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SOME AERODYNAMIC PROPERTIES OF SPRAYS

by

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INTRODUCTION

In recent years attention has been given to the momentum of sprays particularly in scaling problems for systems where jets and sprays are used, e.g. furnaces. Little is known, however, of how momentum is distributed within a spray between the drops and the entrained air, and how this distribution varies with the distance from the nozzle. This information would be useful in a number of cases where sprays and dispersions are involved in processes of heat and mass transfer. In general, the well-known aerodynamic laws governing the motion of particles cannot be applied to estimate this distribution, firstly, because of interference between particles and secondly, because of deformation of liquid drops in flight. During the course of work on the extinction of fires with water sprays from pressure nozzles, however, methods were developed for measuring certain spray properties from which a useful picture of aerodynamic conditions within a spray could be obtained. In this paper a description of those methods is given and their use illustrated.

MEASUREMENT OF SPRAY PROPERTIES

The measurements made which were particularly relevant to the aerodynamic properties of a spray were:

(a) the reaction at the nozzle
(b) the force exerted on a flat obstacle
(c) the velocity of entrained air current
(d) the flow rate distribution in the spray.

The above properties could all be measured rapidly and with simple apparatus. In all cases the components of the forces and velocities parallel to the spray axis were measured.

(a) The nozzle reaction was measured by a method similar to that used by Collins[1], but with the refinement of a means to minimize errors caused by stresses in the apparatus (Fig.1). This was achieved by using short flexible joints in the pipe system, and making thrust measurements with the pipe system in the position it occupied when at rest.

(b) The force of the spray on a flat obstacle was measured by placing in the spray a letter balance surmounted by a flat circular plate on which the spray impinged; the force was indicated directly on the balance.

(c) The velocity of the entrained air current was measured with the apparatus shown on the left hand side in Fig.2. The spray was projected downwards into the upturned end of a tube bent at a right angle. The bulk of the spray separated out at the bend and the prevailing air current was measured by an anemometer placed at the end of the long limb. A correction for the reduction in velocity due to the resistance of the tube was obtained from a calibration using a wind tunnel.

(d) The flow rate distribution was measured by catching the spray in an array of vessels.

In addition a method of measuring directly the velocity of the drops in a spray was developed (2, 3). However, the method was cumbersome since a very large number of measurements had to be made at any given point in the spray and a statistical analysis was required before a reasonable estimate of drop velocity could be obtained. It was also difficult to allow for sources of error caused by the apparatus itself. Although methods have been described for measuring the velocity of drops in a thin sheet of spray(4), and for spray close to a nozzle(5) as far as the authors are aware there is no simple method for an extensive turbulent spray; it will, however, be shown later how it is possible under some conditions to obtain a useful estimate of drop velocity without recourse to direct measurement.

Apparatus

Tests were carried out on six nozzles of the type used for the extinction of fires. They are listed in Table 1 together with information on certain properties of the sprays they produced. Four nozzles, the design of which has been described elsewhere(6), were superficially very similar in that each contained six pairs of impinging jets 9/64 in. diameter arranged in a circle, but small differences in the nozzles resulted in very different sprays being produced. The other two nozzles were proprietary swirl nozzles with a hole in the centre of the swirl plate. The nozzles were mounted to spray vertically downwards from a height 8 ft above the floor (Fig.2) and measurements were made of the air current in a plane 6 ft below the nozzle, of the force on an obstruction and of the flow rate in a plane 7 ft 6 in. below the nozzle. The measurements were made on the axes of the nozzles and at distances increasing by units of 1 ft on eight equi-spaced radii. This procedure gave the pattern of these properties in the planes in which they were measured.

RESULTS

Figs.3, 4 and 5 give respectively the pattern of the air current, the force on a flat obstacle and the flow rate at 50 lb/in^2 pressure for the four nozzles based on impinging jets. There is a marked difference between the flow rate patterns for the different nozzles, but the differences between the force patterns are less marked and those between the air velocity patterns even less marked.

Calculation of mean drop velocity

Before describing the methods of calculating the drop velocity, three parameters with dimensions of velocity will be defined, based respectively on the reaction at the nozzle, the entrained air velocity and the force exerted at an obstacle. These parameters are:

(1) V_n, the momentum mean velocity of the drops at the nozzle, obtained by dividing the reaction at the nozzle by the flow rate through the nozzle.

