渦券 노즐의 理論分析(Ⅲ)
-힘이 粒子形成에 미치는 影響-

Theoretical Analysis on the Swirl Type Nozzle(Ⅲ)
-Effects of Forces on the Droplet Formation-

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摘 要

渦券 노즐에 作用되는 힘은 噴頭의 導溝 및 渦室의 機能에 의하여 軸方向力과 半徑方向力으로 分類되고, 이 두개의 힘은 微粒化의 過程에 各各의 特性을 주고 있다.

半徑方向의 힘은 噴頭에서 噴射되는 粒子에 剪斷力으로서 作用하지만 이 힘의 크기는 물방울의 直徑 100 μm을 基準하여 2.4m/s의 速度 以內의 範圍이었으며, 그 速度範圍는 다음 유도된 式으로 算出할 수 있었다.

$$V_{ot} = \left(\frac{8g\sigma}{d\gamma}\right)^{1/2}$$

軸方向力은 아래 유도된 式과 같이 噴射液流의 굴절각에 매우 민감하게 영향을 미치었고, 그 크기는 半徑方向力에 比較하여 큰 값을 나타내었다.

$$V_{\ell} = \sigma\left[\frac{1}{2}\rho_a \sin 2\theta_d - 4(\mu+\eta)\frac{\ell}{r_o}\right]^{-1}$$

I. Introduction

Kinetic force applied in the swirl type nozzle will be divided into two directional forces(4,5,6) by passing the liquid through tangential passages of the swirl groove; the longitudinal force and the tangential force.

The longitudinal force will produce the turbulence in the liquid which causes aerodynamic wave motion resulting from an interplay with surface tension, also it will give rise to air friction when it impacts the air into which the liquid is injected.

The tangential force will act directly against surface tension of the liquid in a lateral direction, and it will disintegrate the liquid partially at the outer surface of the ligament as the centrifugal force which is produced from an interplay of the tangential force and the ligament radius.

If the kinetic force is larger than the surface tension and the viscosity of the liquid, the disintegration will be developed by the combined effects of those forces in some modes as shown in Figure 1(1).

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II. Theories on the tangential force and the longitudinal force

A. The Tangential Force

The tangential force acts mainly against surface tension of the ligament in a lateral direction as shear force[2] corresponding to the magnitude of the tangential velocity inside the ligament as shown in Figures 1(2) and (3).

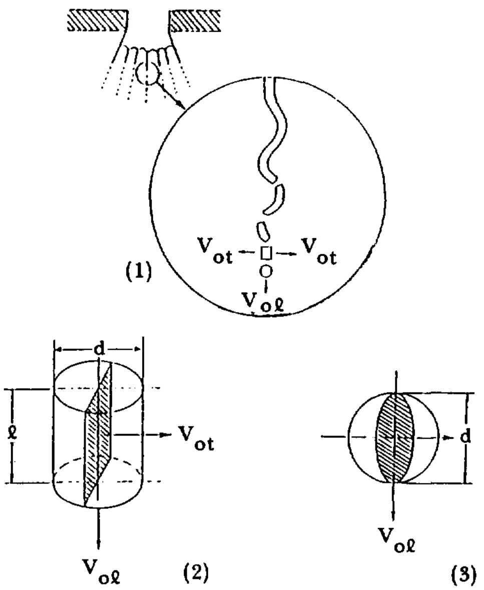


Figure 1. Features of ligaments.

A column [Figure 1(2)] will be produced in the initial stage at the tip of the orifice and then the column will be changed into a spherical form [Figure 1(3)] if surface tension is balanced with the applied force.

The balanced forces (or pressure) are calculated in Eq.(1) for the column and Eq.(2) for the spherical form respectively.

