

A MODEL STUDY OF LIQUID ATOMIZATION

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ABSTRACT

A photographic analysis of the complex process of the atomization of a liquid jet in a gaseous environment has been studied using a model, the dimensions and fluid characteristics of which are determined by similarity criteria. The jet fluid and the gaseous environment were simulated by two immiscible liquids viz, a sugar solution and a transparent oil respectively. The influence of viscosity, surface tension and density of the jet fluid on the atomization characteristics has been analysed. The velocity for the onset of secondary atomization has been determined with various fluid properties and from the above study, two non-dimensional parameters corresponding to this condition have been obtained.

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LIST OF SYMBOLS

A	=	constant term
D	=	dimensionless droplet diameter
F	=	resulting force from surface tension
$H = d/v_o t$	=	Homochronity number
K	=	constant term
L	=	break up length
$M = \mu_1 / \mu$	=	viscosity ratio
$N = \rho_1 / \rho$	=	density ratio
P, P_g	=	dimensionless liquid, gas pressure
Q	=	volumetric discharge
R	=	dimensionless radial co-ordinate
$Re = \frac{2v\rho a}{\mu}$	=	Reynolds number based on nozzle diameter
$Re_1 = \frac{2v\rho b}{\mu} av$	=	Reynolds number based on jet diameter
S	=	dimensionless space
T	=	dimensionless time
U, V	=	dimensionless gas, liquid velocity
$W = \frac{2\rho w^2 a}{\sigma}$	=	Weber number based on nozzle diameter
$W_1 = \frac{2\rho_1 w^2 b}{\sigma} av$	=	Weber number based on jet diameter
X, Y, Z	=	dimensionless co-ordinates
$Ze = \frac{\mu}{\sqrt{2\rho\sigma a}}$	=	Ohnesorge number based on nozzle diameter
$Ze_1 = \frac{\mu}{\sqrt{2\rho\sigma b} av}$	=	Ohnesorge number based on jet diameter
Θ	=	absolute temperature $^{\circ}K$
Θ_c	=	absolute critical temperature $^{\circ}K$
a	=	nozzle radius
b	=	initial radius of the jet
b_{av}	=	average radius of the jet
c	=	droplet diameter

d	= nozzle diameter
e	= natural logarithmic base
f	= function of non-dimensional groups
g	= acceleration due to gravity
i, j, k	= vector notations
l	= length co-ordinate
m	= wave number
n	= constant term
p	= liquid pressure
p_o	= liquid pressure at a definite point
p_i	= liquid pressure inside the droplet
p_a	= air pressure
p_s	= pressure due to interfacial tension
p_g	= surrounding gas pressure
q	= time rate of growth of disturbance
r	= radial co-ordinate
r_1, r_2	= radii of curvature of the droplet.
t	= time co-ordinate
t_o	= duration of the process
u	= gas velocity
u_1	= critical gas velocity for break up of the droplet
v	= liquid velocity
v_1	= velocity of the droplet
v_o	= discharge velocity of the liquid
v_m	= mean liquid velocity
w	= relative velocity of liquid jet
w_1	= relative velocity of liquid droplet
x, y, z	= normal cartesian co-ordinates

- μ, μ_1 = absolute viscosity of liquid, gas
 ρ, ρ_1 = density of liquid, gas
 σ = interfacial tension between two fluids
 σ_0 = interfacial tension at 0°C
 θ = temperature in 0°C
 Φ, Ψ = velocity distribution functions
 π = 3.14159
 α = amplitude of disturbance at time t
 α_0 = initial amplitude of disturbance
 γ = kinematic viscosity of liquid
 γ_1 = kinematic viscosity of gas
 λ = wave length

Superscript

- ' = real system
 '' = model system

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I INTRODUCTION

When a jet of liquid issues from a nozzle into gaseous surroundings, its shape is distorted by certain disturbances. These disturbances may be vibrations of the injector, imperfect roundness of the nozzle, presence of dust particles in the orifice and the influence exerted on the jet by the surrounding gas. These distortions start from the tip of the nozzle and the jet becomes unstable i. e., the distortions never decay to zero, but continue increasing in amplitude and finally cause disintegration into droplets. This process of disintegration is known as atomization and it consists of two stages, primary and secondary. In the primary stage, atomization takes place due to initial disturbances and surface tension. In the secondary stage, the disintegrated drops are further split into smaller droplets by the effect of fluid dynamics i. e., the simultaneous effects of inertia, surface tension and viscosity.

Analytical description of the atomization process is extremely complex owing to great mathematical difficulties encountered. Therefore, the investigation of the atomization process is usually experimental. This method however may also have great difficulties due to the small size and relatively large velocities of the droplets formed.

The object of the present study is to conduct a model test as described by Popov (1)* of the phenomenon of atomization of a liquid fuel, the environmental properties of which are close to its critical point i. e., high temperature and pressure, and also to observe the effects of fluid properties and fluid dynamics on the secondary atomization process. This model test facilitated the investigation by making larger dimensions and smaller velocities possible. A proper choice of liquids was made to represent the jet fluid and its surrounding medium.

* Bracket refers to reference.

This choice was governed by the necessity to satisfy the various criteria of similarity. With the selection of liquid-liquid system in the model test the effects of compressibility and evaporation which are present in the real system (liquid-gas) were eliminated.

The jet is formed by injecting one liquid into a large immiscible transparent quiescent medium of the surrounding liquid. By studying the behaviour of this model jet, the nature of the disintegration of a real jet whose environment is near the thermodynamic critical point of the injected liquid can be studied more effectively as the influence of thermodynamics, heat and mass transfer is completely eliminated. Due to transparency of the surrounding region, the jet behaviour can be clearly observed, photographed at gradually increasing velocities and subsequently a photographic analysis can be made.

The interactions between the jet and the surrounding environment in the region where atomization takes place were investigated. The velocity of the jet at which secondary atomization occurs was determined for different nozzle diameters, density, viscosity and surface tension. The role played by each of these in causing instability, disintegration of the jet and subdivision of droplets was examined by taking a large number of photographs.

A review of earlier disintegration theories which has a direct bearing on this matter was made and the results obtained from the present study were correlated with some earlier observations. An attempt is made to find a nondimensional parameter which will determine the onset of secondary atomization.

II GENERAL NATURE OF A SUBMERGED JET

A submerged jet occurs when a fluid is discharged into a fluid at rest. A surface of separation arises due to the velocity difference between the jet and the surrounding region leading to the formation of eddies which give rise to a pronounced degree of instability. These eddies move in a random fashion resulting in a lateral mixing process. The kinetic energy of the incoming fluid is steadily converted into the kinetic energy of turbulence and the latter steadily decays due to viscous action. The flow velocity continues to decrease and the fluid from the surrounding region is accelerated as it is entrained. As a result, the cross section of the jet will steadily increase in magnitude with distance from the efflux section.

A schematic longitudinal section of the turbulent submerged jet is shown in figure 1 b. The outer boundary represents the surface on all points of which the velocity is equal to zero. There are three distinct regions of the flow. The region I consists of an annular mixing region surrounding a central core, near the exit of the nozzle, in which velocity is constant and equals to outflow velocity. This region extends to the end of this core (about 5 nozzle diameters). In region II, known as the transition region, mixing occurs throughout the entire section and the central velocity decreases with increase in distance. This region extends to a distance of about 8 nozzle diameters. As the fluid enters the region III, called the main region its velocity profiles reach an asymptotic state. In this region, the central velocity is inversely proportional to the distance from some point O near the jet mouth and all profiles are similar. The end of this region occurs when the centre line velocity becomes of negligible magnitude at a distance of about 100 nozzle diameters from the efflux section.

III REVIEW OF JET DISINTEGRATION STUDIES

The disintegration of a liquid jet depends on the degree of its instability. In some cases, atomization does not occur for some time after the liquid jet leaves the nozzle; in others, atomization occurs very close to the nozzle. There are three types of break-up as shown in figure 2. The first type occurs at low velocities. This was first studied by Rayleigh (2). Neglecting the effects of the surrounding medium, he considered the stability of a nonviscous cylindrical liquid column by imposing an arbitrary small disturbance on the surface of the liquid jet. The equation for arbitrary small disturbance is of the form

$$a = a_0 e^{qt} \left(m \frac{x}{b}\right)$$

where a_0 is the initial amplitude of disturbance, q is the time rate of growth of amplitude, x is the axial distance, b is the initial radius of the jet and m is the wave number. The wave length of disturbance λ is given by the equation $\lambda = 2\pi b/m$. He had shown that the deformation due to this disturbance is stable or unstable depending on whether the wave length λ of the varicosity* is less or greater than the circumference of the cylinder. By calculating the change in potential and kinetic energy from the unperturbed condition, he had also shown that the maximum instability i. e., the kind of disturbance which leads most rapidly to the disintegration of a cylindrical mass, occurs when $\lambda = 4.51 \times 2 b$.

In the second type, as the velocity of the jet increases, the jet assumes a wavy form due to the resistance of the surrounding medium. Here the resisting force due to viscosity of the surrounding medium is greater than the surface forces.

Weber (3) had shown that q , the time rate of growth of disturbance depends on the dimensionless term $\frac{2\rho_1 a w^2}{\sigma}$ which is known as Weber number W . It represents the ratio of inertia to surface tension

* varicose means periodically narrower and wider.

force. He determined the value of λ for which q is maximum and its value increases with increase in viscosity of the jet fluid.

In the third type, the liquid issues from the nozzle at such a speed that its inertia is too great to allow any marked oscillation of either type to form along the jet surface. The droplets already formed are further subdivided at a greater rate, under the combined effect of inertia, surface tension and viscosity.

A photographic investigation of a jet of several liquids was made by Haenlin (4). He arrived at the conclusion that there were four separate and distinct processes responsible for the eventual disintegration, namely:

- 1) Break up into drops due to rotationally symmetric oscillations of the jet surface, due to the effect of surface tension and primary disturbances. [figure 2a]
- 2) Break up into drops due to oscillations with slight additional effect of air friction. [figure 2b]
- 3) Break up through waviness of the jet assisted by air friction [figure 2c]
- 4) Complete and immediate disruption of the jet due to the chaotic dispersion of the liquid.

He had also shown the variation of the break up length i. e. , the distance from the nozzle to the point of break up, with increase in velocity of the jet. [figure 2d]

Ohnesorge (5) had shown that the break up length of a jet passes successively through three phases and the transition from one phase to the next occurs at increasingly higher Reynolds numbers. It is also a function of a dimensionless term, containing viscosity, surface tension, density and orifice diameter :

$$Ze = \mu / \sqrt{2 \rho a \sigma}$$

which is known as Ohnesorge number. This number is in fact a function of Reynolds number and Weber number. If the Reynolds number is high

enough, direct atomization takes place without intermediate steps.

Probably a more satisfactory explanation of the disintegration of a high speed jet is that, proposed by Castleman (6) and referred to as the ligament* theory. According to this theory, "a portion of the mass of the liquid is caught up by the passing air at a point where its surface is ruffled and, being anchored at the other end, is drawn into a fine ligament. This ligament is quickly cut off by the rapid growth of a dent in its surface, and the detached mass, being very small is quickly drawn up into a spherical drop". If the ligaments formed are of such lengths as to be unstable, the disturbances caused by the resistance of the passing air are sufficient to initiate their immediate collapse.

Tomotika (7) analysed the instability of a long cylindrical column of viscous liquid in an infinite mass of another liquid of different viscosity and density. He concluded that the wave lengths are the smallest when the two viscosities are almost equal. Maximum instability occurs when this viscosity ratio takes some finite values and it increases indefinitely when the ratio tends to zero or infinity.

By assuming that the break up of drops occurred when the drag forces exceeded the inertia forces by a certain (experimentally determined) factor, Littaye (8) derived the following equation for the criterion of secondary atomization:

$$\frac{\rho_1 w_1^2 c}{\sigma} \simeq \frac{N^{1/3} W^{2/3}}{2} = \text{Constant.}$$

where w_1 is the relative velocity of the droplet, c is the diameter of the droplet formed and N is the ratio of gas to liquid density.

Miesse (9) had shown the variation of disintegration wave length λ as a function of $\sqrt{W}$ for different values of Ze . He concluded that the boundary between two regions of atomization occurs for $\sqrt{W} = 8.95$.

*refers to the shape assumed by the fluid which is pulled away from the surface of the jet.

Kuehn (10) made extensive studies of sprays using different liquids and injection pressures. He came to the conclusion that at low injection pressures, the effect of viscosity is predominant while at higher pressures, the effect of interfacial tension (liquid / adjoining gas) is predominant.

The effect of the variation in air pressure around a droplet was considered by Klusener (11). If the droplet is in a state of equilibrium, the outer pressure p_a and the interfacial tension pressure p_s give rise to a pressure p_i inside the droplet, and this internal pressure is constant at any point on the surface. Hence,

$$p_i = p_a + p_s = \text{Constant.}$$

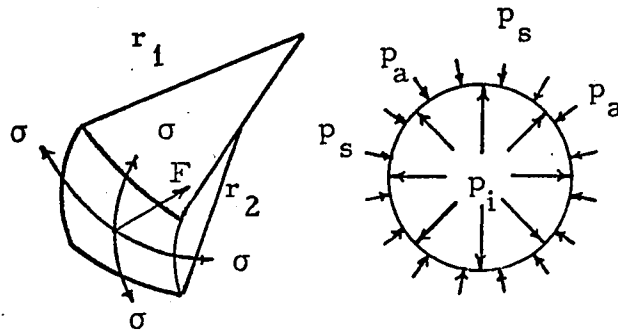


Figure 1 a

Diagram of Forces Acting on a Droplet.

r_1, r_2 = radii of curvature.

σ = interfacial tension (liquid/air)

F = resultant force due to interfacial tension (liquid/air)

p_i = pressure inside the droplet

p_a = air pressure

p_s = pressure due to interfacial tension (liquid/air)

The direction of the resultant interfacial tension p_s on the the droplet surface is inwards because the attraction between the free surface and inner liquid molecules is greater than that between the free surface and the adjoining air just over it. According to Klusener, "The droplet will be stable so long as any change in the air pressure p_a from one point on the surface to another can be balanced by a change in the surface tension pressure such that p_i remains constant. At a point where p_a increases, the droplet will become flatter due to the decrease in the value of p_s . If the value of p_s is small compared with p_a , then any appreciable change in p_a cannot be balanced by a corresponding change in p_s to keep the value of p_i constant. The outer pressure p_a may then change the shape of the droplet in such a way that a further decrease occurs in p_s at certain points and finally causes the collapse of the droplet, splitting it into two or more smaller droplets. This division immediately increases the value of p_s by reducing the radius r , and p_s may now be large enough to accomodate the variations in air pressure p_a . If p_s is still too small, further sub-division will take place until a droplet is obtained so small that its interfacial tension pressure p_s is large enough to ensure a constant value of p_i for all points on the droplet surface."

Lane (12) studied the break up of droplets in an air stream. He found that the secondary droplets into which a drop was shattered, were progressively smaller as the velocity of the air stream was increased. Due to the variation of aerodynamic pressure over a droplet placed in an air stream, the start of its sub-division takes place according to a relationship of the form : $(u_1 - v_1)^2 c = \text{Constant}$, where u_1 is the critical velocity of air required to break the droplet ; v_1 is the velocity of the drop and c is the diameter of the drop.

According to Hinze (13) there is a critical velocity at which the splitting of the drop takes place depending on the liquid viscosity, as it will delay and damp out any tendency for deformation.

IV SIMILARITY CRITERIA FOR ATOMIZATION

a) Derivation of Similarity Laws

The criteria for similarity are determined according to the method proposed by Popov (1), by considering the equation of motion for a fluid element of the jet and the surrounding gaseous medium. From the Navier Stokes Equation, the motion of an element of fluid can be analytically described as :

$$\frac{\delta v}{\delta t} + (v \text{ grad}) v = g - \frac{1}{\rho} \text{ grad } p + \frac{\mu}{\rho} \Delta v \quad 1)$$

$$\text{The continuity equation is : } \text{div } v = 0 \quad 2)$$

where t , g , v , p , μ , ρ denote the time, acceleration due to gravity, velocity, pressure, viscosity, and density respectively. To obtain the solution for the pressure and the three velocity components, four equations are necessary. The other two equations can be found from the boundary conditions of pressure and the the distribution of liquid velocity at the exit of the orifice. The pressure difference which arises through the action of interfacial tension between the liquid and the adjoining gas, can be written as :

$$p = p_g + \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \quad 3)$$

where p is the liquid pressure, p_g the gas pressure, and r_1 and r_2 are the principal radii of curvature of the surface element. When $r_1 = r_2 = c/2$ the equation (3) takes the form :

$$p = p_g + \frac{4\sigma}{c} \quad 4)$$

The other boundary conditions are given by the distributions of liquid and gas velocities v and u respectively, at the exit orifice

$$\text{i.e., } v = \phi(r, \gamma, t); \quad u = \psi(r, \gamma_1, t) \quad 5), 6)$$

where r is the radius for any outlet section of the nozzle.

The functions 5 and 6 contain the kinematic viscosity terms γ, γ_1 since velocity distribution depends on the internal resistance of the fluid.

All the variables in the above equations are made dimensionless by introducing the following units of measure :

d diameter of the exit orifice, t_o duration of the process, $v_m = 4Q/\pi d^2 t_o$, mean exit velocity of the liquid, u denotes the gas velocity, p_o pressure at a definite point within the system. ρ_1, μ_1 denote the density and viscosity of the surrounding gaseous medium. It can be written now :

$$v = v_m V, u = v_m U, t = t_o T, x = d X, y = d Y, z = d Z, l = xi + yj + zk = d (Xi + Yj + Zk) = d S, r = d R, c = d D, \mu_1 = \mu M, \rho_1 = \rho N$$

where the capital letters denote the corresponding dimensionless magnitudes, for example U, V denote the dimensionless distribution of velocity at the exit orifice, X, Y, Z denote the dimensionless coordinates, M and N represent the ratios of viscosity and density between the two fluids and so forth.

Taking into account that scalar components of $\delta v / \delta t$ are of the form $\delta v_x / \delta t$, those of $v \text{ grad } v$ of the form $\delta v_x^2 / \delta x$, those of Δv of the form $\delta v_x^2 / \delta x^2$ etc. the equations 1, 2 and 4 can be transformed to :

$$\frac{v_m}{t_o} \frac{\delta V}{\delta T} + \frac{v_m^2}{d} (V \text{ grad}) V = g - \frac{1}{\rho} \frac{p_o}{d} \text{ grad } P + \frac{\mu}{\rho} \frac{v_m}{d^2} \Delta V \quad 7)$$

$$\frac{v_m}{d} \text{ div } V = 0 \quad 8)$$

$$p_o P = p_o P_g + \frac{4}{d} \frac{\sigma}{D} \quad 9)$$

By dividing the equations 7, 8, and 9 by v_m^2/d , v_m/d and p_o respectively the following dimensionless equations are obtained.

$$\frac{d}{v_m t_o} \frac{\delta V}{\delta T} + (V \text{ grad})V = \frac{g d}{v_m^2} - \frac{P_o}{\rho v_m^2} \text{grad } P + \frac{\mu}{\rho v_m d} \Delta V \quad (10)$$

$$\text{div } V = 0 \quad (11)$$

$$P = P_g + \frac{4 \sigma}{p_o d} D \quad (12)$$

Considering the gas flow two equations similar to 10 and 11 are obtained.

$$\frac{d}{v_m t_o} \frac{\delta U}{\delta T} + (U \text{ grad})U = \frac{g d}{v_m^2} - \frac{P_o}{\rho v_m^2} \frac{1}{N} \text{grad } P_g + \frac{\mu}{\rho v_m d} \frac{M}{N} \Delta U \quad (13)$$

$$\text{div } U = 0 \quad (14)$$

Introducing the respective measuring units, equations 5-6 take the form as

$$v_m V = \phi(d R, \gamma, t_o T) \quad (15)$$

$$v_m U = \psi(d R, \gamma M/N, t_o T) \quad (16)$$

The preceding procedure applied for reducing the equations to dimensionless form cannot be further used here since the equations 13 and 14 are not given in concrete form. As the left hand side of these equations shows the dimension of velocity so the function of the right hand side must show the dimension of velocity. In the functions $R, M, N,$ and T are dimensionless, so the coefficients which are evidently made up of the magnitudes $d, \gamma, t_o,$ must have the dimension of velocity (length/time). Therefore, two combinations of the form $d/t_o, \gamma/d$ are taken into account in each function from the coefficients $d, \gamma,$ and t_o . If the equations 13 and 14 are divided by v_m there are obtained on the left hand side the dimensionless velocities U, V and on the right hand side from d/t_o and γ/d , the dimensionless criteria

$$\frac{d}{t_o v_m} = \frac{1}{H} \quad \text{and} \quad \frac{\gamma}{v_m d} = \frac{1}{Re}$$

where Re is the Reynolds number and H is the Homochronity number.

