# Drop Formation in Air Prior to Jetting

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Many investigations of drop formation from nozzles have been conducted. More studies were made on liquid-liquid systems than on liquid-gas systems. For the former, extensive reviews were given by Clift et al. (1978), Godfrey and Hanson (1982), and Hirata (1982); for the latter, very limited quantitative information is available on drop formation prior to jetting. All semiempirical equations proposed for liquid-liquid systems ought to be reducible to the case of liquid-gas systems by omitting terms which come into existence because of a liquid continuous phase. This, however, appears not to have been done so far. The results of an investigation on prejetting liquid drop formation in still air using low viscosity liquids are reported here.

## Experimental

Liquid from a constant-head tank flows into a glass syringe equipped with a vertically oriented nozzle. Smaller nozzles, #24, #21, and #18, are each 1 cm in length, with diameters ($d_i$, $d_o$) of (0.0311, 0.056), (0.05, 0.084), and (0.09, 0.127), respectively. Larger nozzles, #1 and #2, are 2.9 and 2.7 cm in length, with ($d_i$, $d_o$) of (0.17, 0.23) and (0.43, 0.5), respectively. The liquid flow rate was regulated by a needle valve located upstream of a rotameter. Distilled water and water saturated with isobutanol were used. Their density, surface tension, and viscosity are, respectively, 998 and 990 kg/m$^3$, 72, and 27.3 $m$N/m, and 896.4 and 1,470 $\mu$N · s/m. Experiments were conducted at 22.6 ± 0.5°C. Drop frequency was measured at various liquid flow rates by means of an infrared light emitter and a photodiode. The voltage was monitored by a microcomputer or, for more speedy response, by a drop counter. This means of frequency measurement was calibrated against that using a stroboscope. Stroboscope was also used in high frequency measurement. Liquid flow rate was measured by weighing the liquid collected in a given time, the weight being accurate to 0.1 mg. This weighing method gives flow rates which are more dependable than those provided by a rotameter, for which it is not unusual to have a range of reading over which flow rates can not be determined to the accuracy desired. Flow rate and drop frequency were measured simultaneously.

In the experiments, liquid flow rates up to that for jetting were investigated for nozzles #24, #21 and #18. In fact, the flow rate at which jetting occurs is not clearly defined. At moderate flow rates, a drop detaches from the nozzle and falls along the path of the previous drop. At a sufficiently high flow rate, drop formation begins to be irregular. A drop forming at the nozzle tip wobbles before detachment; drops thus formed are different in size and fall along different paths in air. As the flow rate is increased further, there is a flow rate at which the sizes of formed drops appear to be more or less uniform again. These drops fall in one line in air. At still higher flow rates, a very short water cone appears at the nozzle tip, and drops form and detach from the cone. When the flow rate is increased further, the column length suddenly increases and a long jet is formed. The above described changes in dripping-to-jetting also depend on the liquid and nozzle. For distilled water with a #2 nozzle, the sudden increase in the length of the jet is just like that for water saturated with isobutanol with all five nozzles. However, for distilled water with nozzles other than #2, the increase in jet length is not as sudden, but is more adjustable by controlling the flow rates. The changes that take place between dripping-to-jetting occur in a range of flow rates which is very narrow for small nozzles and somewhat less narrow for larger nozzles. Also, the jetting flow rate obtained when the flow rate is increasing is different from that when the flow rate is decreasing from a flow rate at which jet has already been formed. This difference in jetting flow rates is affected by the size of the nozzle and the kind of liquid. This difference is negligible for small nozzles and more pronounced for larger nozzles. Also, the difference is smaller with distilled water than with water saturated with isobutanol. A more quantitative description of the region from dripping-to-jetting will require a more delicate control of the flow rate. In this work, with the flow rate increasing, the highest flow rate at which drops of the same size fall along the same path with regular drop spacing is referred to as the jetting point.

## Analysis

For static drop formation, liquid flow rate is very low, and therefore, the effect of momentum is virtually negligible. The volume of a detached drop, $v_{ps}$, is found by Tate's equation mod-

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ified by the Harkins-Brown factor, $H$, that is, $H\sigma\pi d_o = v_{ps} g \Delta\rho$, where, as the entire cross-sectional area of the nozzle at the exit was wetted by the liquids, outside diameter, $d_o$, was used. The flow rate and drop frequency are related by $Q = v_{ps} f$. After rearrangement, $Q = HX$ is obtained, where $X = (\sigma\pi d_o f)/(g\Delta\rho)$. Heertjes et al. (1971) and Lando and Oakley (1967) have provided the correlation equations for $H$.