Column; $d\ell P = 2\ell\sigma$

$$P = \frac{2\sigma}{d} \qquad (1)$$

Sphere; $\frac{\pi d^2}{4} \times P = \pi d\,\sigma$

$$P = \frac{4\sigma}{d} \qquad (2)$$

where, p = pressure applied from the outside force

d = diameter of the particle or the column

σ = surface tension

In the assumption that the frictional loss does not happen in the nozzle, Bernoulli's theorem derives the following equation on the same elevation level,

$$\frac{P_o}{\gamma} + Z_1 = \frac{P_1}{\gamma} + Z_1 + \frac{V_1^2}{2g} = Z_1 + \frac{V_o^2}{2g}$$

$$\frac{P_o}{\gamma} = \frac{V_o^2}{2g} = \frac{V_{ot}^2}{2g} + \frac{V_{o\ell}^2}{2g}$$

$$P_o = \frac{\gamma V_o^2}{2g} = \frac{\gamma V_{ot}^2}{2g} + \frac{\gamma V_{o\ell}^2}{2g} \qquad (3)$$

$\frac{\gamma V_{ot}^2}{2g}$ in Eq.(3) corresponding to the tangential force equals P as described in Eqs.(1) or (2).

Column; $\frac{2\sigma}{d} = \frac{\gamma V_{ot}^2}{2g} \rightarrow d = \frac{4g\sigma}{\gamma V_{ot}^2}$ or

$$V_{ot} = \left(\frac{4g\sigma}{d\gamma}\right)^{1/2} \qquad (4)$$

Sphere; $\frac{4\sigma}{d} = \frac{\gamma V_{ot}^2}{2g} \rightarrow d = \frac{8g\sigma}{\gamma V_{ot}^2}$ or

$$V_{ot} = \left(\frac{8g\sigma}{d\gamma}\right)^{1/2} \qquad (5)$$

where, P_o = gage pressure

V_o = velocity at the orifice

γ = specific weight of liquid

g = acceleration of the gravity

V_{ot} = tangential component of V_o

$V_{o\ell}$ = longitudinal component of V_o

If the tangential force is assumed to be centrifugal force as shown in Figure 2, it only encounters to the surface tension force of the liquid at right outside the tip of the orifice in order to tear the ligament up partially at the outer surface of the ligament, its marginal value is derived as Eq.(6).

$$2\sigma \leqq 2\int_0^{\frac{\pi}{2}} F_t r_o \sin\xi \, d\xi = 2 F_t r_o$$

$$\sigma \leqq F_t r_o, \text{ since } F_t = m\frac{V^2}{r_o}$$

$$V \geqq \left(\frac{\sigma}{\rho}\right)^{1/2} \qquad (6)$$

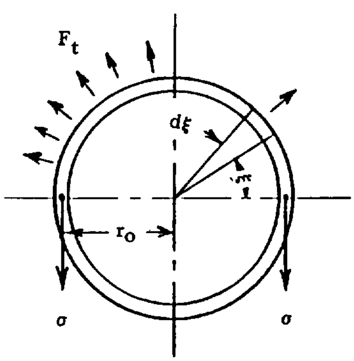


Figure 2. Centrifugal force to surface tension force.

B. The Longitudinal Force

The longitudinal velocity is essential to all atomizers not only for disintegration of the bulk liquid but also for transportation of the resulting droplets to the targets. The longitudinal velocity has a function to arise the turbulence in the liquid which causes aerodynamic wave motion resulting from an interplay with surface tension.

When the liquid is ejected from the orifice, the liquid ligament will immediately be acted on by two opposing forces; the surface tension force and the shear stress due to the viscosity which tend to draw the liquid back to its original position against the aerodynamic forces which tend to push or cut the liquid outward in the right front of the orifice.

If the aerodynamic forces exceed the physical forces of the liquid, unstable waves will be produced and later break up into fine droplets.

In the method which the liquid ligament contacts with the aerodynamic forces, two types are assumed as shown in Figure 3; one is a straight column emitting in a parallel with the aerodynamic forces being in the opposite direction and the other is a wavy column arising from an interaction of aerodynamic forces with surface tension with an angle of θ_d to the nozzle axis.