Equations 13 and 14 can now be written as :

$$V = \phi(Re, H, R, T) \quad (17)$$

$$U = \psi(Re, H, R, M, N, T) \quad (18)$$

The integration of the system of differential equations for the liquid and gas with the boundary conditions will yield the functions of V, U, P, P_g and D , that will evidently contain the space term S and time T , from the comparison of two situations. The size of the droplet, therefore can be expressed as a function of the form :

$$D = c/d = f \left(\frac{d}{v_m t_o}, \frac{g d}{v_m^2}, \frac{P_o}{\rho v_m^2}, \frac{\mu}{\rho v_m d}, \frac{\sigma}{P_o d}, M, N, U, V, S, T \right) \quad 19)$$

It is known that every similarity criterion can be replaced by the exponential product formed with any other criteria of the criterial equation 19. Therefore, a substitution can be made for $\frac{\sigma}{P_o d}$ by the following non-dimensional group.

$$\left(\frac{\sigma}{P_o d} \right)^{1/2} \left(\frac{P_o}{\rho v_m^2} \right)^{1/2} \frac{\mu}{\rho v_m d} = \frac{\mu}{\sqrt{\sigma \rho} d} = Ze \quad 20)$$

Ze represents the criterion introduced by Ohnesorge (5) for the disintegration of a droplet without the effect of air forces. The dimensionless constant Ze combines density, viscosity and interfacial tension of the liquid and the nozzle diameter. It gives a characteristics value of the liquid for atomization. Reynolds number Re compares the inertia force with the viscous force and it determines the turbulence of the flow. The homochronity number H establishes the relationship between the parametric value of the time t_o and its characteristics value d/v_m which represents the time interval for the rate of the changes in the system as a result of the motion of the medium. So H represents the sense of a dimensionless time. For similar processes, this number can be written as :

$$\frac{v'_m t'_o}{d'} = \frac{v''_m t''_o}{d''} \quad 21)$$

where the full scale and the model magnitudes are denoted by single and double prime respectively. Since $v_m = 4Q/\pi d^2 t_o$ the equation 19 takes the form :

$$\frac{Q'}{d'^3} = \frac{Q''}{d''^3} \quad \text{or} \quad \frac{Q'}{Q''} = \frac{d'^3}{d''^3}$$

So the outflowing liquid volume Q' of the full scale and of the model Q'' must, during the corresponding times t_o' and t_o'' stand in the same ratio as the volumes d'^3 and d''^3 or the volumes of the systems. For a steady flow this geometric condition is evidently satisfied. Hence, the criterion H need not be further considered. The disintegration of the jet takes place due to the effect of inertia, surface tension and initial disturbance. The movement of a droplet may be affected by the action of gravity when its velocity is very low but gravity has no role on the process of secondary atomization which takes place at much higher velocity. So the group gd/v_m^2 , known as Froud number which takes account of gravity force is not significant either for a horizontal jet or a vertical jet at the point of secondary atomization. Therefore, this number is similarly omitted. It is assumed that there is conservation of momentum at every section of the jet i. e., the pressure in the jet is constant. For an incompressible fluid, the material property or the density is constant. Therefore, the criterion, $p_o / \rho v_m^2$ known as Euler number is deleted also.

The criterial equation 19 for the liquid atomization at large velocities can therefore be reduced to the following simplified form :

$$D = f (Re, Ze, M, N, U, V, S, T) \quad 22)$$

b) Selection of System Fluids, Nozzles and Pump

Two model fluids which represent the actual jet fluid and the surrounding environment, were chosen largely on the basis of the preceeding similarity analysis. For an identical atomization process to take place in the model the conditions for $D' = D''$ i.e., $Re' = Re''$, $Ze' = Ze''$, $M' = M''$, $N' = N''$ etc. must be fulfilled. The condition for the distribution of liquid velocity at the exit section ($V' = V''$) was satisfied by achieving geometric similarity of the nozzle and the supply system. The number of bends, sharp edges which could cause initial disturbance was made as small as possible. The atomization process was conducted in a closed chamber without any specific motion of the surrounding fluid. So the condition for the distribution of gas velocity at the exit section ($U' = U''$) was not considered. The time can be counted after the start of the process assuming $V = 0$ for $T = 0$ i.e., no liquid flow takes place at the start of the process. Hence at corresponding points ($S' = S''$) and at corresponding times ($T' = T''$), the atomization process in the model test will be similar to the actual system.

The actual system to be considered, for example, could be n-heptane, n-octane or liquid Co_2 jet at their respective critical pressures and at temperatures (near critical) of 250° , 275° and $25^\circ C$ respectively. To satisfy the similarity criteria, colourless transparent mineral oil was selected for the gaseous environment and a sucrose solution for the jet fluid. The sucrose solution was prepared by adding chemical sugar to ordinary water at $25^\circ C$. At this temperature, its viscosity varies from 0.893 to 44.3 c. p. and the density from 1.0 to 1.5 gm/c. c. The physical properties of n-heptane, n-octane, liquid Co_2 at the described values of pressure and temperature and those of mineral oil at $25^\circ C$ are listed below.

	density		viscosity		interfacial tension
	ρ (gm/c. c)		μ (c. p.)		σ (dynes/cm)
n-heptane	0.234 (15) *		0.0845 (18)		0.228 (liquid/air) (19)
n-octane	0.234 (15)		0.0955 (18)		0.448 (liquid/air) (19)
liquid Co_2	0.665 (17)		0.065 (17)		0.463 (liquid/air) (16)
mineral oil	0.840		3.24		48.0 (oil / water) (14)
water	1.00		0.893		72.0 (water/air)

During the selection of the system fluids, care was taken to insure that no mixing or any chemical reaction can take place between the fluids and that the surrounding medium is clear and transparent. This was to facilitate photography. From the above considerations, a solution prepared from water was found to be most suitable, since water and oil are immiscible in nature.

The similarity criteria were fulfilled for 45% concentration of sucrose solution. At the same temperature and pressure conditions described for n-heptane, air has a viscosity of 0.0277 c. p. and a density of 0.064 gm/c. c. With this system, the similarity criteria take the following forms :

$$M' = (\mu/\mu_1)' = 0.0845/0.0277 = 3.25$$

$$M'' = (\mu/\mu_1)'' = 10.4/3.24 = 3.2$$

$$N' = (\rho/\rho_1)' = 0.234/0.064 = 3.66$$

$$N'' = (\rho/\rho_1)'' = 1.201/0.84 = 1.45$$

In the model system the condition of equal viscosity ratio was achieved but the condition of equal density ratio was not. The density ratio could have been made equal either by increasing the density of sucrose to 5.1 gm/c. c or by using an oil of density 0.328 gm/c. c. But the density of sucrose can not be raised above 1.5 gm/c. c as the water becomes saturated after addition of sugar 60% by weight at room temperature

* bracket refers to reference.

and moreover its viscosity increases with increase in density. Since the density of most of the oils lies in the range 0.7 to 0.9, a clear oil having a density of 0.328 gm/c.c was not found. Therefore, the density of the oil as used in the experiment is more than the desired value, hence it may have some effect on the atomization process. The normal pressure forces acting on the moving droplet (from the surrounding medium) will be more and it will slightly hasten the splitting up process.

The nozzle size and the velocity of the jet for similar type of atomization were determined for the model system from the conditions : $Re' = Re''$ and $Ze' = Ze''$.

$$\frac{v' d' \rho'}{\mu'} = \frac{v'' d'' \rho''}{\mu''} \quad 23)$$

$$\frac{\mu'}{\sqrt{\sigma' \rho' d'}} = \frac{\mu''}{\sqrt{\sigma'' \rho'' d''}} \quad 24)$$

$$d'' = d' (\mu''/\mu')^2 (\rho' / \rho'') (\sigma' / \sigma'') \quad 25)$$

The nozzle diameter d'' in the model test is obtained from equation 25. The corresponding atomization velocity is determined from the equations 23 and 24 as :

$$(v' / v'') = (\mu'' / \mu') (\sigma' / \sigma'') \quad 26)$$

From equations 25 and 26 it is apparent that by increasing the viscosity and reducing the surface tension and the density of the jet fluid, the atomization velocity can be reduced and the experiment can be performed with a larger diameter nozzle. It is then possible to analyze the atomization phenomenon of a higher velocity jet by conducting a simple model test.

From the similarity criteria, three different nozzle diameters were determined corresponding to the three different systems in an environment of air near their respective critical point. A sample calculation to arrive at the above nozzle diameters is shown below. The capacity of the pump was determined from the consideration of the amount of solution required to obtain the desired jet velocity in the model.

A n-heptane ($C_7 H_{16}$) jet of diameter 0.5 mm at $250^\circ C$ and 25 atmospheres of pressure is considered. The viscosity at $250^\circ C$ is determined by the relation (18)

$$\mu = A / (K + \theta)^n \text{ where } A = 445.97, K = 180.14 \text{ and } n = 2.1871$$

$$\mu = 445.97 / (180.14 + 250)^{2.1871} = 0.0845 \text{ c.p.}$$

The interfacial tension (liquid/air) at $250^\circ C$ was determined from (19) by the relation $\sigma = \sigma_o (1.0 - \theta / \theta_c)^{1.21}$ where σ_o refers to the interfacial tension (liquid/air) at $0^\circ C$. σ_o is calculated by finding the Parachor number from (20). Parachor number for n-heptane is : $4.87 \times 7 + 17.1 \times 16 = 307.6$. With this value, σ_o is found to be 15 dynes/cm. The critical point temperature θ_c was found to be $540^\circ K$ from (15). Thus $\sigma_{250} = 15.0 (1.0 - 523 / 540)^{1.21} = 0.228 \text{ dynes/cm}$. The density, and viscosity of air at the same temperature and pressure as that of n-heptane are obtained from (15 and 17) and those values are 0.064 gm/c.c and 0.0277 c.p. respectively. The model fluid of 45% concentration of sucrose solution has a viscosity of 10.4 c.p. ; density of 1.201 gm/c.c and interfacial tension (oil / water) of 48.0 dynes/cm. From the similarity criteria

$$(\mu'' / \mu') = (10.4 / 0.0845) = 123$$

$$(\sigma' / \sigma'') = (0.228 / 48) = (1.0 / 211)$$

$$(\rho' / \rho'') = (0.234 / 1.201) = (1.0 / 5.13)$$

From the equation 25,

$$(d'' / d') = 123^2 (1.0 / 5.13) (1.0 / 211) = 14.1$$

Considering 0.5 mm size of the nozzle in the actual system, the nozzle size for the model test was determined as 7.05 mm i.e., 0.278 inch.

Similarly the nozzle sizes in the test for the different systems are determined and their values are tabulated below :

System	Nozzle diameter
1. n- heptane / air	0.278 inch.
2. liquid Co_2 / air	0.516 inch.
3. n-octane / air	0.813 inch.

V EXPERIMENT FOR ATOMIZATION STUDY

a) Description of Equipment

An experimental set-up was designed in order to perform the photographic study of the atomization of a liquid jet. A tank of dimensions 12 in x 18 in x 48 in (capacity 55 gallons) was fabricated with glass walls for the purpose of the study. The tank was positioned on a table as shown in figure 3. At the bottom of the tank an outlet pipe of 0.5 in diameter was provided in order to drain the injected liquid back to the supply tank. In order to have this outlet pipe connection, one of the tank walls was fabricated with 0.25 inch thick plexiglass. It was observed that when the container was full of liquid, the stainless steel angles connecting the tank walls exhibited an outward bending due to the liquid pressure. This was prevented by means of mild steel frames fabricated with threaded rods fitted at suitable intervals along the height of the tank. It was also noticed that the cement joining the tank walls to the stainless steel angles was slowly being eroded due to some chemical reaction with the environmental fluid (oil) . This resulted in a colour change of the fluid making it semi-transparent presenting much difficulty for photography. This was successfully avoided by pasting a thick layer of epoxy glue over the surface of the cement in between the angles and the tank walls.

A 45 gallon oil drum was used as the container for the injected liquid. The inside surface of the container was painted in order to avoid the possibility of any rust formation.

A centrifugal pump coupled with a single phase A. C. motor (0.25 h. p.; 900 r. p. m.) was used to deliver a continuous discharge of up to 45 gpm at a head of 10 ft. The pump was connected to the supply tank through three gate valves and one union joint. The gate valve V 7 was used for draining the supply tank.

The suction and delivery pipes were of 1.25 in and 1.0 in diameter respectively and the discharge of the pump was controlled by means of a 0.75 in needle valve. A by-pass system was incorporated in the delivery line as shown in figure 3. The nozzle was fitted to the end of the main pipe by the internal thread at a position about 3 ft from the bottom of the experimental tank. A pipe of larger section was introduced in the flow circuit above the control valve NV in order to avoid the possibility of initial disturbance due to the valve opening, particularly at low velocity.

The pump and the liquid flow through the pipe caused a certain amount of vibration in the entire system. This resulted in transverse oscillations of the jet surface, causing alterations in its behaviour. To eliminate this effect, a flexible connection was provided in the main pipe; a heavy plate was attached to its lower portion [figure 4] just below this connection and it was placed over a mild steel plate above the top of the container. With the above arrangement, the vibration at the tip of the nozzle was completely eliminated. This was checked by observing no formation of waves at the tip of the nozzle when it just touches the liquid surface.

The velocity of the liquid jet was measured by the rise of the liquid column in the experimental tank over a specified time. For this purpose, a scale was attached to the front wall of the container and the readings were taken with the help of a magnifying glass. Each measurement was repeated three times and the average of those was taken as the effective reading.

b) Arrangement for Photography.

The arrangement for photography is shown in figure 5. A single lens reflex camera was placed at a distance of 4 ft in front of the experimental tank. The flash unit (Mecablitz 184) was placed at a distance of 6 ft behind the tank and its front wall was covered with a tracing paper to reduce the intensity of light. The flash unit was connected with the camera by a long flash cord. The back side of the experimental vessel was also covered with tracing paper to avoid any possible reflection and to provide a diffused lighting background. With the help of a stroboscope, the shape of the jet was first observed and the oscillating jet appeared to be stationary when its frequency is synchronised with flashes of the stroboscope. The stroboscope is used for the purpose of better visualisation as it provides an instant source of intense light at a particular region. The start of disintegration of a jet into a couple of smaller droplets was clearly observed and the point of secondary atomization was determined exactly. The stroboscope was then switched off and all the photographs were taken at a lens opening of 5.6 with only flash light. The above procedure eliminated the possibility of any stray light at the instant of photography. This arrangement was found to be the most suitable after making a few trials with different positions of the photographic units. All the photographs were taken with black and white Panatomic X film of 16 din after an initial trial with a higher speed film.

c) Experimental Procedure

A transparent oil (Mentor 29, supplied by Imperial Oil Ltd) was used in the experiment as the model environmental fluid. The density, viscosity and interfacial tension between the oil and water were 0.834 gm/c. c, 3.24 c. p. and 48 dynes/cm respectively. The oil was pumped from the oil drum to the main tank by means of a hand reciprocating pump. A sucrose solution was prepared with a specified concentration. Its density was determined by a hydrometer ; its viscosity with a 'Canon' viscometer by calculating the time during which a specified amount of the solution passed through its small constriction. The interfacial tension between oil and water was varied by adding Kodak Photo Flo Solution (normally used for wiping out minute traces of water left on film after processing), to the sucrose solution. The reduced surface tension values were taken from the Kodak specifications. In order to achieve a sharp contrast for photography, the sucrose solution was coloured with a dye 'Cresol Red'. This dye normally does not mix with oil but it was found later that due to the repeated use of the solution, particularly with high velocity jets , very slight mixing took place.

When the control valve was opened, the jet fluid passed through the oil medium and was deposited at the bottom of the experimental tank, thereby developing an interface with the oil. Due to the continued flow of the jet, the level of oil in the experimental tank continued to rise. This rise in oil level could influence the behaviour of the jet , but was avoided by maintaining almost a constant level of the interface by operating the drain valve about one inch below the interface, before the start of each observation. The drain valve was kept at such an opening that it drained almost an equal quantity of the sucrose solution as the inflow from the nozzle.

This means that the depositing fluid, before coming to rest and separating itself from the oil medium, was forced out through the drain valve. This process automatically contaminates the jet fluid to a certain degree. A small tank was introduced in the draining circuit of the jet fluid to enable removal of the contamination before its repeated use in the cycle of operation.

When the jet outlet was first opened, some air bubbles were observed in the jet. This was due to the presence of air trapped in the pipe. The formation of air bubbles altered the normal pattern of the jet behaviour. These air bubbles were eliminated by closing the valve V 1 and by-passing the liquid through the bleed valve and the flexible tube back to the small tank employed for separating the sucrose solution from oil. During the first operation of the bleed valve, it was observed that a certain amount of oil with the trapped air was forced out through the flexible tube.

After allowing the liquid jet to pass through the immiscible oil medium, it was observed that some sort of fungus growth was taking place after some time at the oil-solution interface. The growth of this fungus resulted in the formation of thread like structures which travelled through the oil medium from the interface. Sometimes these structures entered the region of the jet spread and were mixed in the cluster of droplets and appeared in the view of camera. This was avoided by filtering the sucrose solution before beginning the experiment and draining the fungus layered sucrose solution from time to time. A time interval was also allowed between the consecutive observations of the high velocity jet in order to allow the dispersed minute droplets to settle.

The nozzles the dimensions of which were determined according to similarity criteria, were fabricated with brass. With

these nozzles several photographs of the jet were taken for different flow regions, namely, laminar, transition and turbulent and the respective flow rates were measured using a stop watch. To determine precisely the onset of secondary atomization, 4 to 5 pictures were taken for each concentration. Approximately one roll of black and white film of 20 exposures was required for each nozzle and for each concentration of the solution. When photography was complete for each concentration, the negative was processed and checked for proper contrast on prints. Then the sucrose concentration was altered and similar photographs of the jet were taken for each concentration.

Before starting the observations, each time the whole piping circuit and the supply tank were washed and cleaned with plain water so that any solution of the old concentration remaining inside the pipe circuit was flushed. The experimental tank was also cleaned with acetone and glass cleaner so that no stains remained on the clear glass surface. The solution was again coloured and filtered so that traces of the minute fungus like structures, formed during the previous observations, were removed.