(2) G, the momentum flux in the air stream associated with unit flow rate of spray, obtained by calculating the total momentum flux in the air current at the plane of measurement and dividing by the flow rate through the nozzle.

i.e. $G = \frac{\Sigma \rho v^2 A}{R}$

where ρ = density of air.

v = entrained air velocity in an annulus of spray.

A = area of annulus.

R = flow rate.

(3) F, the force at an obstacle per unit flow rate, calculated as

$$F = \frac{\Sigma f A}{R}$$

where f = force per unit area in annulus.

Table 2 gives the values of these parameters for the sprays from the six nozzles at pressures of 25, 50 and 90 lb/in^2 in units of lb force/gal min^{-1}, it is necessary to multiply the values by 192 to obtain dimensions of ft sec^{-1}. Two simple expressions are derived below in each of which V_p the mean momentum velocity of the drops at a plane P below the nozzle is expressed as a simple function of two of these parameters. The first of these expressions is based on an analysis of the momentum of the spray at the plane P and the second on the analysis of the parameter F.

Consider a spray projected freely downwards from a nozzle. The momentum associated with unit mass of liquid as it passes through successive planes below the nozzle will not be constant, since the drops are acted upon by gravity. On passing from the nozzle to a plane P at a distance h below the nozzle the momentum per unit mass of liquid will increase by a quantity gt, where g is the acceleration due to gravity and t is the time taken for liquid to pass from the nozzle to the plane. The momentum which has therefore been given to unit mass of liquid entering plane P will be $V_n + gt$. If pressure differences in the spray are neglected, this momentum is equal to the sum of the momenta which has been imparted to the air stream and the remaining momentum in the liquid drops.

Thus

$$V_n + gt = G_p + V_p \qquad \text{.................(1)}$$

(The subscript p refers to plane P).

The force at an obstacle consists of three components, the drag of the air stream flowing round the obstacle, the force of the impinging water drops and the weight of the accumulated water at the obstacle. From standard formulae for the drag at flat obstacles perpendicular to a turbulent air stream it may be deduced that this drag force is approximately equal to half the momentum flux in the column of air approaching the obstacle. Thus, considering an obstacle at which a flow rate r impinges, it follows that, as an average for the whole spray,

$$rF_p = 0.5\, rG_p + rV_p + W \qquad \text{.................(2)}$$

where rF_p = measured force

$0.5\, rG_p$ = drag due to air current

rV_p = force due to impinging drops

W = mean weight of water on obstacle.

It should be added that if the spray is projected horizontally and forces and velocities are measured horizontally then the weight term would disappear from equation 2 which would then reduce to

$$F_p \doteq 0.5\ G_p + V_p \qquad \ldots\ldots\ldots\ldots\ldots(3)$$

It is possible, using equation (1) and the information in Table 2, to estimate the value of V_p in the plane 6 ft below the nozzle. V_n and G_p may be obtained directly from Q and G in Table 2, multiplying by 192 to convert the values to ft/sec. If it is assumed that the deceleration of the drops travelling from the nozzle is constant then it follows that

$$t = \frac{2h}{V_h + V_p} \qquad \ldots\ldots\ldots\ldots\ldots(4)$$

where h = 6 ft the distance between the nozzle and the plane. Substituting for t in equation (1) allows V_p the only remaining unknown to be calculated.

The assumption leading to equation (4) is not quite accurate, since the deceleration of drops decreases as the velocity of the drops diminishes. However, it was generally found in the calculations that the gravity term in equation (1) was of the order of only 10-20 per cent of the drop velocity term, so that it is unlikely that the inaccuracy would have a major bearing on the calculated value of V_p. However, the inaccuracy is such that the calculations would become less reliable as V_p decreased and h increased.

In Fig.6, curves a, b and c show V_p plotted against the mass median drop size D of the sprays for nozzle pressures of 90, 50 and 25 lb/in^2 respectively. D at 25 and 90 lb/in^2 was estimated from the value at 50 lb/in^2 using a correction for the effect of pressure on drop size based on results for single pairs of impinging jets(6).