1). The Straight Column

If the straight column contacts with aerodynamic forces directly in the opposite direction as shown in Figure 3(1), it is nearly impossible to cut some middle points of the column with the induced force from aerodynamic forces in a perpendicular direction because the column is issued continuously from the orifice with constant velocity or acceleration to be moved forwards.

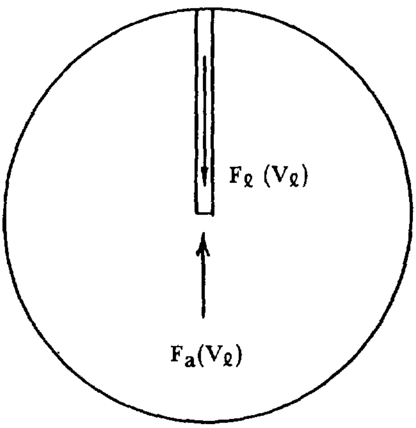
2) The Wavy Column

If the wavy column [Figure 3(2)] keeps

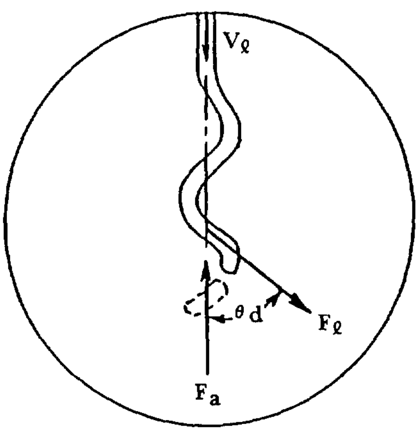
moving in an oblique direction with the angle of θ_d to the direction of the aerodynamic forces, the velocity difference between the emitting liquid and the still air can be taken by the liquid velocity as the relative velocity V_ℓ.

Assuming that the column is a static solid, an oblique cutting phenomenon can be explained by a balance of the physical forces of the liquid opposed to the aerodynamic forces.

The reacting forces resulting from the still air when it is impacted by the liquid jet are expressed in two axes,



(1) Straight column



(2) Wavy column

Figure 3. Enlarged phenomena contacting of the ligaments with the aerodynamic force.

$$F_{ax} = \rho_a V_{ax} Q_a \tag{7}$$

Since Q_a is the unit volume and V_{ax} equals to $V_a \cos\theta_d$ and also V_a equals to $V_\ell \cos\theta_d$, Eq.(7) is reformed in the unit force per the unit area,

$$\begin{aligned}\sigma_x &= \rho_a V_a \cos\theta_d \\ &= \rho_a V_\ell \cos^2\theta_d \end{aligned}\tag{8}$$

In the same manner of Eqs.(7) and (8),

$$\begin{aligned}\sigma_y &= \rho_a V_{ay} \\ &= \rho_a V_a \sin\theta_d \\ &= \rho_a V_\ell \sin\theta_d \cos\theta_d \end{aligned}\tag{9}$$

where, σ_x = X-axis stress
σ_y = Y-axis stress
ρ_a = ambient air density (specific mass)
V_a = relative velocity of the still air to the liquid velocity
V_ℓ = liquid velocity
θ_d = directional angle of the liquid flow to the nozzle axis
V_{ax} = X-axial component of V_a
V_{ay} = Y-axial component of V_a

Therefore, the reacting shear stress acts as follows,

$$\begin{aligned}\tau &= \frac{1}{2}(-\rho_a V_\ell \cos^2\theta_d + \rho_a V_\ell \sin\theta_d \cos\theta_d) \sin 2\phi \\ &= \frac{1}{2}\rho_a V_\ell (\sin\theta_d \cos\theta_d - \cos^2\theta_d) \sin 2\phi \\ &= -\frac{1}{2}\rho_a V_\ell (\cos^2\theta_d - \sin\theta_d \cos\theta_d)\end{aligned}$$

$$\sin 2(90-\theta_d) \tag{10}$$

when the directional angle θ_d is zero, the maximum value is gotten,

$$\tau_{max.} = \frac{1}{2}\rho_a V_\ell \tag{11}$$

However Eqs.(10) and (11) are not available in the practical application because cutting phenomenon is a perpendicular cut occurring at the middle point of the liquid jet, the results of which become the same as the straight column.