Altogether, eight series of observations were conducted. The first series was carried out with plain water (used as jet fluid) at room temperature with its normal physical properties (denoted as 0% conc. case I). The second and the third series were conducted with surface tension reduced to 50 and 30 dynes/cm (denoted as 0% conc. case II and case III) respectively. The remaining five series were carried out with increased viscosity and density of the jet fluid. The physical properties of these different concentrations of the jet fluid and the velocity for the start of secondary atomization corresponding to the respective nozzles and concentrations are described in table I, page 40.

VI DISCUSSION OF EXPERIMENTAL RESULTS

a) Photographic Analysis

A series of photographs were taken for each concentration of the jet fluid, of which three were selected for each nozzle and presented on each figure from 6 to 32. The first represents the jet prior to secondary atomization ; the middle one shows the beginning of secondary atomization and the third one, a velocity much higher than that corresponding to secondary atomization. For a jet fluid with 45% concentration of sucrose, six photographs are presented on two pages for each nozzle. Of these the first three show the views for velocities below secondary atomization; the fourth representing the velocity at secondary atomization, and the last two showing the jet at velocities above the onset of secondary atomization [figures 11, 12, 20, 21, 29, 30]. The photographs shown in figures 33 to 37 illustrate cup-like formations on the jet surface. Alternate nodes which appear on the jet surface above the point of break-up have maximum thickness at the centre and gradual contractions at the ends. The force of resistance from the surrounding medium acts more on the lower portion of each node. Therefore, each node gets deformed into a shape which has maximum thickness at the top and gradual contraction at the bottom. The contracted portion of a similar upper node moves further inside this configuration at higher jet velocity. This configuration is described as cup-like shape. This is formed due to the relative velocity between the cup and the jet and due to the resistance of the surrounding medium. Figure 38 represents the pattern of the jet break-up at different distances from the tip of the nozzle. Contractions in the jet profile, observed at low velocities are shown in figures 39 and 40. A comprehensive picture of the jet photographs are given in tables II, III and IV.

Proper contrast was achieved on prints by using a high contrast photographic paper F-5. In spite of this, sharp contrast was not achieved in some of the prints. This is due to the fact that proper contrast between the jet and its surrounding was not obtained due to slight amount of mixing of the dye of the jet fluid with the surrounding medium. All the prints are such made by adjusting the enlargement ratio so that the prints show the same size of the jet

at the exit of each nozzle. Hence the enlargement ratio for the smallest diameter (0.278 in) nozzle is maximum and due to this, the prints represent the minimum length of the jet and therefore comparatively less number of droplets were visible on the prints, particularly at the velocity corresponding to the onset of secondary atomization. From the photographs it is evident that the shape of the jet converges initially and diverges afterwards. If an envelope is drawn on the surface of disintegrated droplets, then region I will extend to the convergent portion of the jet from the nozzle tip and region II will indicate the atomization region. Region III is not so evident.

The behaviour of the jet with variation of velocity, surface tension, viscosity, density and nozzle diameters, as observed in this experiment, is described below under each sub-heading.

Effect of Velocity

When the velocity of the jet is very low, dripping takes place and the drops, as they pass through the surrounding medium undergo a series of oscillations [figures 11a, 20a]. The outstanding feature of a low velocity jet is the formation of a relatively large spherical mass of liquid at the extreme end of the column. Apparently an initial amount of injected liquid is retarded with respect to the remainder of the stream [figures 6a, 16a, 24a] resulting in a local concentration, which is pulled into spherical shape by the capillary action of the fluid. The mass continues to form until it becomes greater in dimension than that of the undisturbed jet. Then instability of the motion causes it to separate from the remainder of the liquid. and it proceeds as a single drop. Larger drops are formed in this manner. At higher velocities, the concentration of the liquid constituting the leading portion of the jet and the accompanying large droplets cease to appear in the photographs. The smaller size droplets increase in numbers and are formed closer to the

nozzle [figure 13 c]. The wave length of the oscillation decreases with increase in velocity [figure 6].

It was also observed that the break up length i. e. , length of the jet between the nozzle and the point of disintegration , decreased with increase in velocity in the lower range [figures 13, 19]. Previous experimental observations show that the break up length increases with increase in velocity of the jet in the absence of air motion [Reference 4, figure 2 d]. This is due to the fact that at high velocity the straight portion of the jet is same as the diameter of the nozzle, but at low velocity there is a gradual contraction of the jet profile from the tip of the nozzle [figure 39].

Above the velocity corresponding to the start of secondary atomization, cup like formations were observed in the jet surface and inside each cup, a thread like structure linking the centre of the cup and a similar upper cup was observed [figures 33 to 37]. The distance between the two consecutive cups, tends to increase downwards from the nozzle tip. At higher velocities cup-like formations appear closer to the tip of the nozzle and the linking ligament tends to become continuous up to a certain distance and breaks these shapes, resulting in greater number of droplets.

Effect of Surface tension

The behaviour of the leading portion of a jet depends on simultaneous effects of fluid pressure and surface tension of the liquid. At low velocity the leading portion will be formed primarily under the action of surface tension. The jet oscillates about the central axis and alternate elongations and contractions appear on the jet surface at periodic intervals above the point of break up [figures 9a, 16a]. It was observed that the drop forming process and the range of drop sizes depend on the manner in which the leading surface reacts to the

the combination of forces acting. Multiple drops are observed during dripping [figure 20 a] as the liquid is severely deformed by unequal surface and pressure forces. The shape of the liquid is so irregular that the capillary forces are incapable of gathering it into a single drop.

Photographs which were taken by reducing the surface tension to 50 and 30 dynes/cm, are shown in figures 7, 16, 25 and 8, 17, 26 respectively. It was observed that atomization takes place at much lower velocities and the size of the drop is also smaller. Figure 20 b shows the disintegration of a jet due to capillary action. With a surface tension of 30 dynes/cm, the atomization was found to take place at the minimum possible velocity required for the formation of the jet in case of nozzles of diameters 0.516 in and 0.813 in respectively.

Effect of Viscosity

Several photographs of the jet were taken with increase in viscosity of the jet fluid from 0.893 c. p. to 44.2 c. p. while maintaining the same viscosity of the environmental fluid 3.24 c. p.

It was found from the present experiment that the secondary atomization velocity did not vary appreciably with increase in viscosity of the liquid jet. Usually the viscosity of the jet liquid tends to decrease the turbulence of the flow and the rate of splitting of droplets already formed. So more viscous liquids will tend to disintegrate at higher velocities. This may not be always true as in the present case. Here the density of the surrounding liquid medium is greater than the density of the surrounding gas in the real system. Hence the rate of disintegration of the jet is increased. It can be seen from the experiment that the density of the surrounding medium has got greater effect on the jet velocity at the start of secondary atomization, than the viscosity of the

jet liquid. Moreover, the liquid turbulence accelerates the disintegration of the liquid jet by ruffling its surface close to the nozzle. But at the point of secondary atomization of a liquid jet, its viscosity has got probably little effect on the disintegration of the droplet.

With a viscosity of 44.2 c. p. wavy disturbances were found to appear on the jet surface at higher velocities [figure 14 c]. Formation of thin ligaments were observed. These ligaments were long and slow to collapse into droplets. During formation of ligaments fine threads of liquid are pulled away from the surface of the jet. At higher viscosities the jet was found to be more compact and penetrating.

Effect of Nozzle Diameter

It is a well known fact that the liquid jets from large nozzles penetrate farther than jets from small orifices. This is due to the reason that at the same discharge velocity, the momentum of the discharged liquid increases in proportion with d^2 (d is the nozzle diameter) while the area of the jet exposed to the resistance of the surrounding medium increases in proportion with d . Thus for larger nozzles, the resistance from the surrounding medium will be relatively smaller and the jet penetration will be larger. Most of the photographs showed this faster disintegration of small jets, other conditions being the same.

Effect of density

In the present experiment the density of the jet liquid was varied in the range (1.0 to 1.258 gm/c.c) while maintaining the same density of the environmental fluid 0.84 gm/c.c. The effect of the density of the jet liquid alone was found to be negligible. It was known from earlier studies (10) that liquids of higher density will produce more compact and penetrating jets which may be more difficult to atomize and disperse in the surrounding medium. Lee (21) had shown that the disintegration of a liquid jet in vacuum is much slower than in air and the jet breaks into relatively large drops in vacuum than in air. He had also shown that with increase in air density, the disintegration of the jet at a given distance from the nozzle becomes greater and the size of the droplets is also reduced.

Effect of distance from the nozzle.

The total length of the jet is shown on two photographs in the figure 38, the top of the second, being a continuation of the first. These photographs represent the disintegration of a low velocity jet at various distances from the nozzle. It is apparent from these photographs that the disintegration is a progressive affair, as the distance from the nozzle increases, so does the degree of atomization, until the drop velocity becomes so low that no further sub-division takes place.

b) Criteria for Secondary Atomization

The jet velocities were calculated by taking into consideration the respective nozzle diameters; these velocities are shown in table I as well as being given with the appropriate figure. With these velocities the following non-dimensional parameters were found for each nozzle and listed in table V.

$$W = \text{Weber No} = \frac{2 \rho_1 v^2 a}{\sigma}$$

$$Re = \text{Reynolds number} = \frac{2 v \rho a}{\mu}$$

$$Ze = \text{Ohnesorge number} = \frac{\mu}{\sqrt{2 \rho \sigma a}}$$

where v is the velocity of the jet. Since the velocity of the surrounding medium is zero, the relative velocity w is equal to the jet velocity v . The nozzle radius, viscosity, interfacial tension of the jet fluid, the densities of the liquid and environmental fluid are represented by a , μ , σ , ρ and ρ_1 respectively. It was observed from table V that the Weber number computed from nozzle diameter remains almost the same for each nozzle but varies with different nozzles. Littaye's (8) criterion for the onset of secondary atomization is

$$\frac{\rho_1 w_1^2 c}{\sigma} \approx \frac{N^{1/3} W^{2/3}}{2} = \text{constant.}$$

He considered the break-up of a drop of diameter c . The density of the surrounding medium ρ_1 is constant. So for each concentration the density ratio N is specified, but the Weber number varies with different nozzles. Therefore the quantity $N^{1/3} W^{2/3}$ does not remain constant. So Littaye's criterion for the onset of secondary atomization for a liquid jet is not verified.

The measurement of jet diameters was done just above the point where the node of the jet becomes first unsymmetrical or where the lumped mass is first formed. In most of the figures, at the point of secondary atomization there is no formation of any blob. In some of the figures where a blob is formed on the jet surface, the measurement of the jet diameter becomes rather difficult. But the blobs do not change their shape appreciably. The velocity of the blob as observed in the experiment is negligibly small compared to the velocity of the jet. So there is almost no change in mass conservation of the liquid at the point of measurement of the jet diameters and hence this measurement is justified. The average of these were calculated for three different nozzles of diameters 0.278, 0.516 and 0.813 inch respectively. Taking account of the size magnification ratio, the values of the average jet diameters for different nozzles are 1.96, 3.03 and 3.78 mm respectively. On the basis of these average jet diameters, the jet velocities for the start of secondary atomization and the nondimensional numbers were calculated. The nondimensional parameters-Weber number, Reynolds number and Ohnesorge numbers based on average jet radius b_{av} are denoted by W_1 , Re_1 , and Ze_1 respectively in tables VI and VII. Weber number has been found to remain constant [table VI] in the range of 1 to 4. The velocity for the onset of secondary atomization can be determined from this number for a particular jet fluid. Therefore this number can be described as the criterion for the beginning of secondary atomization for a liquid jet and from the present study its value varies from 1 to 4.

A number of previous investigators (22 to 25) have measured the critical conditions for break-up of drops in a gaseous medium. Merrington and Richardson (22) deduced that the critical speed corresponding to break-up of drops in still air occurs at Weber number of 7 to 10. Lane's (12) results indicated a critical value of 5.5 for the

Weber number which decreased with decrease in initial radius of the drop. Volynski (23) had shown that this critical value varies in the range of 11 to 15. All these previous investigators (22 to 25) had done experiments with the shattering of a drop. The present experiment is not concerned with the shattering of a liquid drop but it is concerned with the break-up of a liquid column or a stream. The object of the present experiment is to find out the condition for the secondary atomization which begins to occur for a liquid jet. The two situations are different and therefore Weber numbers are also different.

The Ohnesorge number which was found to vary over a wide range [table VI] was multiplied by the viscosity ratio and the following nondimensional number was obtained.

$$Ze_1 \times \mu_1 / \mu = \frac{\mu_1}{\sqrt{2 \rho \sigma b_{av}}}$$

where b_{av} is the average jet radius and μ_1 is the viscosity of the surrounding medium. [table VII]

The above nondimensional number was found to remain almost constant at 2.75×10^{-4} . This parameter does not contain any velocity term but there is a velocity term implicit in this parameter. The average jet diameter is in fact, a function of jet velocity. This number depends on jet velocity in addition to the physical properties of the fluid. Therefore it provides an important information for the secondary atomization of a liquid jet. Hence it can be described as another criterion for secondary atomization and from this study its value remains almost constant at 2.75×10^{-4} .

CONCLUSION

This photographic study of a model liquid jet, in an immiscible liquid medium, has shown how the disintegration of a real fluid jet in a gaseous environment actually takes place due to the action of interfacial tension, viscosity and inertia.

The velocity of the jet for the onset of secondary atomization has been found to

- a) decrease with increase in nozzle diameter
- b) decrease with decrease in interfacial tension.
- c) vary not significantly with viscosity.

From the experimental data, for the start of secondary atomization two non-dimensional parameters are determined. One is Weber number and the other is Ohnesorge number multiplied by the viscosity ratio. By considering the average jet diameter, the Weber number has been found to remain constant in the range of 1 to 4. The other non-dimensional term depends on the jet velocity and describes the fluid characteristics for which atomization can take place. By considering the average jet diameter, the value of this number remains almost constant at 2.75×10^{-4} .

A peculiar cup like form of disintegration has been observed throughout the experimental study. This kind of cup like structures on the jet surface has not been photographed in earlier experimental observations. This is due to the effect of inertia and viscosity of the surrounding medium.

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TABLE I

PROPERTIES OF JET FLUID AND VALUES OF SECONDARY ATOMIZATION VELOCITIES
BASED ON NOZZLE DIAMETERS

Properties of Jet Fluid				Atomization Velocity (in/sec) Corr. to			
Sl No	Sucrose Conc. %	Density ρ (gm/c.c)	Viscosity μ (c. p.)	Interfacial tension (liquid/air) σ (dynes/cm)	Nozzle I dia. 0.278"	Nozzle II dia. 0.516"	Nozzle III dia. 0.813
1.	0% (Case I)	1.0	0.893	72	25.8	6.0	2.85
2.	0% (Case II)	1.0	0.893	50	12.05	3.82	1.85
3.	0% (Case III)	1.0	0.893	30	5.95	1.91	1.742
4.	25%	1.095	2.01	72	22.0	5.22	3.3
5.	33%	1.13	3.92	72	19.2	5.42	2.86
6.	45%	1.203	10.4	72	18.95	4.35	2.24
7.	55%	1.257	20.2	72	19.2	5.2	2.09
8.	60%	1.286	44.3	72	22.5	4.88	2.51

TABLE II

FIGURE CAPTIONS

Figure numbers corresponding to nozzle diameters.		Conc.	Particulars of the jet fluid and observations from the photographs.
I	II	III	
0.278 in	0.516 in	0.813 in	
6	15	24	Plain water with normal σ (72 dynes/cm), μ (0.893 c. p.), ρ (1.0 g/cc). Increase in frequency of oscillation with increase in velocity [6b, 15b, 24c]* The lumped mass at the point of break up [6a, 15a, 24a] due to inter play of σ and μ . Atomization at lower velocity with nozzle of larger diameter.
		0% case I	
7	16	25	Reduction only in σ to 50 dynes/cm. Atomization velocity decreases with reduction in σ . Break up of a portion of a jet [16a]
		0% case II	
8	17	26	Reduction only in σ to 30 dynes/cm. Atomization velocity decreases. Smaller droplets formed. Atomization takes place at minimum velocity with nozzle III [26a]. Effect of reduction in σ
		0% case III	
9	18	27	Normal σ , increase in μ and ρ to 2.01 c. p. and 1.09 g/c. c. Smaller drop- lets closer to the nozzle with increase in velocity. Alternate swellings and contractions on the jet surface. Maximum wave length of disturbance at the point of break up [9a]
		25%	

* bracket refers to figure number.

TABLE III
FIGURE CAPTIONS

Figure numbers corresponding to nozzle diameters.			Conc.	Particulars of the jet fluid and observations from the photographs.	
I	II	III			
0.278 in	0.516 in	0.813 in			
10	19	28	33%	Normal σ , increase in μ and ρ to 3.92 c. p. and 1.13 g/cc. No significant variation in atomization velocity, due to increase in μ . The viscosity effect of the surrounding medium predominant.	
11, 12	20, 21	29, 30	45%	Normal σ , increase in μ and ρ to 10.4 c. p. and 1.203 g/c. c. Decrease in break up length with increase in velocity. Drop of larger size formed due to capillary instability [11b, 20b] Oscillation and deformation into spherical shape of a drop that moves away from the axis due to aerodynamic force [11a]. Drops of various sizes under the same condition of dripping [20a]. No dripping with nozzle of diameter 0.813 in.	
13	22	31	55%	Normal σ , increase in μ and ρ to 20.2 c. p. and 1.259 g/c. c. Finer ligaments result into smaller droplets. [22c]. Atomization takes place at minimum velocity with nozzle III. No significant variation in atomization velocity.	

TABLE IV

FIGURE CAPTIONS

Figure numbers corresponding to nozzle diameters.			Conc.		Particulars of the jet fluid and observations from the photographs.	
I	II	III				
0.278 in	0.516	0.813 in				
14	23	32	60%		Normal σ , increase in μ and ρ to 44.2 c.p. and 1.286 g/cc. Wavy disturbance found on the jet surface [14c]. A portion of the liquid squeezed in lateral direction (buckling) [14b]. No significant effect of increase in μ on atomization velocity.	
33	34, 35	36, 37	* diff.		Cup like formations on the jet surface due to the effect of inertia. With increase in μ it occurs at higher velocity.	
38			0% case I		Jet behaviour at various distances from the tip of the nozzle. Disintegration, a progressive affair, continues till the velocity of the drop-let becomes very low.	
39a, 40a	39b, 40b	39c, 40c	diff.		Gradual contraction of the jet profile at low and at atomization velocity	
					Measurement of jet diameter above the concentrated mass of liquid [40]	

* means different.