Fig.7 shows similarly the downward velocity of the drops at the nozzle, V_n, (curves d, e and f) and the terminal velocity of drops of the mass median drop size falling freely in air, V_t. Comparing Figs.6 and 7 it will be seen that after falling a distance of 6 ft a considerable amount of deceleration had taken place. Indeed for the finest sprays, the drops had for practical purposes stopped decelerating, since the difference between the terminal velocity and the estimated drop velocity was approximately equal to the mean velocity of the air stream in which the drops, were moving. However, as would be expected, the value of V_p increased with increase of either the drop size of the spray or the pressure at which the spray was projected, although the effect of increasing the pressure from 50 - 90 lb/in^2 was small.

It was not possible to use equation 2 to estimate the drop velocity mainly because W was not known. However, using the values of drop velocity obtained from equation 1, an approximate estimate of the factor W was obtained. This indicated that the weight of water was a substantial portion of the total force at the obstacle and was of the same order as that which could be calculated from considerations of fluid flow and resistance at an obstacle. If the sprays were projected horizontally the drawback of having to allow for the weight of water on the obstacle would not occur. Indeed, the determination of drop velocity in a spray projected horizontally from measurements of force exerted on a pendulum has been widely used in the past(5). In general, however, no correction for the drag of the air current as in equation (3) has been employed.

PRACTICAL APPLICATIONS

A knowledge of the entrained air velocity, drop velocity and force of a spray can in themselves be useful in certain specific cases where sprays are employed. Thus, for example, in the extinction of fire, the stability and combustion intensity of the flame is a function of the entrained air velocity: and the heat transfer between the sprays and hot fluids and surfaces will, in general, be a function of the drop velocity of the spray. A knowledge of the force of the spray is useful whenever it is possible that the impingement of a spray may cause damage to sensitive equipment. The gas current accompanying a spray is also of prime importance in determining whether drops impinge against obstacles and it follows that the entrained air current is important in operations in which sprays impinge against surfaces.

An important use of information on the aerodynamic properties of sprays is in deciding what laws govern the behaviour of a spray when subjected to opposing or deflecting forces. In fire fighting, three such forces are commonly met with: the upward force of the flames, the lateral force of wind and the downward force of gravity. The last two forces are also factors which enter the use of sprays in agriculture. It has been found(7) that the size of drops in a spray which can penetrate to the seat of a fire against the upward motion of the flames decreases as the entrained air current in the spray increases, and for fine sprays very little of the spray can penetrate against the upward motion of the flames if the momentum flux in the latter is greater than the downward momentum in the entrained air current in the spray. It is common knowledge that the throw of sprays is generally much greater than the value that may be calculated from the throw of individual drops, since the drops are carried along in the entrained air current. In this connection analyses of the throw of a spray on the basis either of the entrained air current(8,9) or the total momentum flux(10) have indicated relationships between the throw, on the one hand and the pressure the flow rate, and the cone angle on the other which are broadly confirmed in practice.

Finally there are many processes in which sprays are projected into gas streams for the purpose of carrying out some mass or heat transfer operation or for removing dust from the gas. It is desirable to know in many of these operations the extent of the regions in which the spray influences the motion of the gas and in which the drop velocities have a value appreciably greater than terminal velocity. A knowledge of the entrained air current and the mean momentum drop velocity in the spray at various planes could clearly be of use in defining this region. If the region is large compared with the volume of the plant in which the process is taking place transfer coefficients based on the ambient gas velocity and the terminal velocity of the drops might contain a substantial error.

TABLE 1

Properties of Spray Nozzles at 50 lb/in^2

Code	Operating Principle	Spray Pattern	Cone Angle $^\circ$	Mass Median Drop Size m m.	Flow Rate Gal/min.
A	Swirl	Moderately Peaked	65	0.97	14.0
B	Swirl	Peaked	48	0.99	15.5
L	Impinging Jet	Peaked	51	3.2	28.2
M	Impinging Jet	Peaked	100	1.5	26.3
L'	Impinging Jet	Uniform	52	1.3	25.7
M'	Impinging Jet	Uniform	98	0.68	24.1