Since the oblique cut can not be achieved in the middle points of the ligament on the condition of the constant velocity of the ligament moving continuously forwards, the direct cut with an oblique angle θ_d is suggestive in the actual phenomenon.

The unit aerodynamic force τ_a acts obliquely along to the elliptic cross-sectional area S of the ligament as shown in Figure 4(1) and Eq.(12).

$$\tau_a = \frac{F_a}{S}, \text{ since } S = \frac{A}{\sin\theta_d},$$

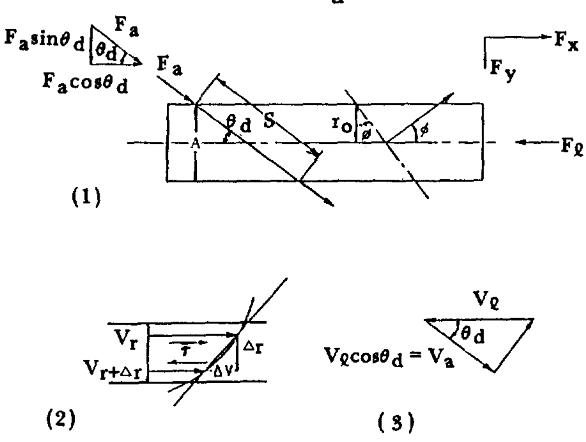


Figure 4. Aerodynamic forces to the ligament.

$$\tau_a = \frac{F_a}{A}\sin\theta_d, \text{ also since } \frac{F_a}{A} = \rho_a V_\ell \cos\theta_d$$

$$\tau_a = \rho_a V_\ell \sin\theta_d \cos\theta_d \tag{12}$$

where, F_a = aerodynamic forces

A = cross-sectional area of the ligament

The maximum value of τ_a is calculated when θ_d equals 45°,

$$\tau_{a,\ max.,\ \theta_d=45°} = \rho_a V_\ell \sin 45 \cos 45$$
$$= \frac{1}{2}\rho_a V_\ell \tag{13}$$

The motion of flow at the nozzle orifice is assumed to be a turbulent flow which is an entirely chaotic motion of fluid masses through the orifice length in every direction. However shearing stress τ_μ has been suggested by Boussinesq(3) to cover usually the combined situation of both viscous action and turbulent action.

$$\tau_\mu = (\mu+\eta)\frac{dV}{dy}$$
$$= (\mu+\eta)\frac{\Delta V}{\Delta r}$$
$$= (\mu+\eta)\frac{V_r - V_r + \Delta r}{\Delta r}$$
$$= (\mu+\eta)\frac{1}{\Delta r}\cdot\frac{1}{4\mu}\cdot\frac{dP}{d\ell}$$
$$\{(r_o^2-r^2)-[r_o^2-(r+\Delta r)^2]\}$$
$$= (\mu+\eta)\frac{1}{\Delta r}\cdot\frac{1}{4\mu}\cdot\frac{dP}{d\ell}$$
$$(2r.\Delta r + \Delta r^2)$$
$$= (\mu+\eta)\frac{1}{4\mu}\frac{dP}{d\ell}(2r+\Delta r)$$

where, μ = absolute viscosity

η = mechanical viscosity (eddy viscosity)

$\frac{dV}{dy}$ = velocity gradient of temporal mean velocity

r_o = radius of the orifice

$\frac{dP}{d\ell}$ = pressure drop per the length of $d\ell$ of the pipe

$(\frac{dP}{d\ell} = \frac{\Delta P}{\ell}$, ℓ = length of the orifice)

The shear stress is changeable according to the position and the flow velocity, and so the maximum value can be arranged when the value of $(2r + \Delta r)$ approaches to $2r_o$.