TABLE V

VALUES OF W, Re AND Ze BASED ON NOZZLE DIAMETERS

Weber No : $W = \frac{2 \rho_1 v^2 a}{\sigma}$				Reynolds No : $Re = \frac{2 \rho v a}{\mu}$				Ohnesorge No : $Ze = \frac{\mu}{\sqrt{2 \rho \sigma a}}$			
corr. to nozzles.				corr. to nozzles.				corr. to nozzles			
I	II	III		I	II	III		I	II	III	
$\times 10^2$	$\times 10^3$	$\times 10^3$	$\times 10^3$		$\times 10^2$				$\times 10^4$		
1. 5.4	4.53	1.93		52*	22.3	16.82		0.487	0.328	0.284	
2. 2.28	3.98	1.51		24.2	14.25	11.0		0.678	0.49	0.382	
3. 2.29	4.37	4.8		12	7.1	9.45		1.375	1.1016	0.795	
4. 3.93	4.15	2.52		21.5	9.4	9.45		1.041	0.782	0.605	
5. 3.14	4.36	1.94		10.12	5.17	4.34		2.025	1.478	1.178	
6. 2.98	2.88	1.22		4.42	1.89	1.54		4.68	3.38	2.71	
7. 3.06	4.53	1.07		2.18	1.08	0.682		9.78	7.34	5.8	
8. 4.07	3.6	1.5		1.17	0.472	0.382		21.35	15.04	12.52	

* means Reynolds number is 52×10^2

TABLE VI

VALUES OF W_1 , Re_1 AND Ze_1 BASED ON JET DIAMETERS

	Weber No : $W_1 = \frac{2 \rho v^2 b}{\sigma}$			Reynolds No : $Re_1 = \frac{2 \rho v b}{\mu}$			Ohnesorge No : $Ze_1 = \frac{\mu}{\sqrt{2 \rho \sigma b}}$		
	corr. to nozzles.			corr. to nozzles.			corr. to nozzles.		
	I	II	III	I	II	III	I	II	III
				$\times 10^{-2}$			$\times 10^{-4}$		
1.	2.66	3.8	3.04	187	97	91	0.925	0.682	0.67
2.	1.09	3.22	2.34	87.5	62	59	1.29	1.02	0.90
3.	1.1	3.54	7.45	43.4	30.8	50.6	2.61	2.11	1.88
4.	1.87	3.35	4.0	78.0	40.7	50.6	1.98	1.625	1.43
5.	1.54	3.63	3.14	36.6	18.8	24.2	3.85	3.08	2.78
6.	1.44	2.34	1.91	16.0	6.68	8.25	8.9	7.03	6.42
7.	1.45	3.66	1.66	7.9	4.68	3.67	18.6	15.25	13.7
8.	1.935	2.91	2.37	4.23	2.05	2.05	41.3	32.0	29.6

TABLE VII

VALUES OF SECONDARY ATOMIZATION VELOCITY BASED ON JET DIAMETERS
AND OF A NONDIMENSIONAL PARAMETER

	Velocity (in/sec) corr to nozzles			μ/μ_1	ρ/ρ_1	$Z_{ef} \times \mu_1/\mu = \frac{\mu_1}{\sqrt{2 \rho \sigma b_{av}}}$ corr. to nozzles.		
	I	II	III			I	II	III
							$\times 10^4$	
1.	338	113.2	82	0.309	1.19	2.99	2.02	2.17
2.	159	72.2	53	0.309	1.19	6.42	3.2	2.91
3.	78	36.1	50	0.309	1.19	8.45	6.72	6.22
4.	288	98.5	94.7	0.62	1.302	3.19	2.66	2.31
5.	252	102.2	82	1.21	1.345	3.18	2.54	2.29
6.	248	82.2	64.4	3.2	1.43	2.78	2.2	2.01
7.	252	98.2	60.0	6.24	1.49	2.99	2.45	2.2
8.	294	92.4	72	13.7	1.53	3.12	2.33	2.15

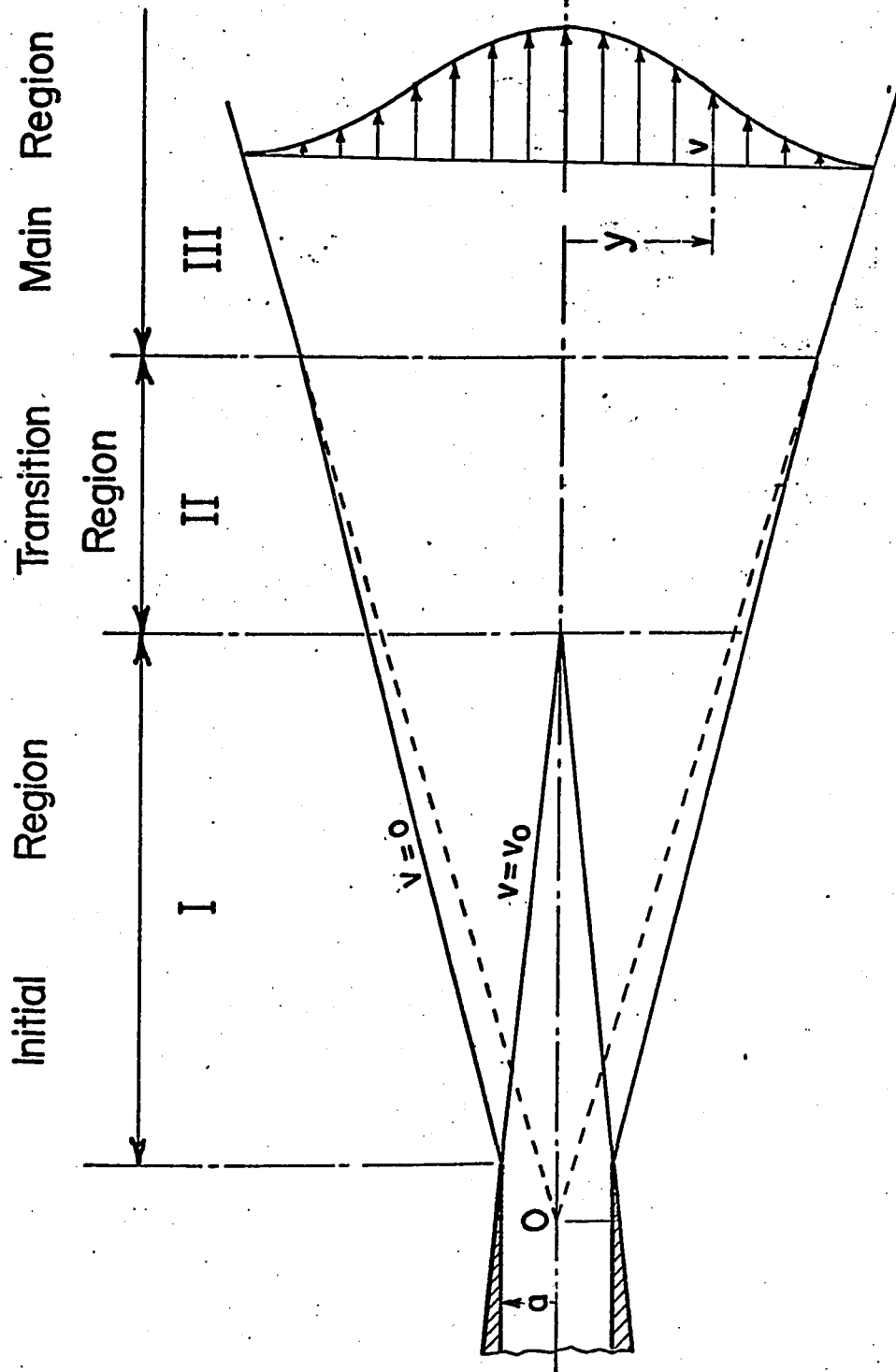
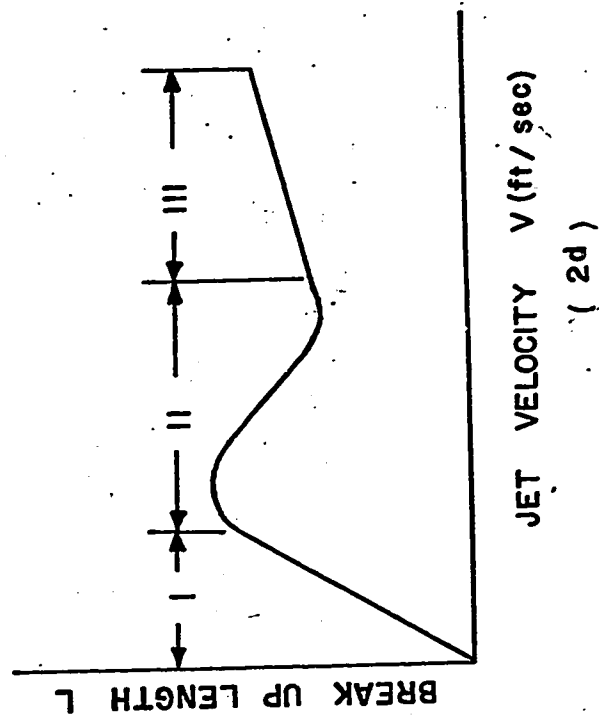


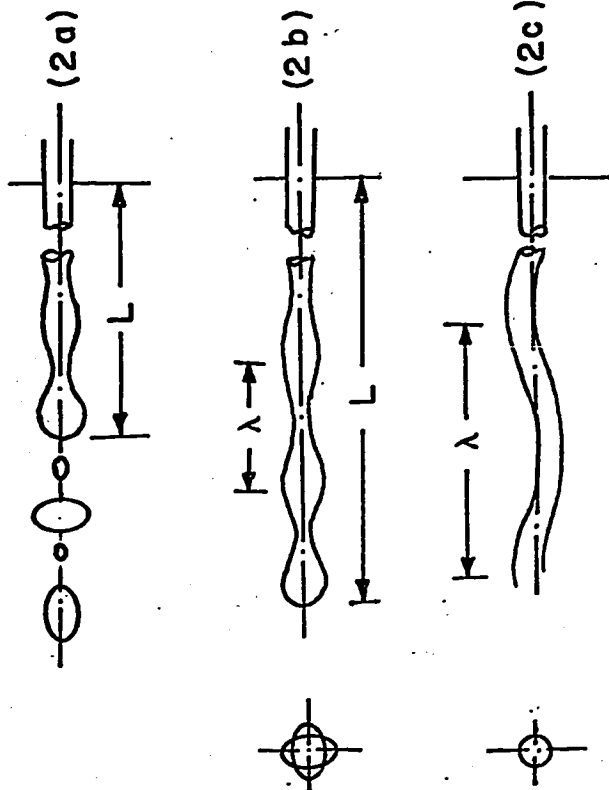
DIAGRAM OF A SUBMERGED JET

Fig 1 b



RELATION BETWEEN L & V

- I BREAK UP WITHOUT AIR EFFECT
 - II BREAK UP WITH AIR EFFECT
 - III WAVE LIKE BREAK UP
- (AFTER REFERENCE 4)



OSCILLATIONS OF A JET

- 2a ROTIONALLY SYMMETRIC OSCILLATIONS
 - 2b OSCILLATIONS WITH AIR EFFECT
 - 2c WAVE LIKE OSCILLATIONS
 - λ WAVE LENGTH
 - L BREAK UP LENGTH
- (AFTER REFERENCE 4)

Fig. 2

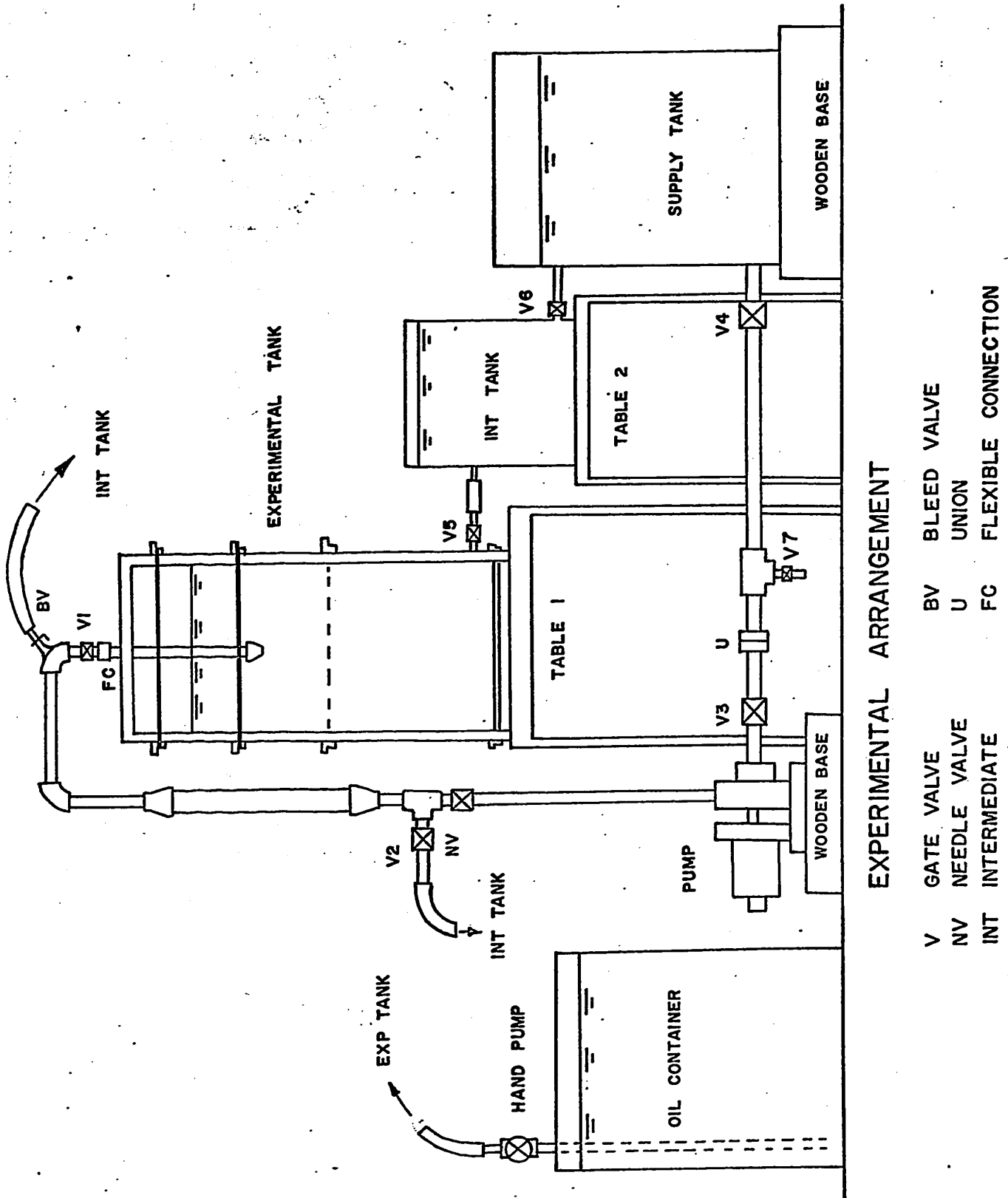
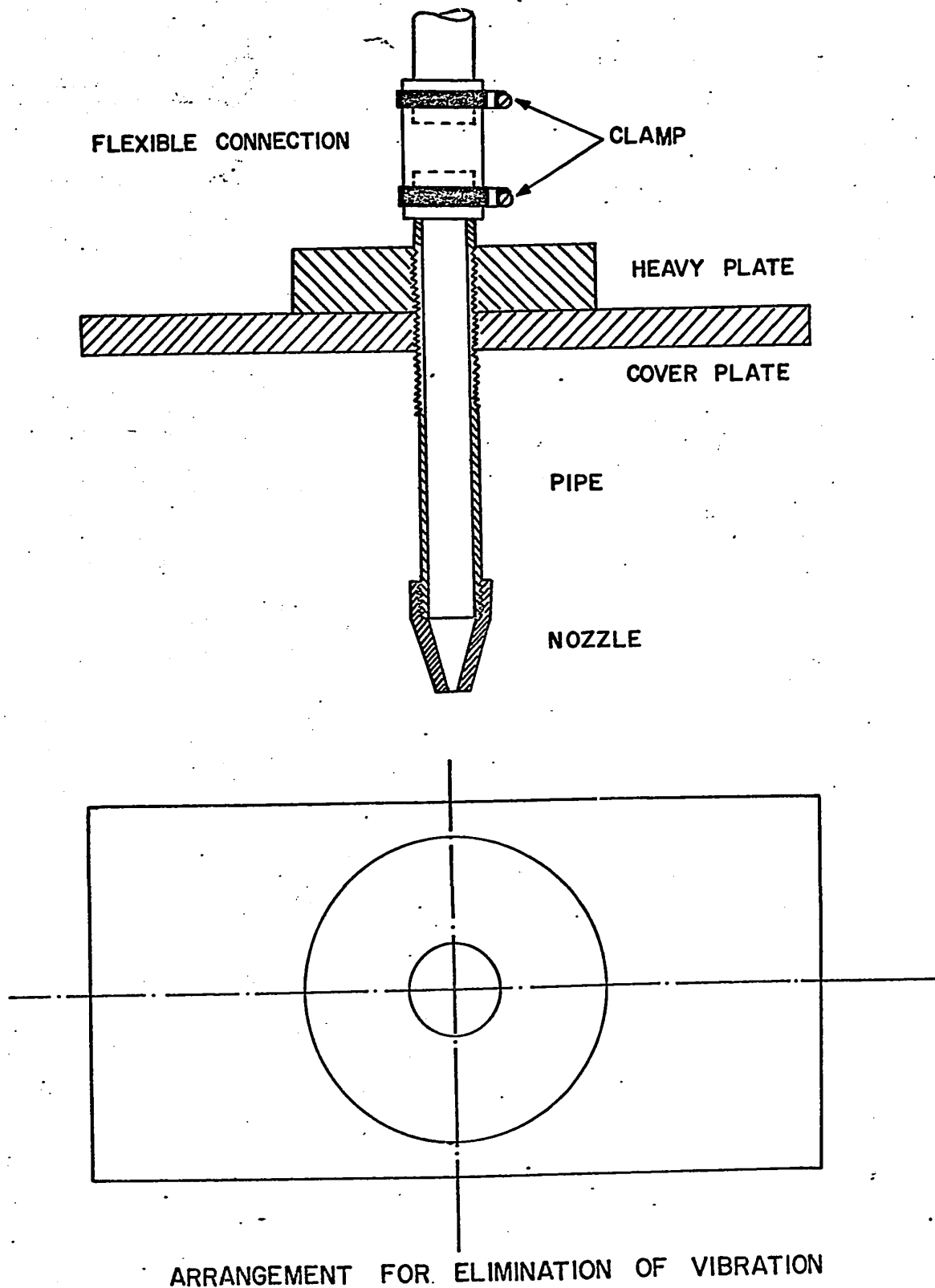
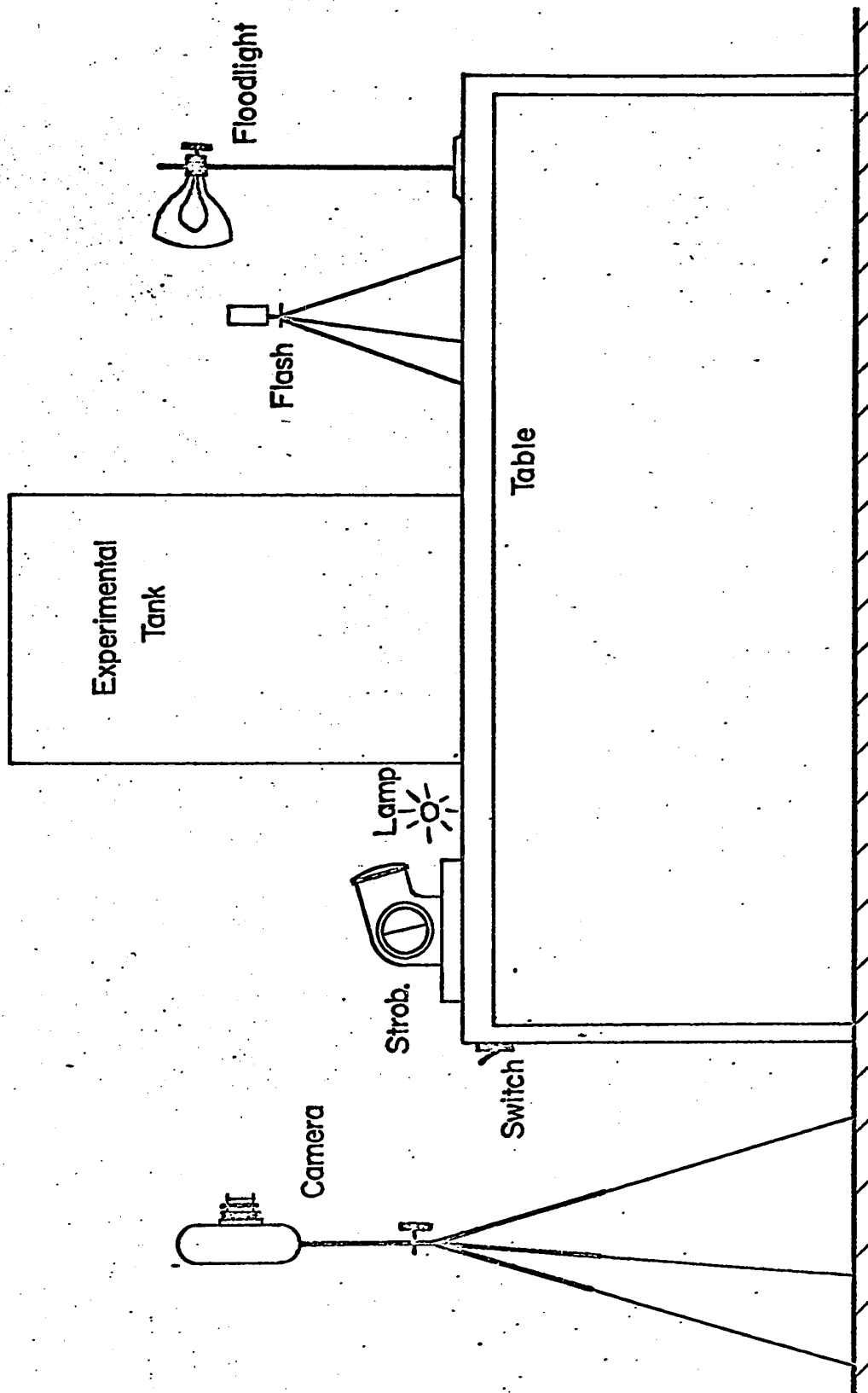


Fig. 3



ARRANGEMENT FOR ELIMINATION OF VIBRATION

Fig. 4



ARRANGEMENT FOR PHOTOGRAPHY

Fig. 5

Dia : 0.278 inch.