TABLE 2

Force Properties of Spray from Nozzles at 50 lb/in^2

Code	Force Per Unit Flow Rate, lb gal^{-1}min.			
	Pressure lb/in^2	Reaction at Nozzle–Q	Mean momentum flux in air stream – G.	Mean force on an obstacle – F.
A	25 50 90	0.261 0.325 0.437	0.182 0.240 0.379	0.29 0.51 0.81
B	25 50 90	0.251 0.363 0.514	0.167 0.244 0.418	0.41 0.51 0.59
L	25 50 90	0.287 0.402 0.537	0.117 0.169 0.298	0.52 0.49 0.60
M	25 50 90	0.221 0.336 0.421	0.113 0.156 0.267	0.41 0.44 0.53
L'	25 50 90	0.215 0.330 0.449	0.129 0.220 0.344	0.32 0.35 0.67
M'	25 50 90	0.157 0.224 0.318	0.102 0.175 0.278	0.18 0.49 0.49

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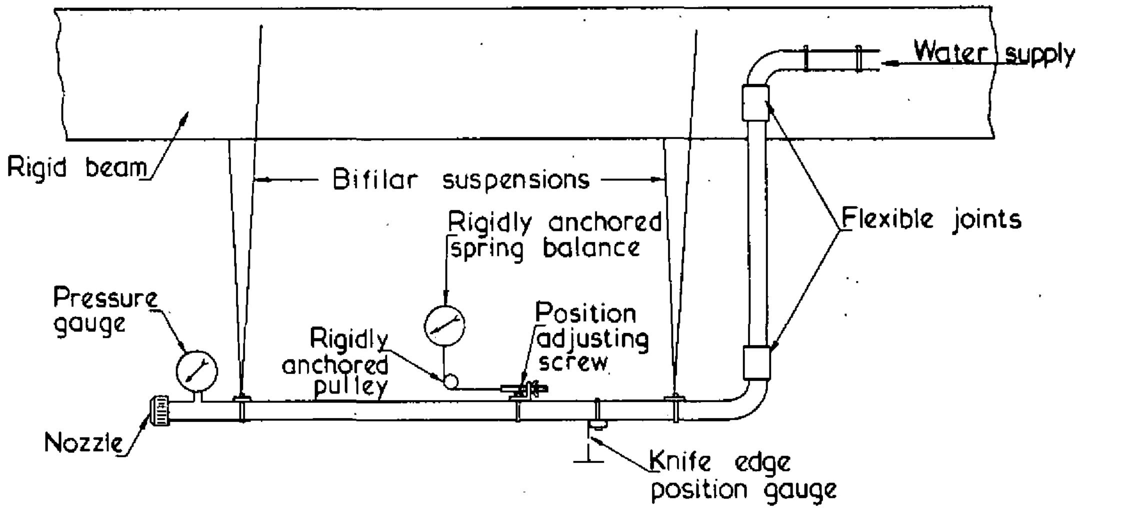