At increased flow rates, dynamic effects become important. The force balance equation for a drop detaching from a vertical nozzle in a gas phase should be analogous to that in a liquid phase except that resistance and reaction forces presented by the latter are now absent. The ideal drop volume, $v_{pi}$, is therefore written as $v_{pi} = [\sigma\pi d_o + d(mu)/dt]/(g\Delta\rho)$. The magnitude of $d(mu)/dt$ is unknown. For liquid-liquid systems, different forms have been used (Izard, 1972; Scheele and Meister, 1968). Johnson and Marschall (1986) in their study of liquid-liquid systems observed that in slow drop formation, a drop-rise velocity during detachment is much larger than the mean velocity in the dispersed phase nozzle, and in fast drop formation, a drop rise velocity during detachment is not much larger than the mean velocity in the dispersed phase nozzle. It is assumed here that this term is equal to the "rate of momentum in" at the nozzle exit. The volume of a detached drop, $v_p$, is the sum of $v_{pi}$ and $v'$, the additional liquid volume that flows into the primary drop during necking, that is, $v_p = Cv_{pi} + v'$, where $C$ replaces $H$ to correct the ideal drop volume for the volume of liquid that remains attached to the nozzle. As $Q$ decreases, $C$ should approach $H$. For a dynamic case, $H$ has been often used in place of $C$, for which, to this date, available information is scant. For $v'$, the equation of Scheele and Meister for liquid-liquid systems was used, that is,

$$v' = b[Q^2 d_o^2 \rho_d \sigma/(g\Delta\rho)^2]^{1/3} \tag{1}$$

where $b$ is an unknown. As $\dot{m} = \rho_d Q$, $u = Q/(60A_i)$, and $Q = v_p f$, then

$$Q = C'X \tag{2a}$$

where

$$C' = C\left[1 - \frac{1}{4}\left(\frac{d_i}{d_o}\right)^2 We + \left(\frac{b/C}{\pi}\right)\left(\frac{\pi}{4}\right)^{2/3}\left(\frac{d_i}{d_o}\right)^{4/3}(Bo'We)^{1/3}\right] \tag{2b}$$

$C = H$ was assumed in this work. Comparison with experimental data showed that $b/C = 1.5$. A constant was used because the contribution of $b/C$ becomes significant only at increased liquid flow rates and the variation of $H$ in this region is small. Equation 2a is similar in form to that for the static case. Both equations require the trial-and-error method to find drop diameter.

## Results and Discussion

For distilled water and water saturated with isobutanol, drop formation in air may be accompanied by satellite drop formation. Photographs taken in the experiments show that with small nozzles, #24 and #21, the drop detaches itself from the pinnacle of a cone-shaped liquid, which stays attached to the nozzle. Satellite drops were not detected. For larger nozzles, besides the parent drop and the residual liquid that remains attached to the tip of nozzle, a long neck is formed. Satellite drops are formed from the neck. For nozzles #18 and #1, one satellite drop was detected by the drop counter. The number of drops indicated by the counter increased regularly by two. The number of parent drops is obtained by dividing that number by two. For nozzle #2, two satellite drops were formed regularly. At low liquid flow rates, satellite drops are very small compared to the parent drop. For the #18 nozzle, satellite drops are hardly visible by the naked eye. At liquid flow rates near those for jetting, satellite drops become larger and measurements become difficult. In this work, the problem is simplified by incorporating the volume of satellite drops into the volume of primary drop, and the resulting volume was taken as the volume of a detaching drop, $v_p$.

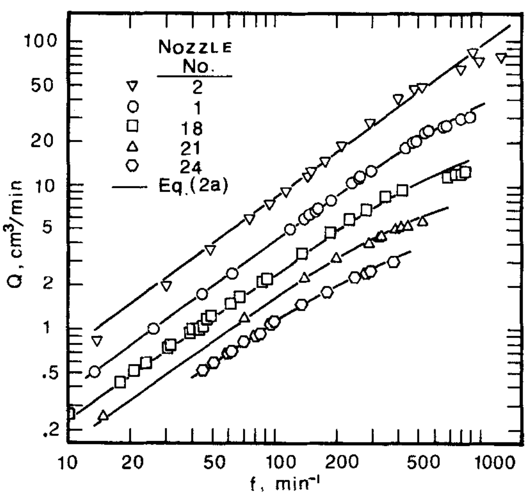
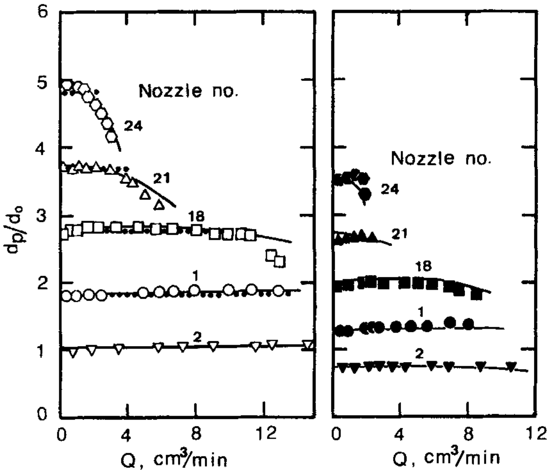


**Figure 1. Distilled water: flow rate vs. drop frequency.**

Figure 1 shows how drop frequency varies with flow rate. Experimental data agree well with that calculated by Eq. 2a. Figure 2 shows the effects of nozzle diameter and liquid flow rate on dimensionless drop diameter, $d_p/d_o$. Drop size is larger for larger nozzles and for liquid with higher surface tension. For small nozzles, a single drop formation is possible at high average liquid velocity at the nozzle. For distilled water, an average



(a). Distilled water

(b).Water saturated with isobutanol.