Conc : 0.0% (Case I)

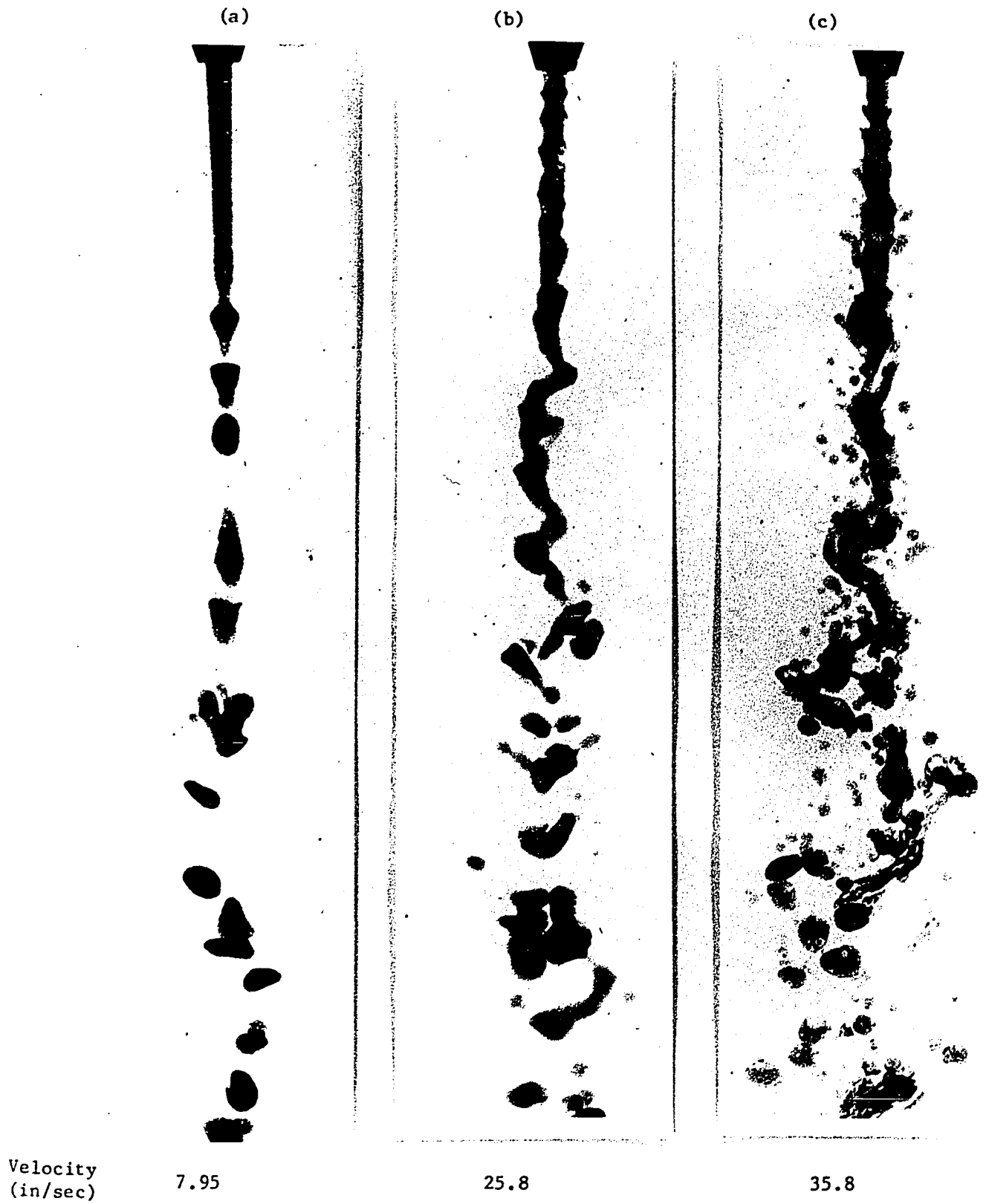


FIGURE 6

Dia : 0.278 inch

Conc : 0.0%(Case II)

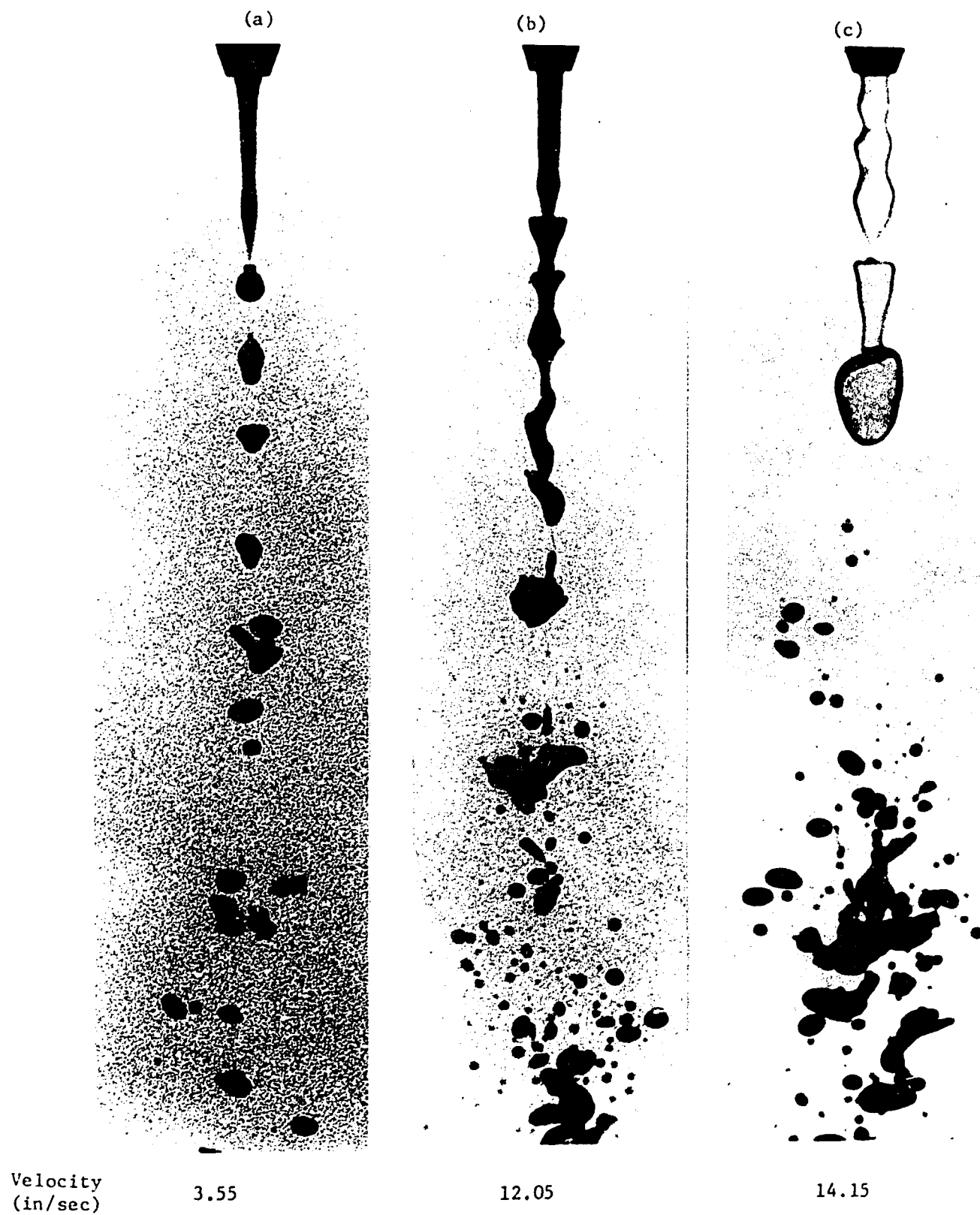
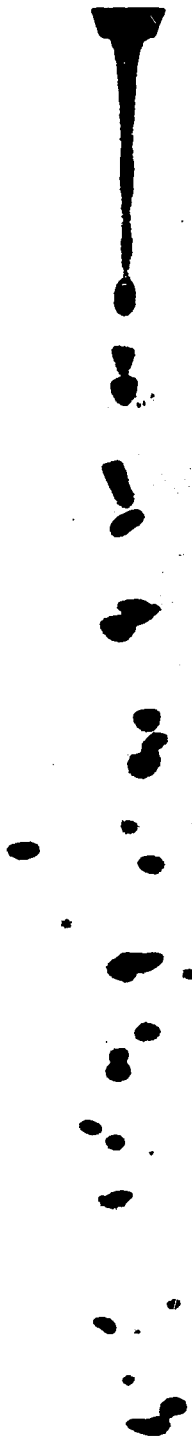


FIGURE 7

Dia : 0.278 inch.

Conc : 0.0% (Case III)

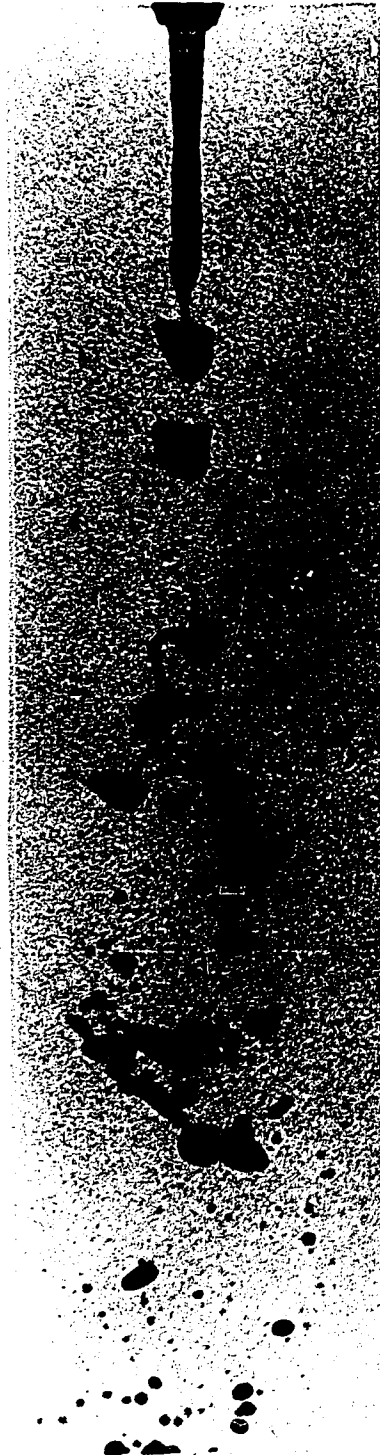
(a)



Velocity
(in/sec)

2.67

(b)



5.95

(c)



24.5

FIGURE 8

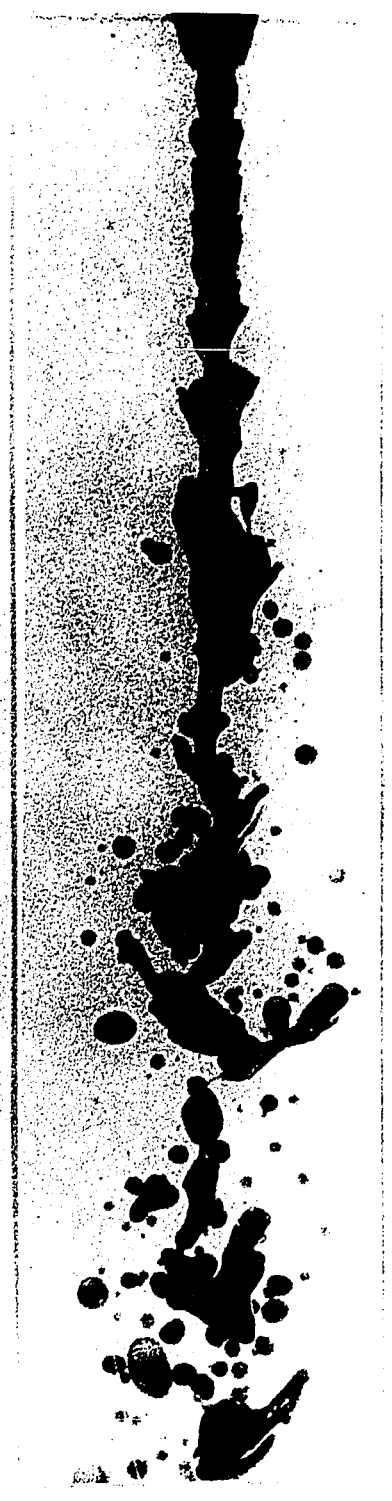
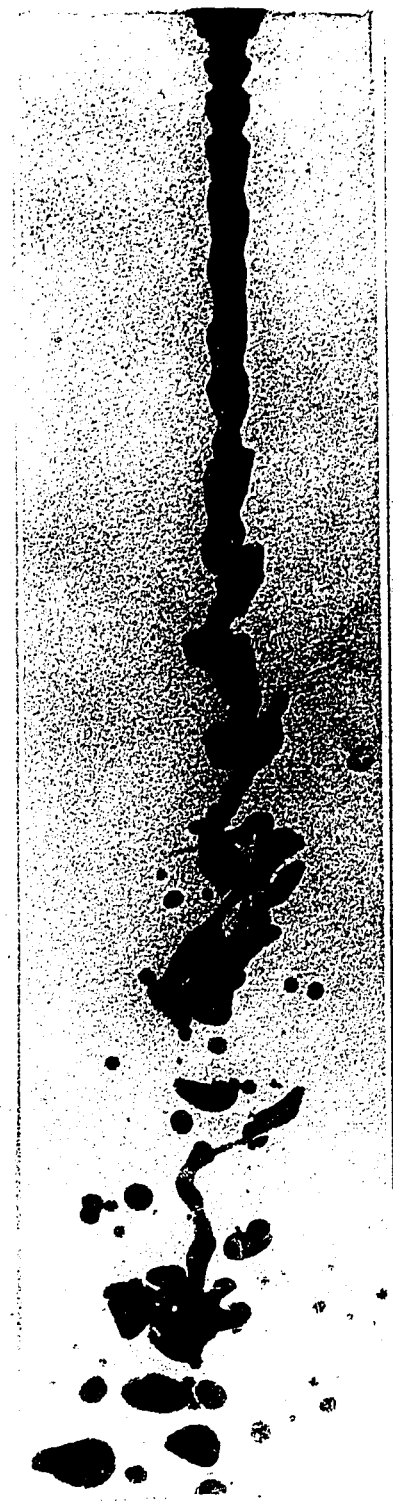
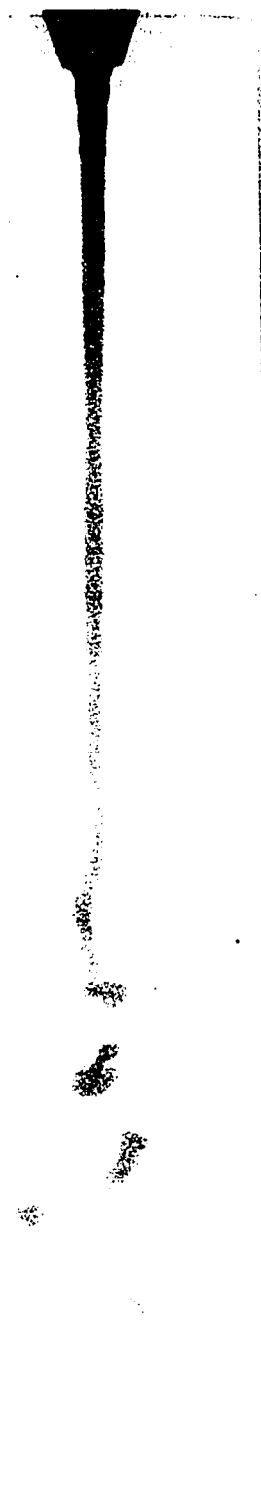
Dia : 0.278 inch.

Conc : 25%

(a)

(b)

(c)



Velocity
(in/sec)

10.35

22.0

39.6

FIGURE 9

Dia : 0.278 inch.

Conc : 33%



FIGURE 10

Dia : 0.278 inch.

Conc : 45%

(a)

(b)

(c)



Velocity
(in/sec)

1.95

6.72

FIGURE 11

Dia : 0.278 inch.

Conc : 45%

(a)



(b)



(c)



Velocity
(in/sec)

18.95

38.5

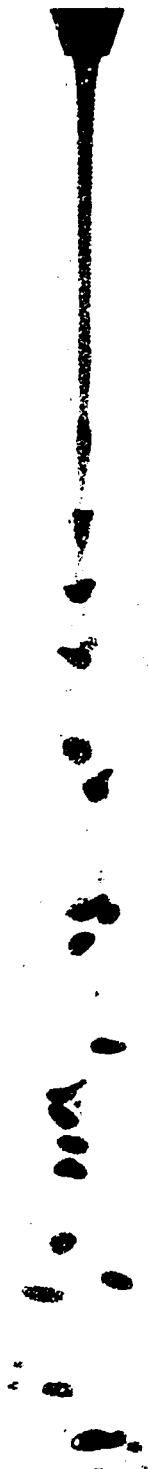
90.0

FIGURE 12

Dia : 0.278 inch.