$$\tau_{\mu,\max.} = (\mu + \eta)\frac{1}{4\mu}\frac{dP}{d\ell}(2r_o)$$

$$= (\mu + \eta)\frac{r_o}{2\mu}\frac{\Delta P}{\ell} \qquad (14)$$

Therefore the unit physical force τ_ℓ of the ligament is derived from the sum of the surface tension force τ_σ and the shear force τ_μ.

$$\tau_\ell = \tau_\sigma + \tau_\mu$$

$$= \sigma + (\mu + \eta)\frac{r_o}{2\mu}\cdot\frac{\Delta P}{\ell} \qquad (15)$$

where, σ = surface tension

Equating two Eqs. (12) and (15),

$$\rho_a V_\ell \sin\theta_d \cos\theta_d = \sigma + (\mu + \eta)\frac{r_o}{2\mu}\cdot\frac{\Delta P}{\ell}$$

$$V_\ell = \frac{2}{\rho_a \sin 2\theta_d}[\sigma + (\mu + \eta)\frac{r_o}{2\mu}\cdot\frac{\Delta P}{\ell}] \qquad (16)$$

In Eq.(16), $\frac{\Delta P}{\ell}$ is replaced by the following equation, which means the pressure drop per the length of ℓ due to passing of the liquid through the orifice,

$$\Delta P = \frac{128\mu\ell Q}{\pi d_o^4} = \frac{8\mu\ell Q}{\pi r_o^4}$$

also since $Q = \pi r_o^2 V_\ell$,

Eq. (16) is reformed,

$$V_\ell = \frac{2}{\rho_a \sin 2\theta_d}[\sigma + (\mu + \eta)\frac{r_o}{2\mu}\frac{8\mu\ell Q}{\pi r_o^4}]$$

$$V_\ell = \frac{2}{\rho_a \sin 2\theta_d}[\sigma + (\mu + \eta)\frac{4\ell}{\pi r_o^3}\pi r_o^2 V_\ell]$$

$$V_\ell = \frac{2}{\rho_a \sin 2\theta_d}[\sigma + (\mu + \eta)\frac{\ell}{r_o}V_\ell]$$

$$\frac{\rho_a \sin 2\theta_d}{2}V_\ell - 4(\mu + \eta)\frac{\ell}{r_o}V_\ell = \sigma$$

$$V_\ell = \sigma[\frac{1}{2}\rho_a \sin 2\theta_d - 4(\mu + \eta)\frac{\ell}{r_o}]^{-1} \qquad (17)$$

This equation shows that the directional angle of θ_d affects the marginal longitudinal velocity V_ℓ so greatly that it can cut the ligament directly when ρ_a, r_o, ℓ and μ are constants, and the marginal velocity reaches to the minimum value when $\theta_d = 45°$.

The velocity of V_ℓ relates to the frequency f of the distrubance and the wavelength λ of drop formation.

$$V_\ell = f\lambda$$

$$\lambda = \frac{1}{f}V_\ell \text{ or } f = \frac{1}{\lambda}V_\ell \qquad (18)$$

substituting Eq. (17) into Eq. (18)

$$\lambda = \frac{\sigma}{f[\frac{\rho_a}{2}\sin 2\theta_d - 4(\mu + \eta)\frac{\ell}{r_o}]} \tag{19}$$

This equation shows that the wavelength λ decreases with either increase of the ambient air density ρ_a or decrease of the surface tension and also decrease of the viscosity.