**Figure 2. Dimensionless drop diameter vs. flow rate.**

velocity as high as 80 cm/s can be reached for nozzle #24. For nozzle #2, however, experimental measurements become difficult at velocities on the order of 10 cm/s. Figure 2b shows that for small nozzles, the calculated results deviate from the experimental results. It was observed in the experiments that this liquid wetted the exterior wall of small nozzles. This could be a cause for the deviation. For nozzle #2, drop diameter is smaller than nozzle diameter.

Experimental data were replotted in the form of Figure 3 for both liquids. At smaller flow rates, the data points for nozzles #24, #21 and #18, fall very close to each other; the data for nozzle #1, somewhat to the right; and the data for nozzle #2, further to the right. In the figure, Eq. 2a was plotted for each nozzle. The agreement is satisfactory. At increased flow rates, the curve for each nozzle, in the order of smaller to larger nozzle, turns away from the rest at *We* of about 0.8 to 1.9, depending on the nozzle and liquid. The black dots in the figure constitute a line which passes through linear portion of the data. This dotted line is represented by a simple equation, $Q = 0.8X$. For distilled water, excepting nozzle #2, the deviation between this equation and experiments for drop frequency is within 15%; with many of the data points, the deviation is much less than 15%, and the deviation in drop diameter is within 6%. For water saturated with isobutanol, with nozzles #21 and #18, the magnitudes of deviations are about the same; for nozzles #1 and #2, the deviations exceed 15% and 6%. With the simplified equation and the relation, $Q/f = v_p$, a representative drop diameter can be determined once liquid and nozzle are given. These diameters are indicated in Figure 2a by black dots for the range of $Q$ (or *We*) in which the equation is applicable. Within the specified *We*, the frequency corresponding to the representative diameter may be quickly estimated.

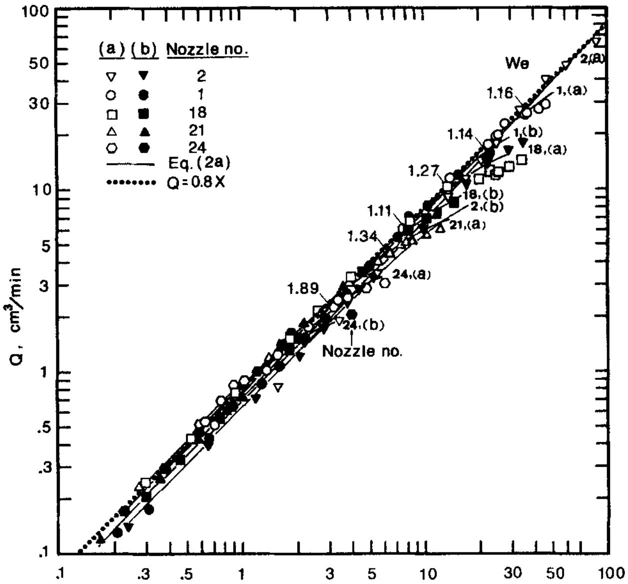


**Figure 3. Flow rate vs. *X*.**
(a) distilled water
(b) water saturated with isobutanol

## Acknowledgment

Thanks are due to Mr. Shiuh-Hoang Leu for assisting in data acquisition, and to Mr. Jyr-Jong Wang for constructing the drop counter.

## Notation

$A_i$ = inside cross-sectional area of nozzle, cm$^2$
$b$ = experimental constant in Eq. 1
$Bo'$ = Bond number, $d_o^2 g\Delta\rho/\sigma$
$C, C'$ = correction factors
$d_i, d_o$ = nozzle diameters, inside and outside, cm
$d_p$ = diameter of detached drop, cm
$f$ = drop frequency, min$^{-1}$
$g$ = gravitational acceleration, 980 cm/s$^2$
$H$ = Harkins-Brown factor
$\dot{m}$ = mass flow rate of dispersed phase, g/min
$Q$ = volume flow rate of dispersed phase, cm$^3$/min
$u$ = liquid velocity at nozzle exit, cm/s
$v_j$ = volume, cm$^3$: $j = pi$ for ideal dynamic drop
$j = ps$ for static drop
$v'$ = volume added during necking, cm$^3$
$We$ = Weber number, $(d_o u^2 \rho_d)/\sigma$
$X = (\sigma\pi d_o f)/(g\Delta\rho)$, cm$^3$/min

### *Greek letters*

$\rho_d$ = density of dispersed phase, g/cm$^3$
$\sigma$ = surface tension of dispersed phase in air, *m*N/m

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*Manuscript received Jan. 4, 1989, and revision received Mar. 9, 1989.*