Conc. : 55%

(a)



Velocity
(in/sec)

5.17

(b)



19.2

(c)



38.5

FIGURE 13

Dia : 0.278 inch.

Conc : 60%



FIGURE 14

Dia : 0.516 inch.
Conc : 0.0% (Case I)



FIGURE 15

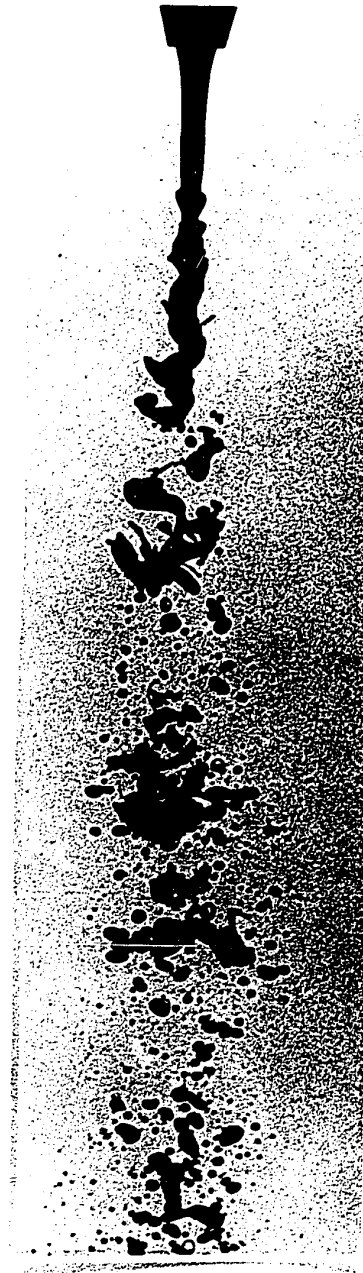
Dia : 0.516 inch.

Conc : 0.0% (Case II)

(a)



(b)



(c)



Velocity
(in/sec)

1.11

3.82

8.9

FIGURE 16

Dia : 0.516 inch.
Conc : 0.0%(Case III)

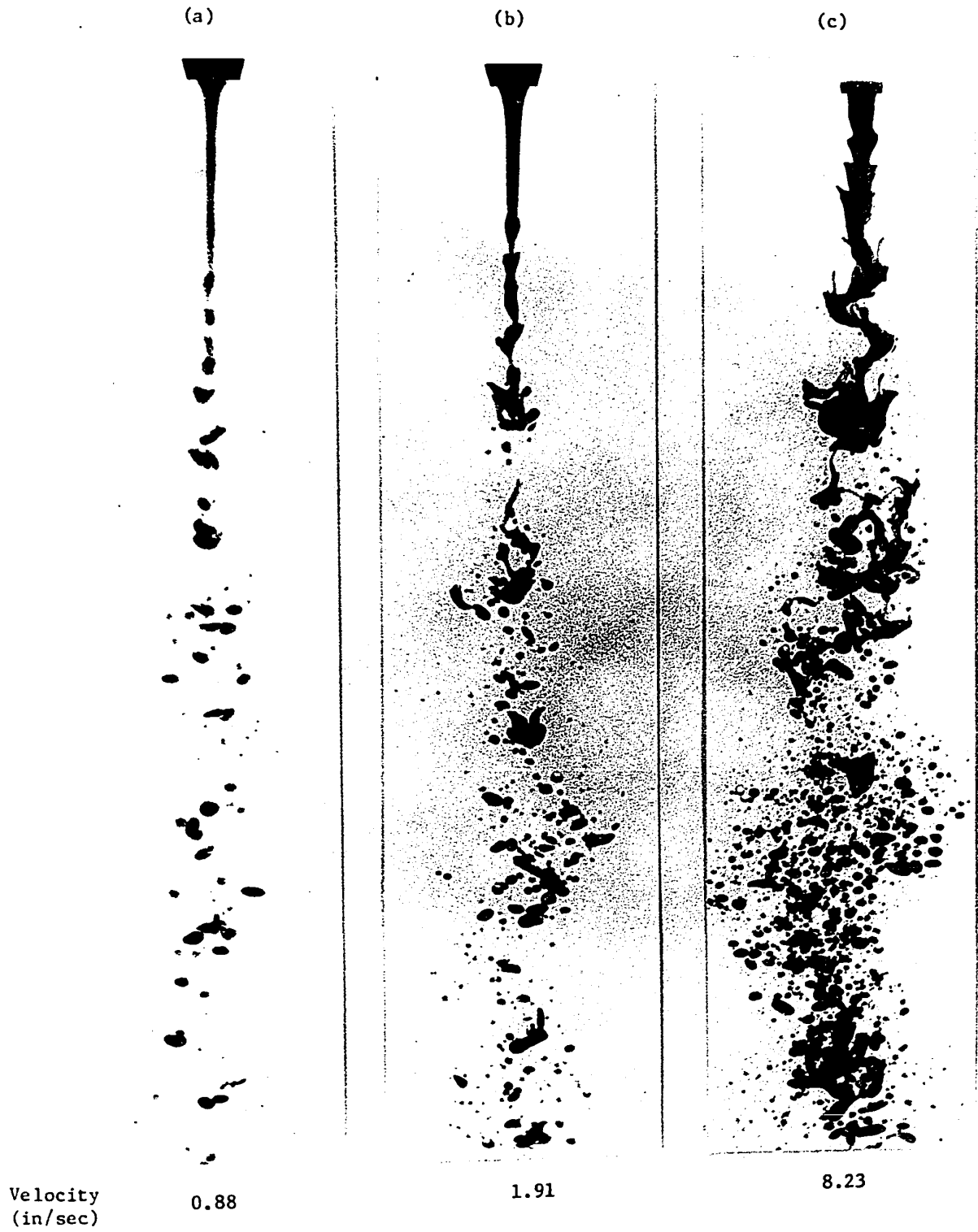


FIGURE 17

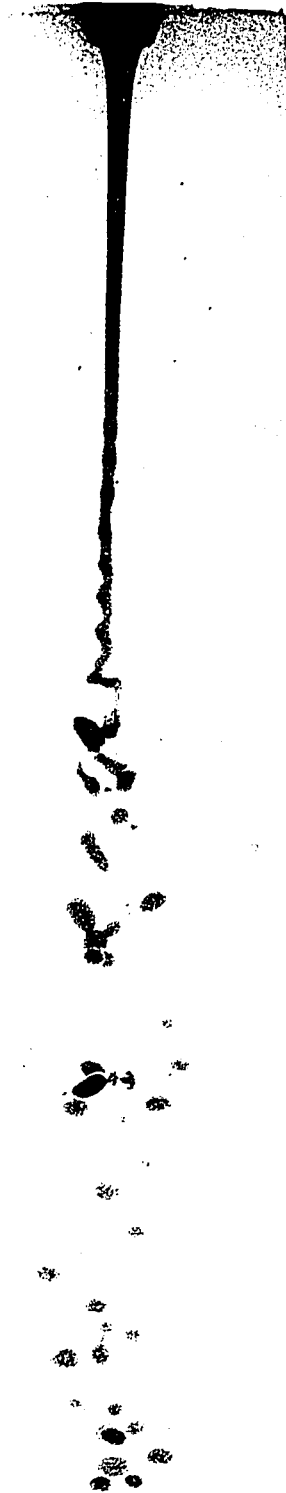
Dia : 0.516 inch.

Conc : 25%

(a)

(b)

(c)



Velocity
(in/sec)

3.25

5.22

22.1

FIGURE 18

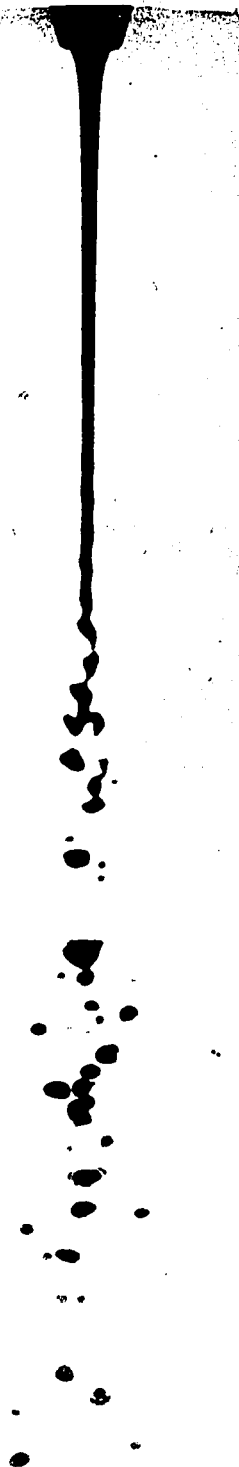
Dia : 0.516 inch.

Conc : 33%

(a)

(b)

(c)



Velocity
(in/sec)

3.72

5.42

13.95

FIGURE 19

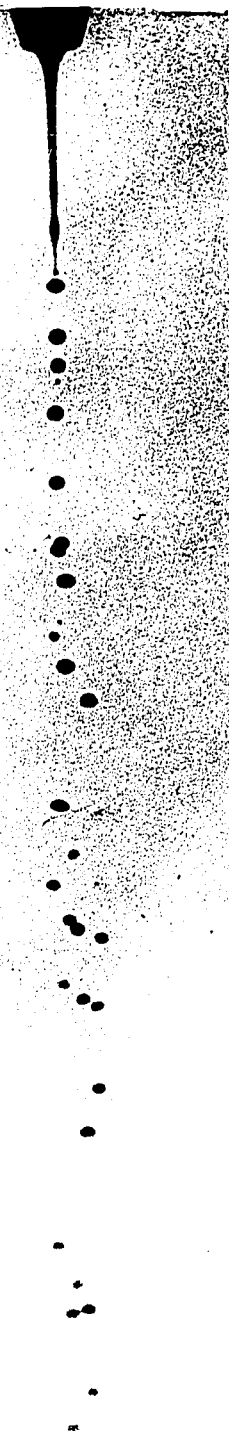
Dia : 0.516 inch.

Conc : 45%

(a)

(b)

(c)



Velocity
(in/sec)

3.12

FIGURE 20

Dia : 0.516 inch.

Conc : 45%



FIGURE 21

Dia : 0.516 inch.

Conc : 55%

(a)

(b)

(c)

Velocity
(in/sec)

1.5

5.2

13.0

FIGURE 22

Dia : 0.516 inch.

Conc : 60%



FIGURE 23

Dia : 0.813 inch.

Conc : 0.0%(Case I)

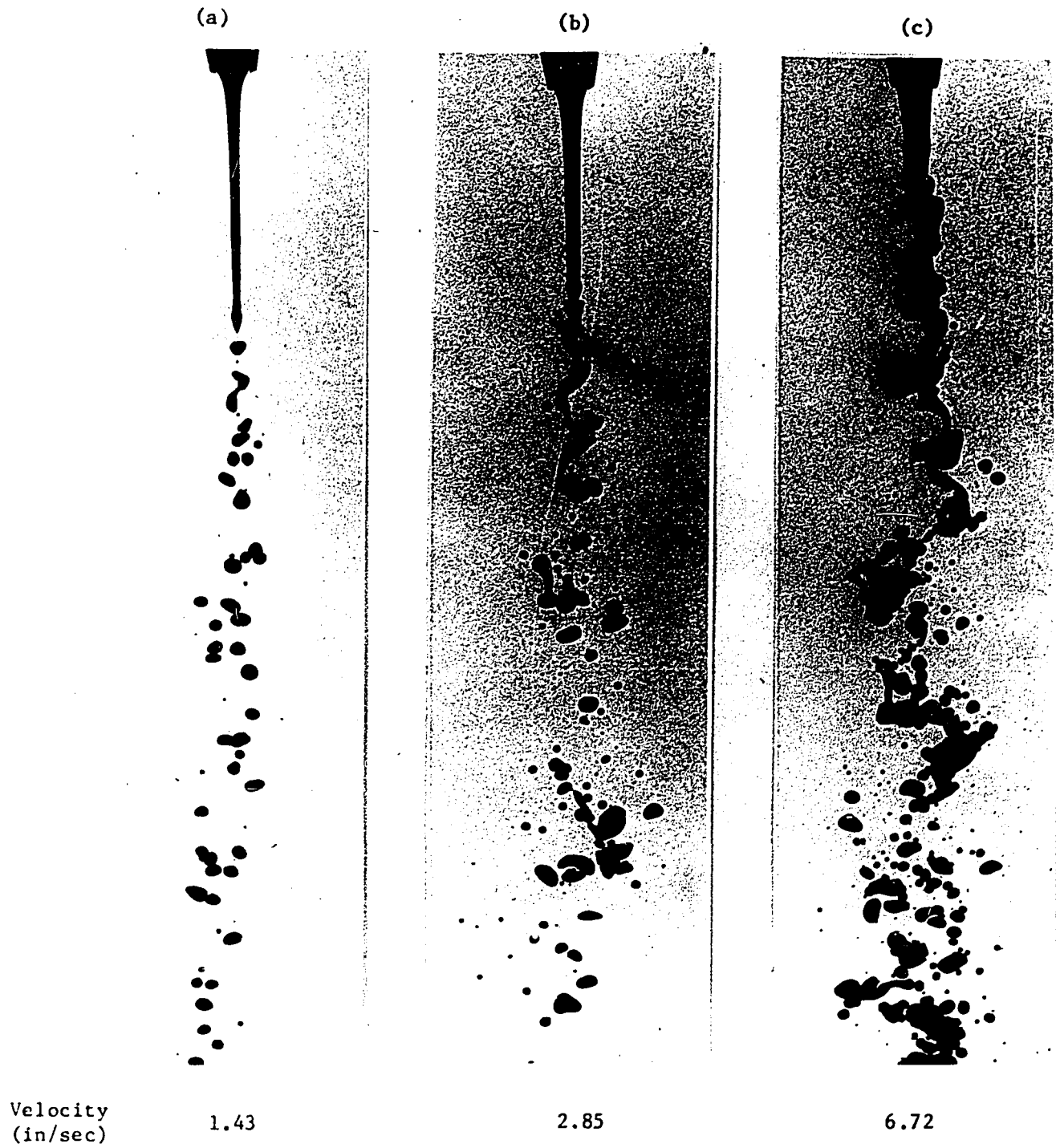


FIGURE 24

Dia : 0.813 inch.

Conc : 0.0% (Case II)

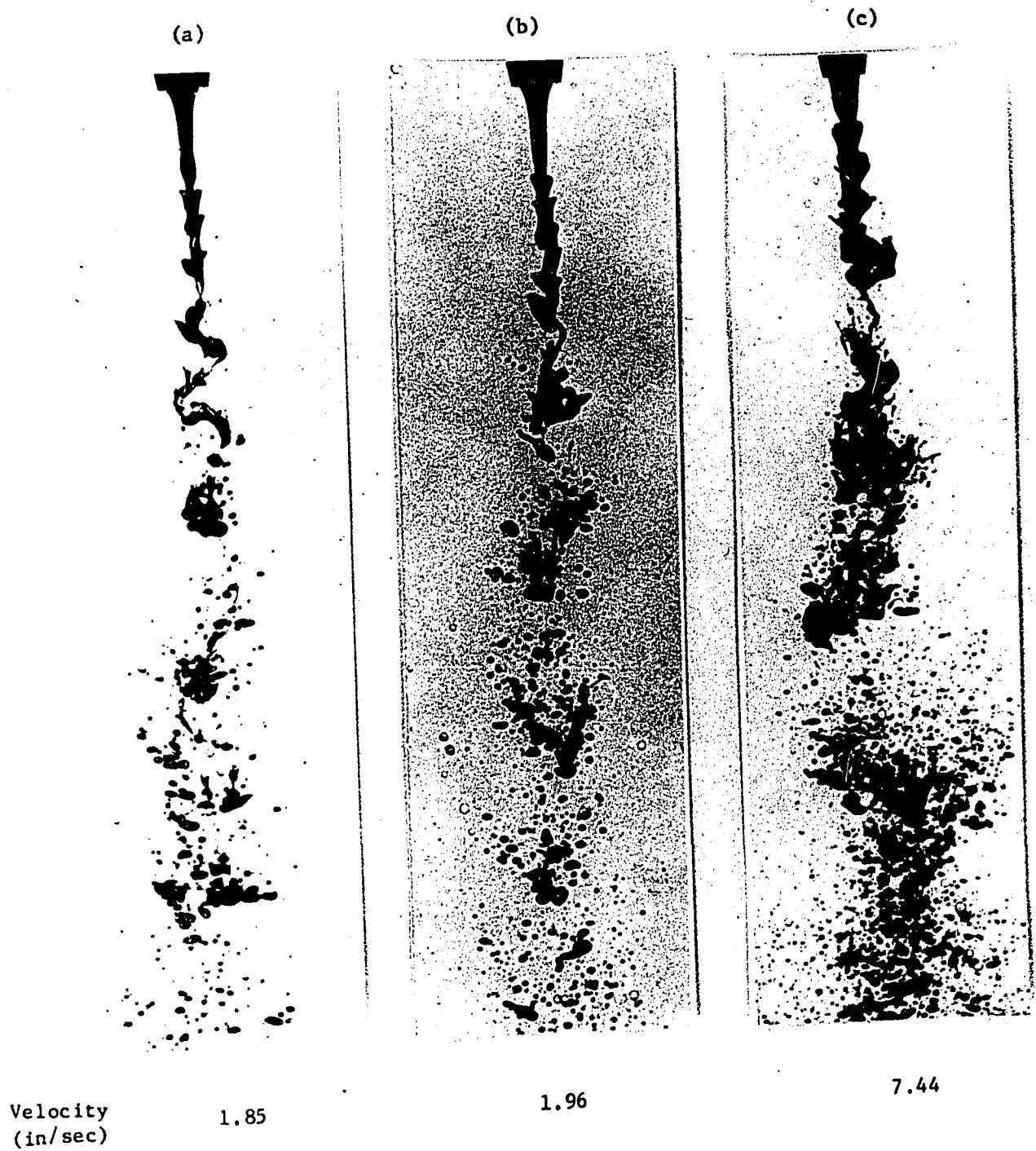


FIGURE 25

Dia : 0.813 inch.

