithmically,

\[ \log_{10}(1/x^a \cdot \frac{dn}{dx}) = \log_{10} a - b/2.3 \cdot x^b \] .................................................... (10)

where \( n \) is the number of liquid droplets having diameter \( x \), \( a \) and \( b \) are constants for the various samples in accordance with the total droplet number and average droplet size which are decided when \( \alpha \) and \( \beta \) are decided and \( \alpha \) and \( \beta \) are constants obtained experimentally but in many cases, \( \alpha = 2 \) and \( \beta = 1 \) but becomes \( \beta < 1 \) as air quantity and air velocity become smaller. The droplet size becomes more non-uniform as \( \alpha \) and \( \beta \) become smaller. When Eq. (10) was applied to the results of this experiment, Figs. 19 and 20 were obtained when plotted on a semi-logarithm graph paper by
varying $\beta$ and it can be seen that they fall on the straight line at $\alpha=2$ and $\beta=1/2.5$ because the second peak is not present and can be expressed by the equation from a relatively low velocity. Now, $a=60$ and $b=2$ from $\alpha=2$ and $\beta=1/2.5$ and consequently, the distribution function of Eq. (8) can be shown in the following form,

$$dn/dx = 60x^2 \exp(-2x^{1/2.5})$$ .......................... (11)

9. Conclusion

Warm water of the same viscosity coefficient as that of gasoline was injected from a nozzle at right angles into air flowing in a tube ($v_a \leq 35 \text{ m/s}$), liquid droplets which pass through the downstream end of the tube were caught, the droplet size measured and the average droplet size and droplet size distribution were obtained. The results obtained were as follows.

1. Average droplet size $\bar{d}$ of liquid droplets which pass through changes with increase in air velocity $v_a$ but this change takes place peakwise and so-called peak phenomenon appear remarkably as tube length $L$ becomes longer, nozzle diameter $D_n$ becomes smaller and quantity of injected liquid $Q_n$ becomes larger. However, the peak phenomenon is not marked when $L$ and $D_n$ become larger and $Q_n$ becomes smaller.

2. Fundamentally, the peak phenomenon takes place in 4 stages as shown in Fig. 4 and each of these was explained qualitatively by stroboscope observation and instantaneous photographs.

3. The effect of the various factors on average droplet size $\bar{d}$ differs to some extent in accordance with the wind velocity but $\bar{d}$ generally becomes smaller the smaller the nozzle diameter $D_n$, and the larger the nozzle flow rate $Q_n$ and tube length $L$.

4. With regard to the effect of water temperature on average droplet size $\bar{d}$, it was found that $\bar{d}$ becomes smaller at both the low temperature side and high temperature side and a maximum appears at about 40°C.

5. When atomizing rate $\gamma$ and average droplet size $\bar{d}$ were made to correspond to each other, it was found that a close correlation did not exist between the changes of both.

6. Maximum droplet size $d_{max}$ indicated almost the same behavior as the change in $\bar{d}$ and a relation of $d_{max} = (1.5-2)\bar{d}$ exists over the entire range of wind velocity.

7. The droplet size distribution is a simple form having only one peak and it was found that it conforms to the distribution equation of $dn/dx = 60x^2 \exp(-2x^{1/2.5})$ from a considerably low velocity.

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