Dombrowski[2] reported that the disturbance frequency f rapidly increased with either increase of the ambient air density or increase of the liquid velocity, and also Bouse[1] suggested the regression equations for the minimum and maximum disturbance frequencies for tap water,

$$f_{min.} = 1130 + 0.5465 f_w - 256.2 \ell og P_n - 0.0558 f_w \ell og P_n$$
$$f_{max.} = 1746 + 1.065 f_w - 458.4 \ell og P_n + 0.2172 f_w \ell og P_n \tag{20}$$

where, $f_{min.}$ or $f_{max.}$ = the minimum or maximum disturbance frequency

f_w = the calculated Weber's frequency in Hz

f_n = the dynamic pressure in kPa

The volume of the droplet due to only the longitudinal flow without the tangential flow is predicted as follows;

$$\frac{4}{3}\pi\left(\frac{D}{2}\right)^3 = \pi r_o^2 \lambda$$
$$D^3 = 6 r_o^2 \lambda$$
$$\therefore D = (6 r_o^2)^{1/3} (\lambda)^{1/3} \tag{21}$$

III. Applications of theories and discussion

If the tap water is taken as a pesticidal carrier, the marginal values of the tangential velocity will be predicted according to Eq.(4) for columns and Eq.(5) for spheres depending on the droplet sizes as Table 1.

(　) in Table 1 is the calculated value of the orifice velocity corresponding to the tangential velocity at the spray angle of 45° giving the marginal value by Eq.(22).

$$V_o = \frac{V_{ot}}{\sin 45^\circ} = \frac{V_{ot}}{0.7071} \tag{22}$$

In practical applications, the tangential velocity to affect the droplet size is very small and limited as a shear function comparatively beyond the magnitude of the longitudinal velocity.

Therefore the effects of the tangential force are useful in the low pressure atomizing devices as shown in Figure 5 in which the marginal tangential velocity was plotted against the droplet diameter of water.

Illustrative example 1 to determine the marginal velocity under the conditions with consideration of centrifugal force;

Liquid: water at 30°C

surface tension, $\sigma = 7.248 \times 10^{-3}$ kg/m

density, $\rho = 101.53$ kg.sec^2/m^4

orifice radius, $r_o = 1$ mm $= 1 \times 10^{-3}$m

[Solution]

$$V \geqq \left(\frac{\sigma}{\rho}\right)^{1/2} = \left(\frac{7.248 \times 10^{-3}}{101.53}\right)^{1/2}$$

Table 1. The marginal values of the tangential velocity depending on the droplet size of water.

(unit; m/s)

d (μm)	100	200	300	400	500	600	700	800	900	1000
Column	1.69 (2.39)	1.19 (1.69)	0.97 (1.38)	0.84 (1.19)	0.75 (1.07)	0.69 (0.97)	0.64 (0.90)	0.60 (0.84)	0.56 (0.79)	0.53 (0.75)
Sphere	2.39 (3.38)	1.69 (2.39)	1.38 (1.95)	1.19 (1.69)	1.07 (1.51)	0.97 (1.38)	0.90 (1.28)	0.84 (1.19)	0.79 (1.13)	0.75 (1.07)

Conditions; $t = 30^{\circ}C$
$\sigma = 7.248 \times 10^{-3}$ kg/m
$\gamma = 995.7$ kg/m^3
$g = 9.8$ m/sec^2

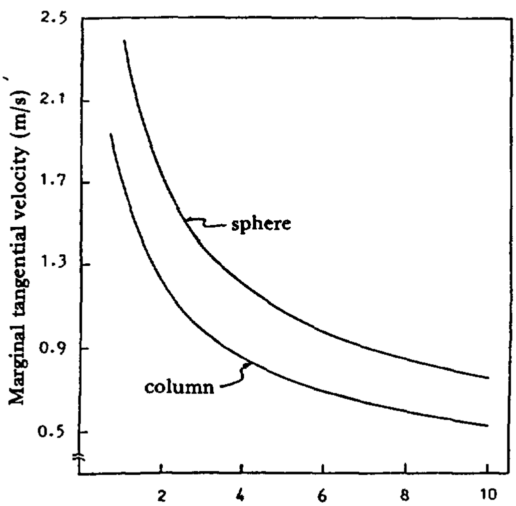


Figure 5. The marginal values of the tangential velocity corresponding to the droplet size of water.

$$V \geqq 8.449 \times 10^{-3} \text{ m/s}$$

This phenomenon may cause to produce the satellite droplet in the practical applications because the velocity in this illustrative example is very small value in comparison with the marginal tangential velocities in Table 1.