Conc : 0.0% (Case III)

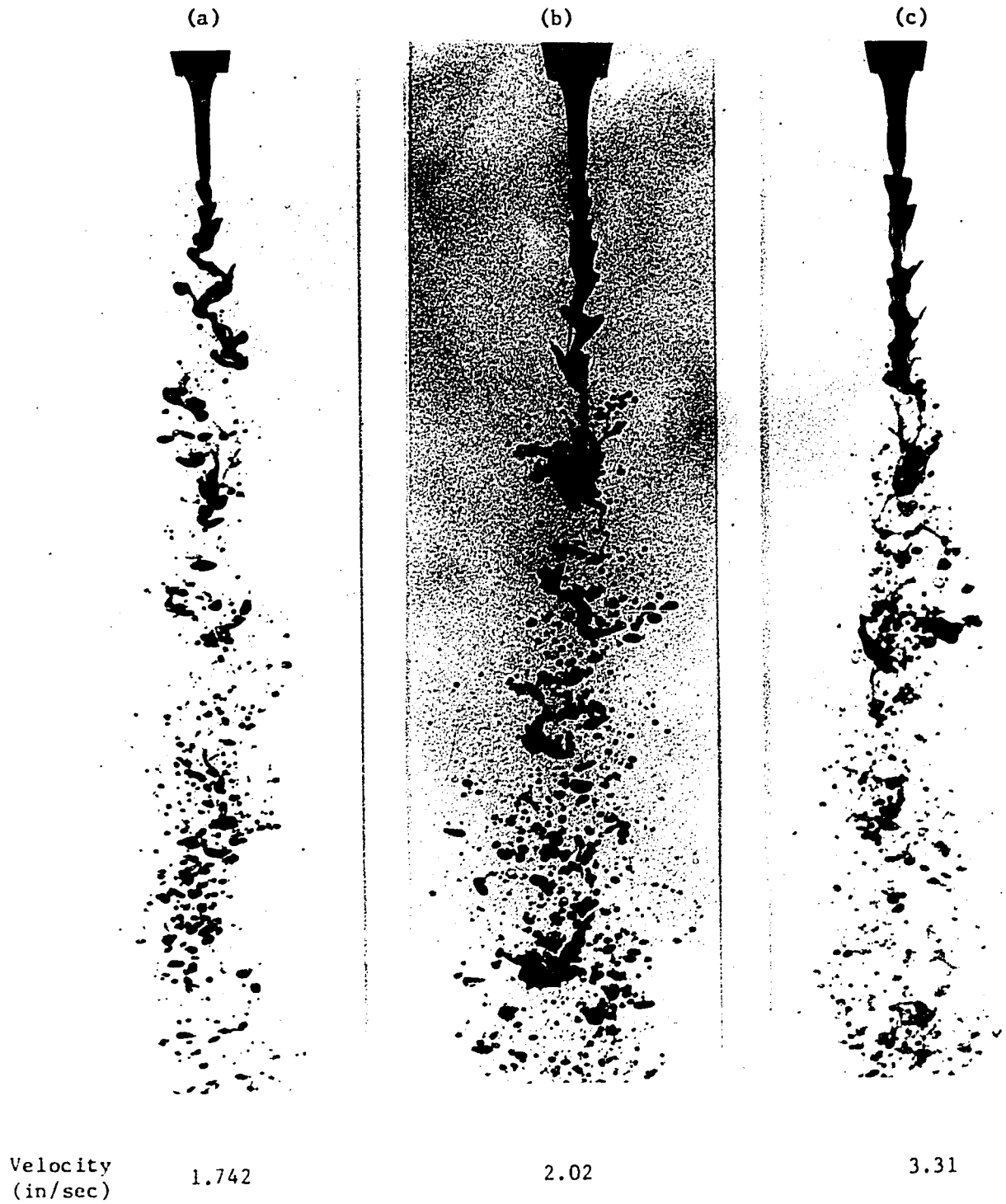
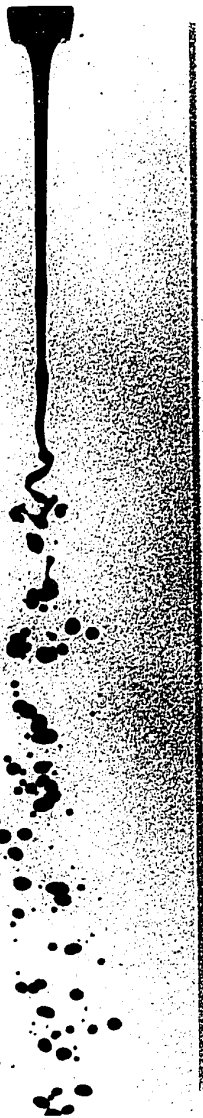


FIGURE 26

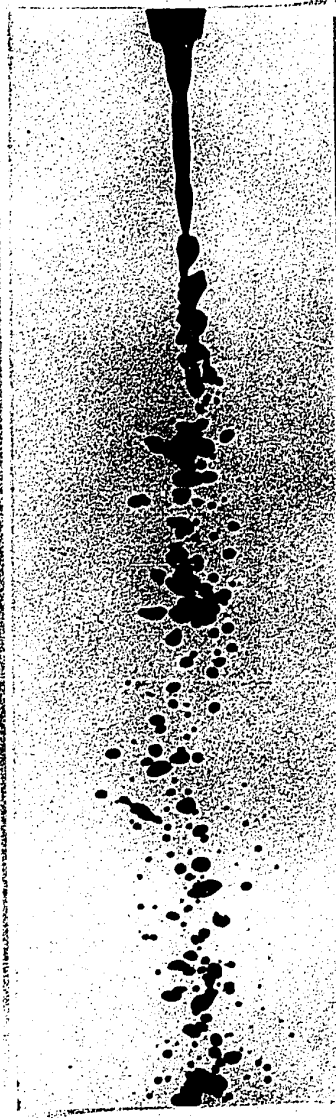
Dia : 0.813 inch.

Conc : 25%

(a)



(b)



(c)



Velocity
(in/sec)

1.19

3.3

11.8

FIGURE 27

Dia : 0.813 inch.

Conc : 33%

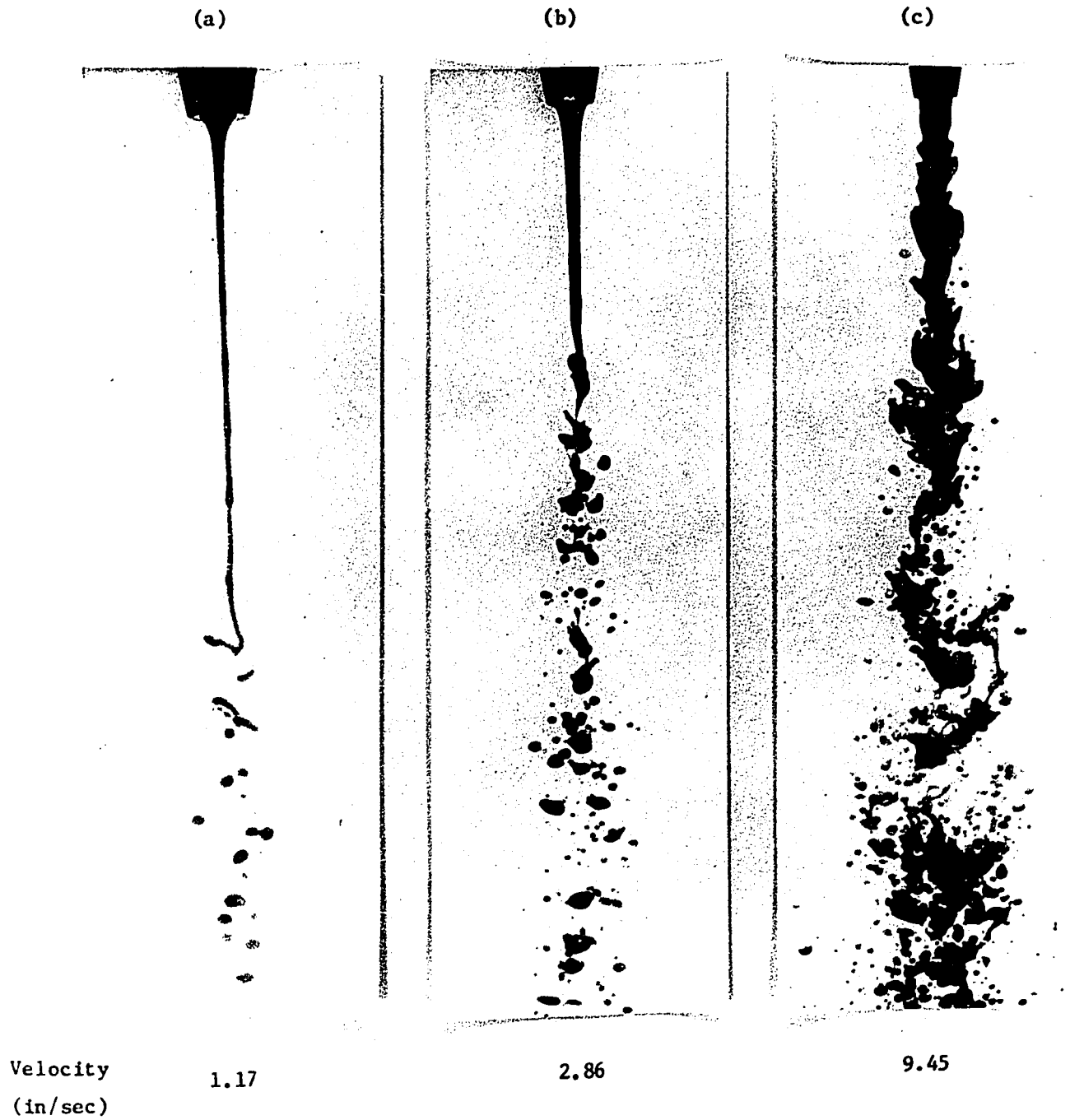


FIGURE 28

Dia : 0.813 inch.

Conc : 45%

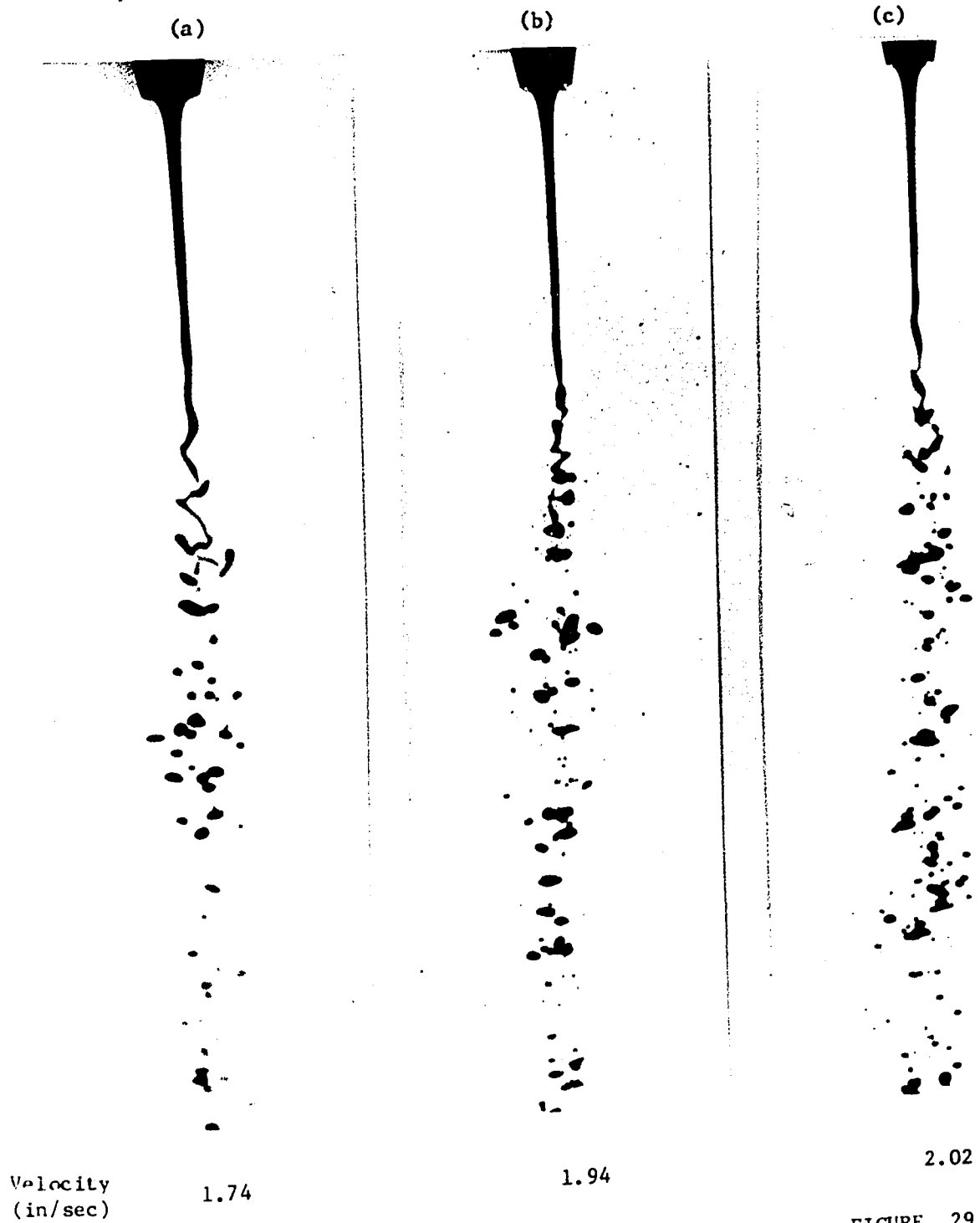


FIGURE 29

Dia : 0.813 inch.

Conc : 45%

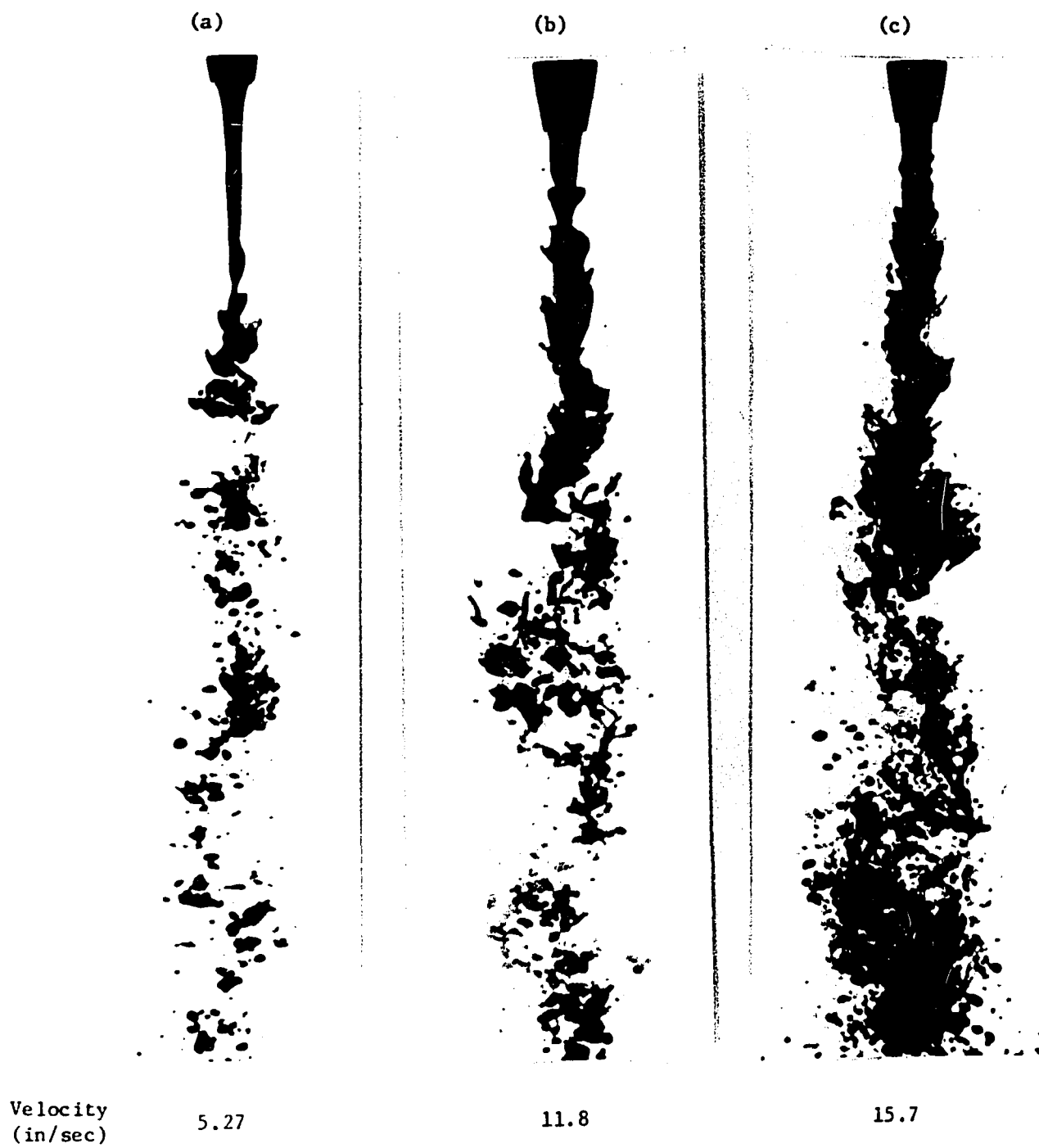


FIGURE 30

Dia : 0.813 inch.

Conc : 55%

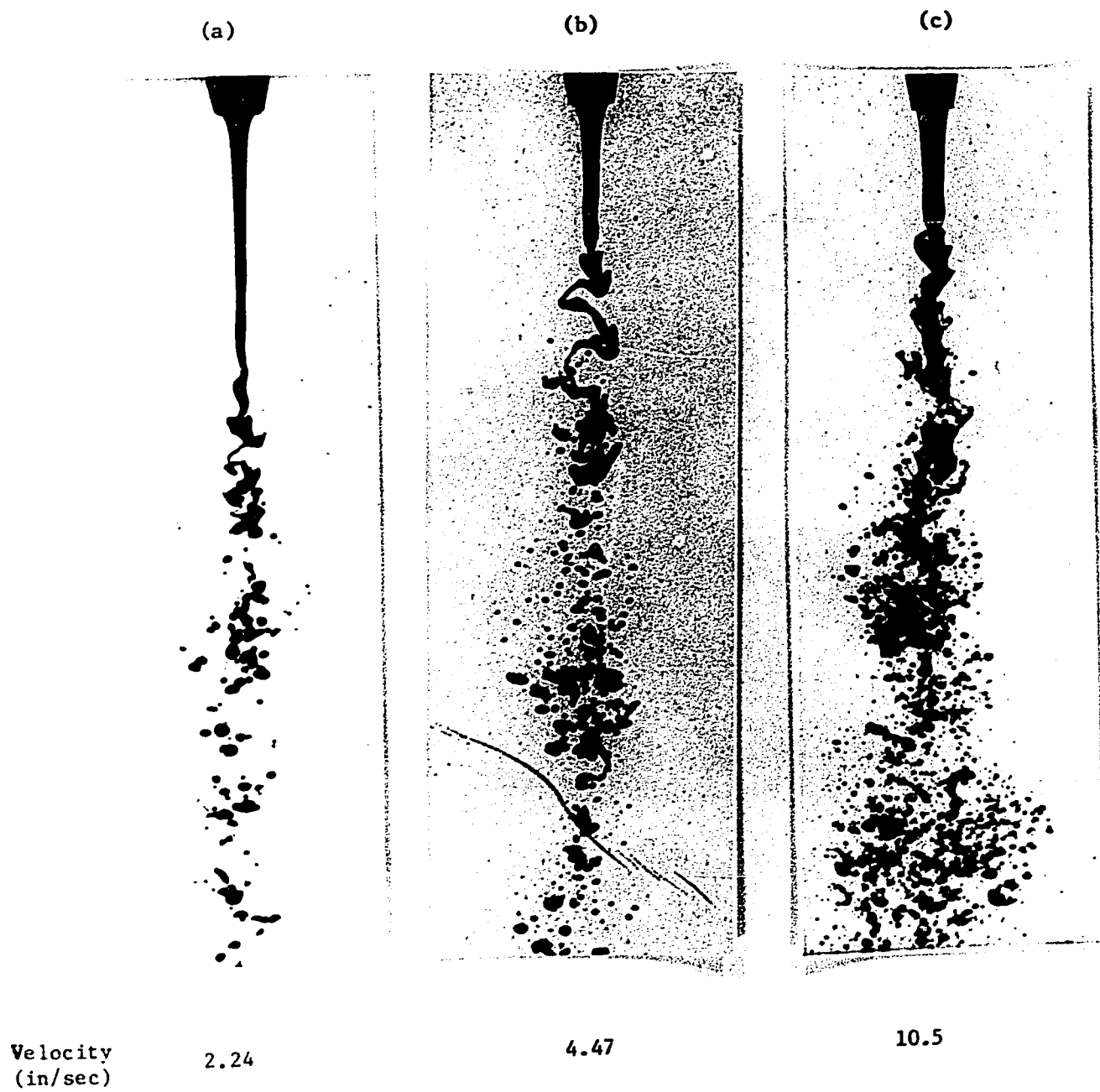


FIGURE 31

Dia : 0.813 inch.

Conc : 60%

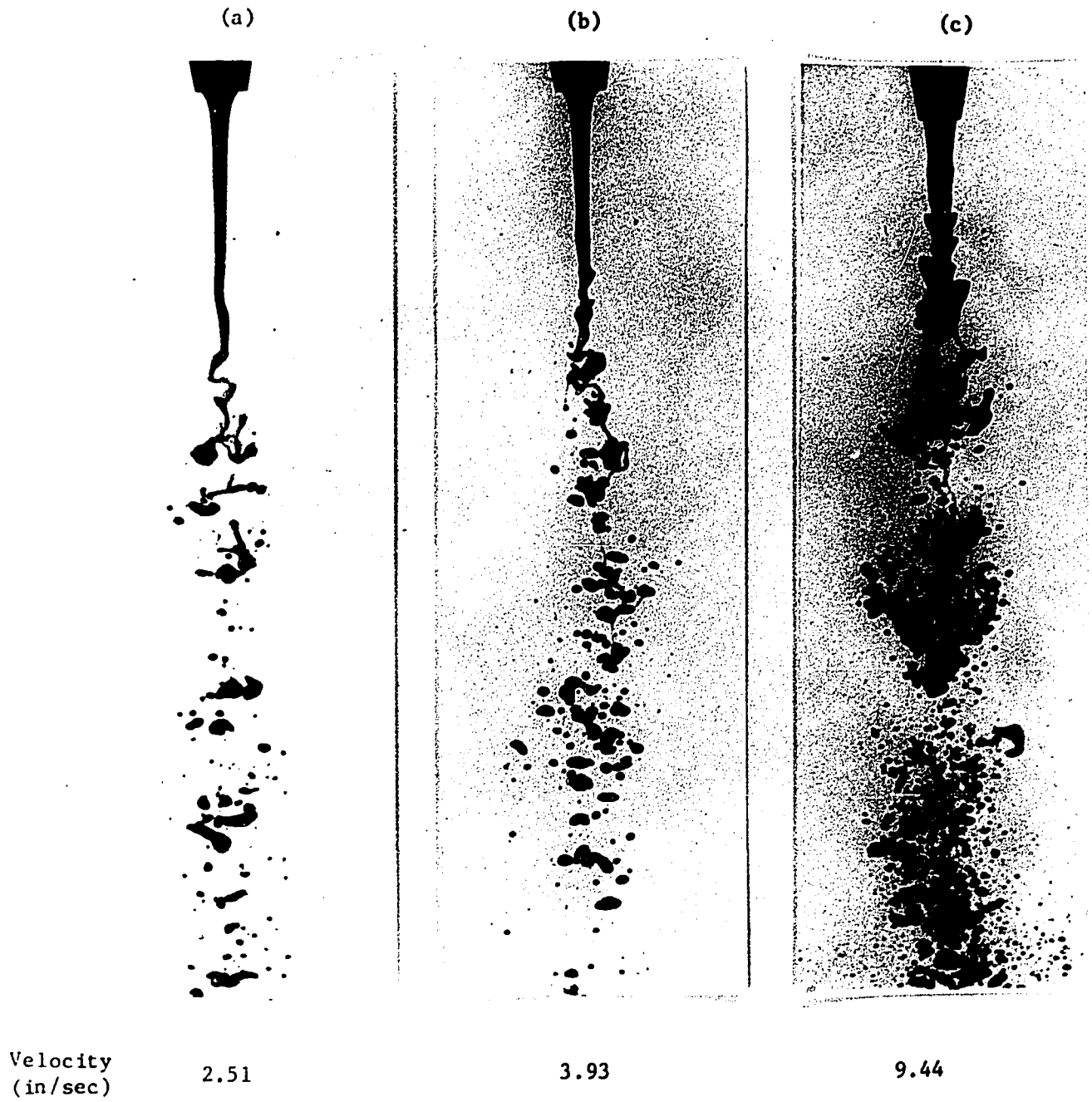


FIGURE 32

Dia : 0.278 inch.

Conc 0.0% (Case I)

(a)



Conc 25%

(b)



Conc 33%

(c)



Velocity
(in/sec)

33.4

30.7

32.3

FIGURE 33

Dia : 0.516 inch.

Conc:0.0%(Case 1)

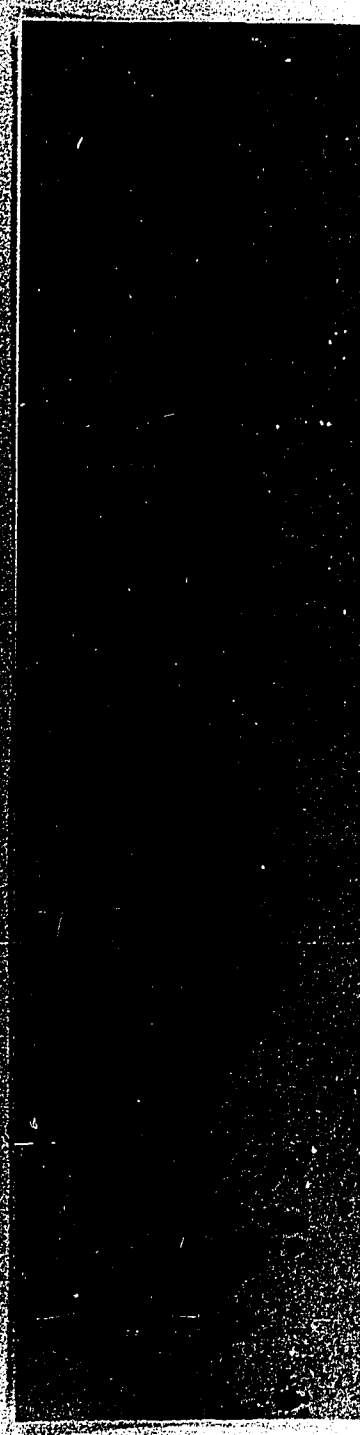
Conc : 25%

Conc : 45%

(a)

(b)

(c)



Velocity
(in/sec)

8.45

9.15

9.0

FIGURE 34

Conc : 33%

(a)



Velocity
(in/sec)

12.1

Dia : 0.516 inch

Conc : 55%

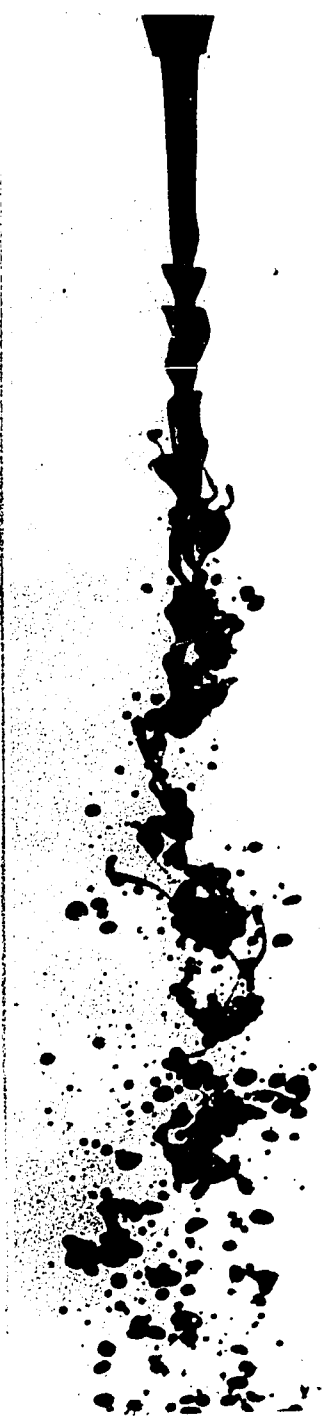
(b)



18.0

Conc : 60%

(c)



17.45

FIGURE 35

Dia : 0.813 inch.

Conc:0.0%(Case II)

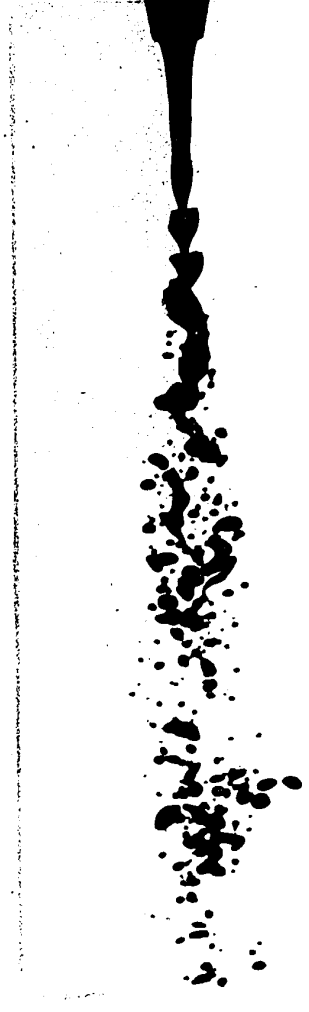
Conc : 25%

Conc : 33%

(a)

(b)

(c)



Velocity
(in/sec)

3.0

4.48

5.17

FIGURE 36

Dia : 0.813 inch.

Conc : 45%

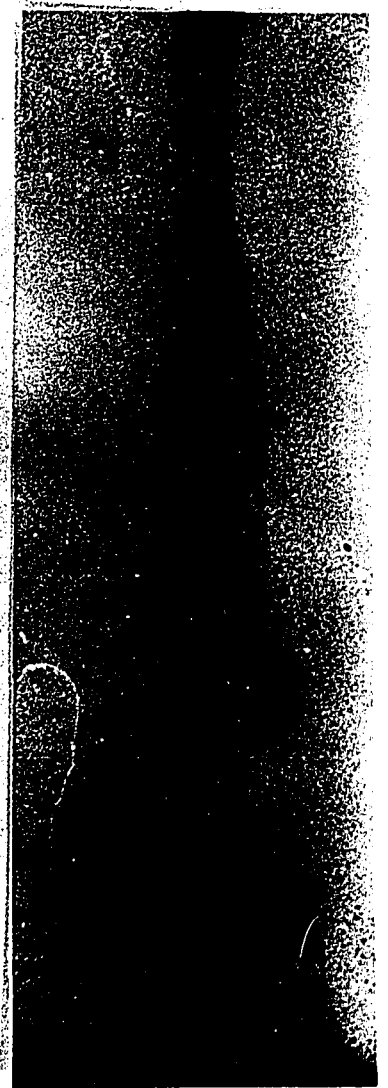
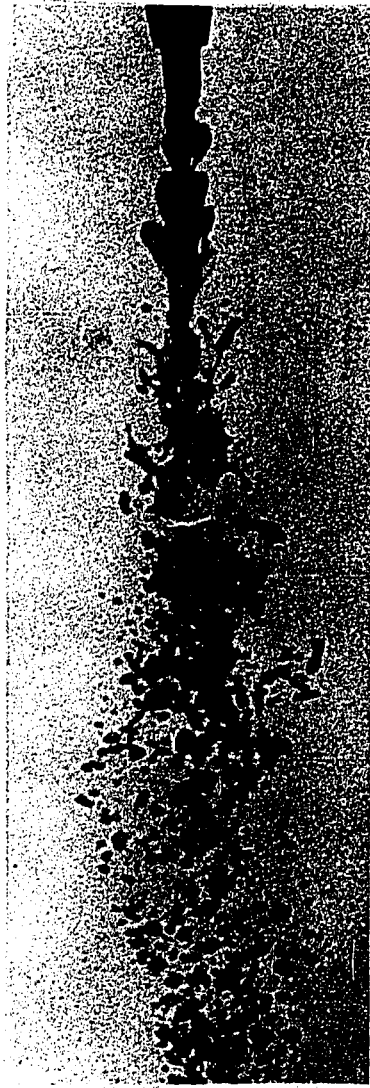
Conc : 55%

Conc : 60%

(a)

(b)

(c)



Velocity
(in/sec)

11.8

10.5

11.8

FIGURE 37

Dia : 0.278 inch.

Velocity : 26 in/sec

Conc : 25%

Distance in inch

4

8

12



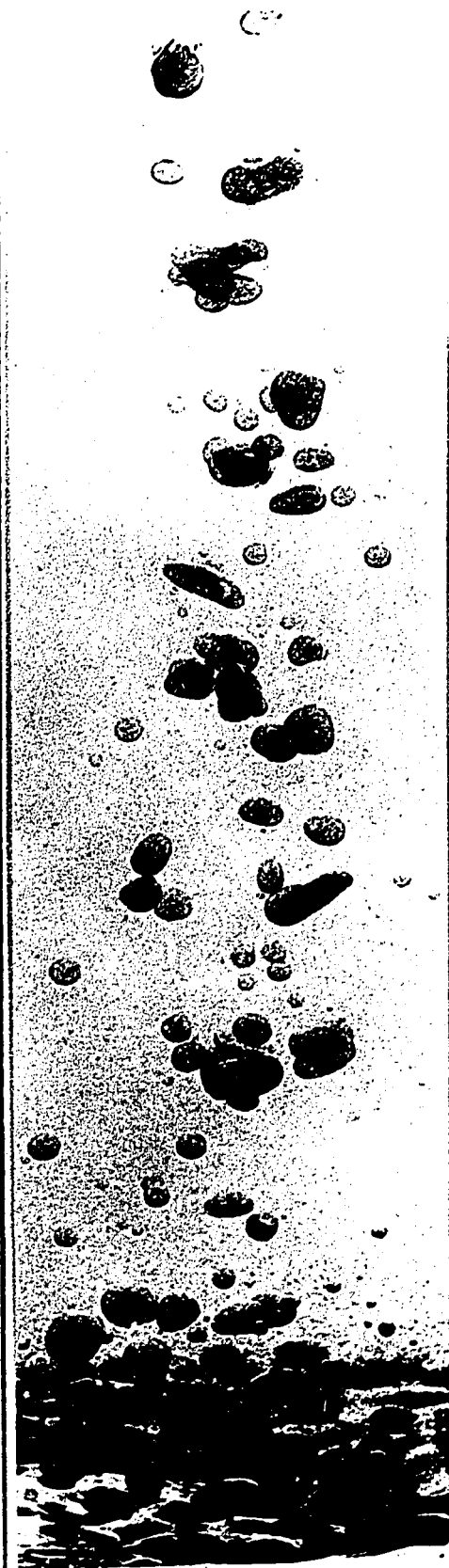
(a)

16

20

24

28



(b)

Dia : 0.278 in

(a)

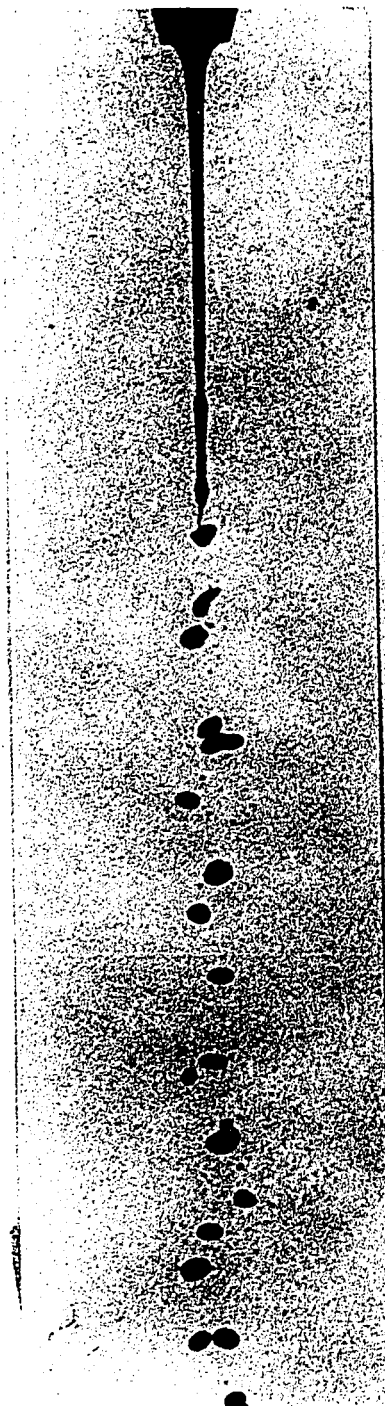


Velocity
(in/sec)

7.69

Dia : 0.516 in

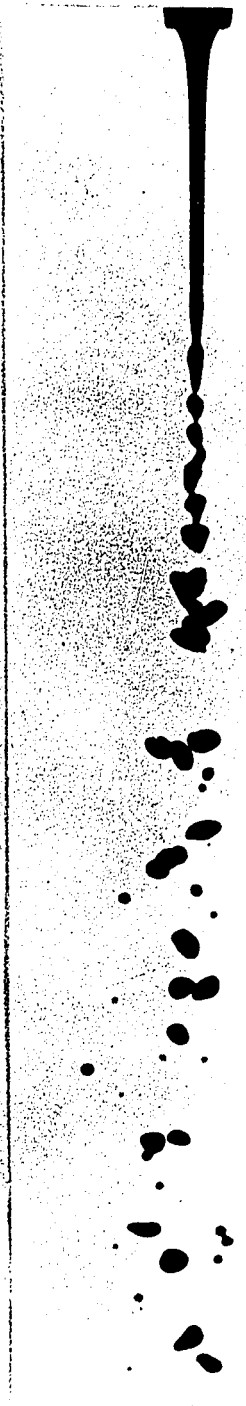
(b)



1.33

Dia : 0.813 in

(c)

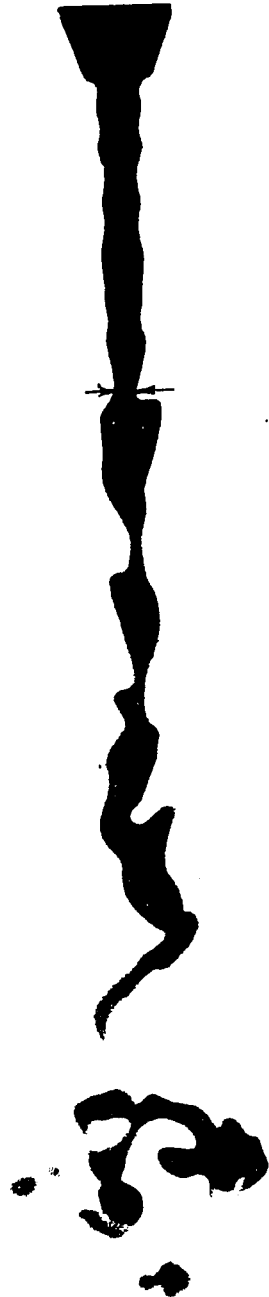


1.49

FIGURE 39

Dia : 0.278 in

(a)



Velocity
(in/sec)

19.2

Dia : 0.516 in

(b)



4.81

Dia : 0.813 in

(c)



3.3

FIGURE 40