Illustrative example 2 to determine the marginal longitudinal velocity in accordance with variation of the directional angle of the liquid flow to the nozzle axis under the liquid conditions;

air density, $\rho_a = 0.1188$ kg.sec^2/m^4
water surface tension, $\sigma = 7.248 \times 10^{-3}$kg/m
water viscosity, $\mu = 81.6 \times 10^{-6}$kg.sec/m^2
water mechanical viscosity as estimated, $\eta = n\mu$, n=20
orifice diameter, $d_o = 2 \times 10^{-3}$ m
orifice length, $\ell = 1 \times 10^{-3}$ m

and then check the disturbance frequency in the above conditions.

[Solution]

$$V_\ell = \sigma \left[\frac{\rho_a}{2} \sin 2\theta_d - 4(\mu + \eta)\frac{\ell}{r_o}\right]^{-1}$$

$$= \frac{0.007248}{0.0594(\sin 2\theta_d) - 0.0068544}$$

The results are as shown in Figure 6 that the marginal longitudinal velocity V_ℓ is very sensitive in effects to atomization depending on the degree of the directional angle of the ligament to the nozzle axis, since both the water viscosity and the air density are very low values.

Substituting Weber's wavelength equation[7] into Eq.(18), the disturbance frequency f was calculated on the basis of the marginal longitudinal velocity corresponding to the directional angle θ_d, and the disturbance frequency was also plotted against the directional angle in Figure 6.

Figure 6 shows that the marginal longitudinal velocity and the disturbance frequency are very sensitive to the degree of the directional angle on the same tendencies in which V_ℓ and f increase together with decrease of the directional angle.

The marginal velocity of 15 m/s which was suggested by Weber[7] approaches approximately to the directional angle of $3°40'$ in this example.

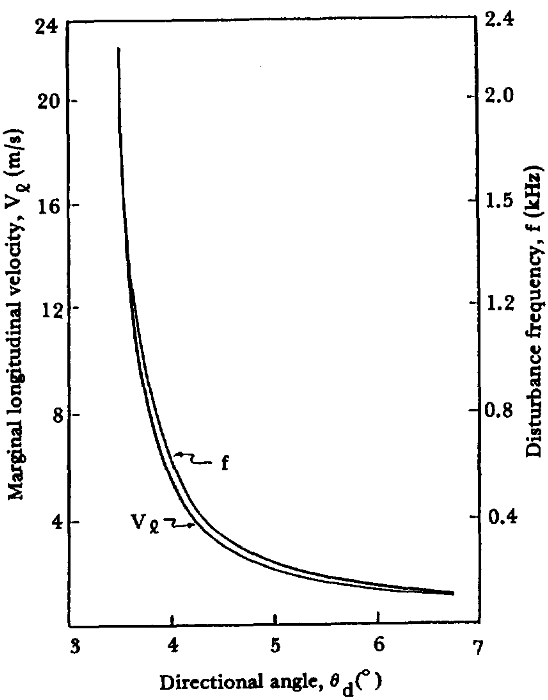


Figure 6. Variations of V_ℓ and f with θ_d for tap water and a 2 mm orifice diameter.

Illustrative example 3 to determine the marginal longitudinal velocity and the disturbance frequency in accordance with the variation of the ratio (ℓ/d_o) of orifice length ℓ to orifice diameter d_o in the same conditions of the example 2 with the exception that the orifice diameter is 184 μm and the directional angle is 4°.

[Solution]

From Eq.(17),

$$V_\ell = \frac{0.007248}{0.00826848 - 0.0068544(\ell/r_o)}$$

The marginal longitudinal velocity was plotted against the ratio of the orifice length

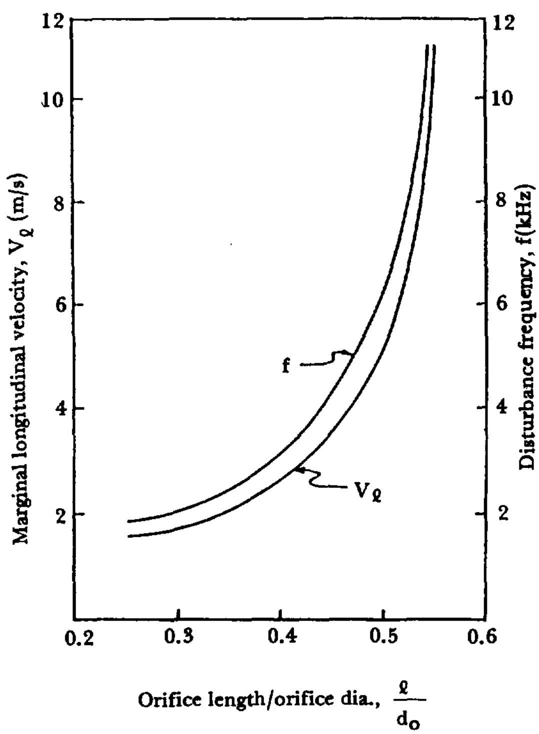


Figure 7. Variations of V_ℓ and f with $\frac{\ell}{d_o}$ for tap water and a 184 μm orifice diameter.

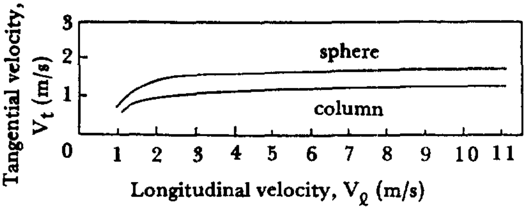


Figure 8. Marginal velocities of V_ℓ and V_t with variations of diameter of column or droplet from 180 to 1000 μm.

to the orifice diameter, and also the disturbance frequency was plotted against the same ratio as used in the calculation of the marginal longitudinal velocity in Figure 7.

The marginal longitudinal velocity and the disturbance frequency increase with increase of the ratio, which implies that the frictional loss increases with increase of the ratio of (ℓ/d_o).

Illustrative example 4 to describe the relationship between the marginal longitudinal velocity and the marginal tangential velocity on the droplet size under the conditions;

liquid temperature, t = 30°C
orifice length, ℓ = 0.10 mm
directional angle, $\theta_d = 4°$
mechanical viscosity as estimated, $\eta = n\mu$, n=20

[Solution]

Eqs. (4), (5) and (17) were used to compute the marginal longitudinal velocity V_ℓ and the marginal tangential velocity V_t depending on the droplet sizes from 180 μm to 1000 μm, and the calculated values were same as shown in Figure 8.

The marginal tangential velocities were very limited with low values of about 2 m/s as compared to the marginal longitudinal velocities being comparatively high values, especially on smaller droplets.

Therefore, good atomization needs comparatively high values of the longitudinal force as compared with low values of the tangential foce so as to produce the desirable size droplets.

IV. Conclusion

Two mechanical forces resulting from the functions of the swirl groove and the swirl chamber – the longitudinal direction force and the tangential direction force – had their own characteristics in the processes of disintegration.

Although tangential forces seemed to act on the ligament of the droplet emitting from the nozzle as shear force, the magnitudes were limited to be less than 2.4 m/s on the criterion of the water droplet diameter of 100 μm, which could be computed from the derived equation:

$$V_{ot} = \left(\frac{8g\sigma}{d\gamma}\right)^{1/2}$$

The longitudinal forces were estimated to affect atomization sensitively according to the directional angle of the flow to the nozzle axis and the magnitudes were relatively high values as compared with the tangential forces,

$$V_\ell = \sigma\left[\frac{1}{2}\rho_a \sin 2\theta_d - 4(\mu+\eta)\frac{\ell}{r_o}\right]^{-1}$$

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