FIG. 1. APPARATUS FOR MEASURING NOZZLE REACTION

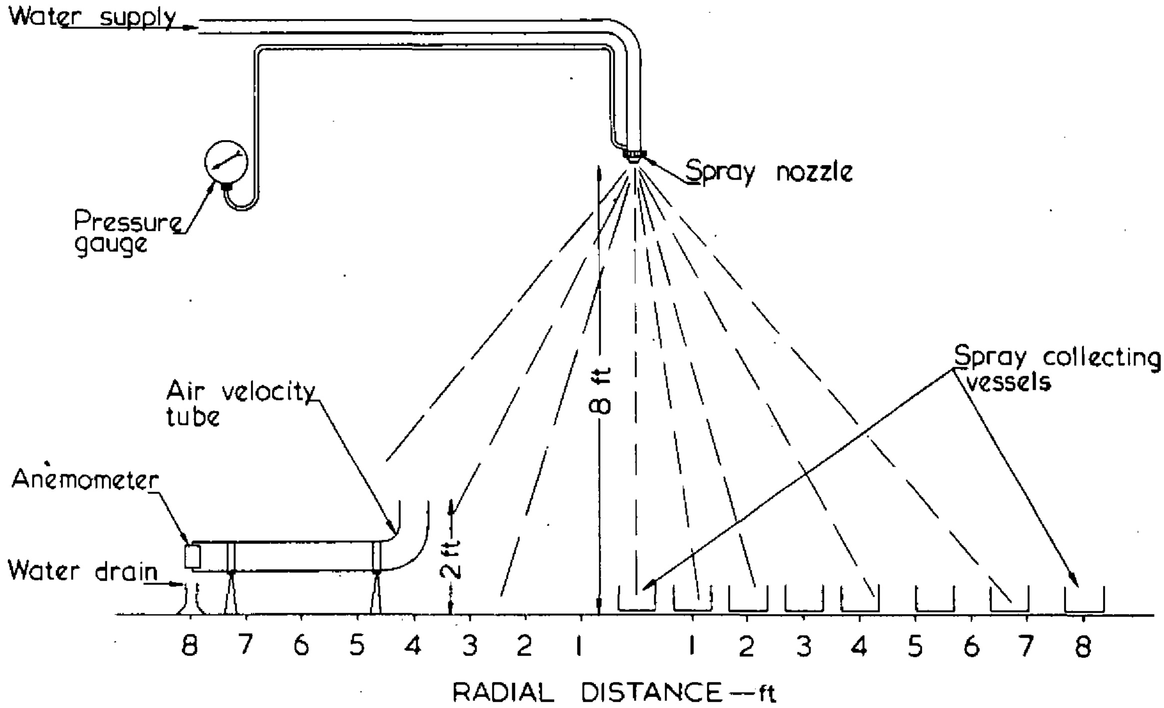

FIG. 2. MEASUREMENT OF SPRAY PROPERTIES BELOW THE NOZZLE

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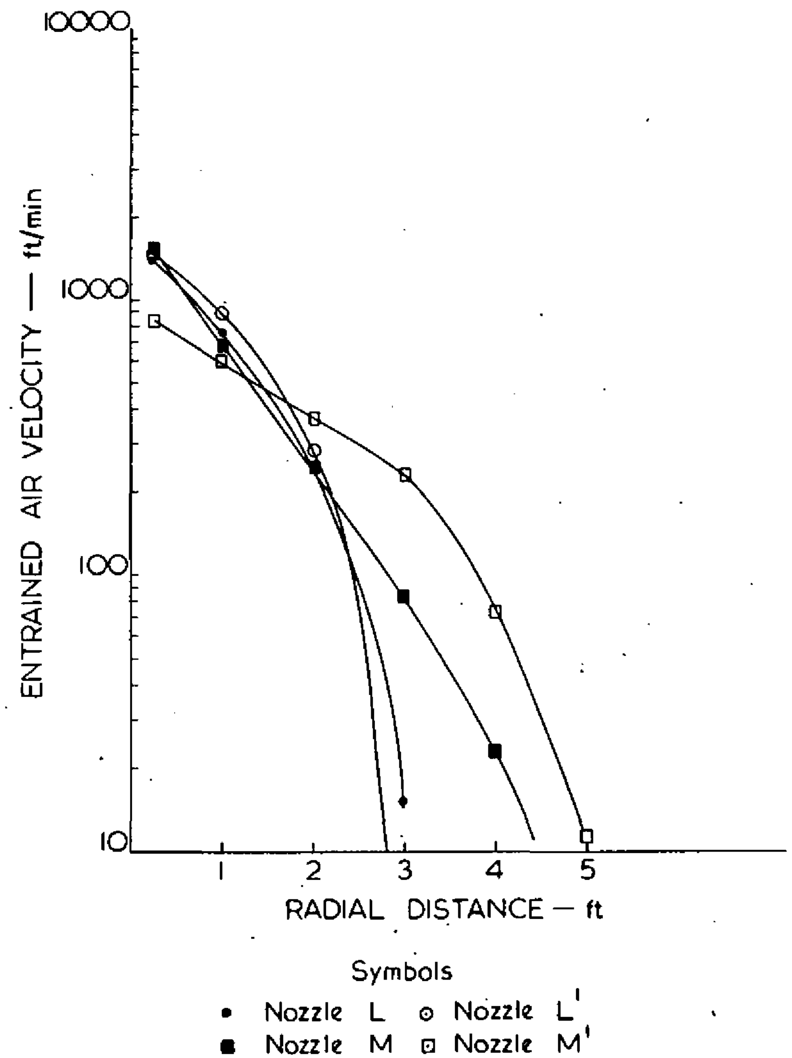


FIG. 3. AIR VELOCITY PATTERN, 6 FT BELOW NOZZLE
NOZZLE PRESSURE 50 LB/IN²

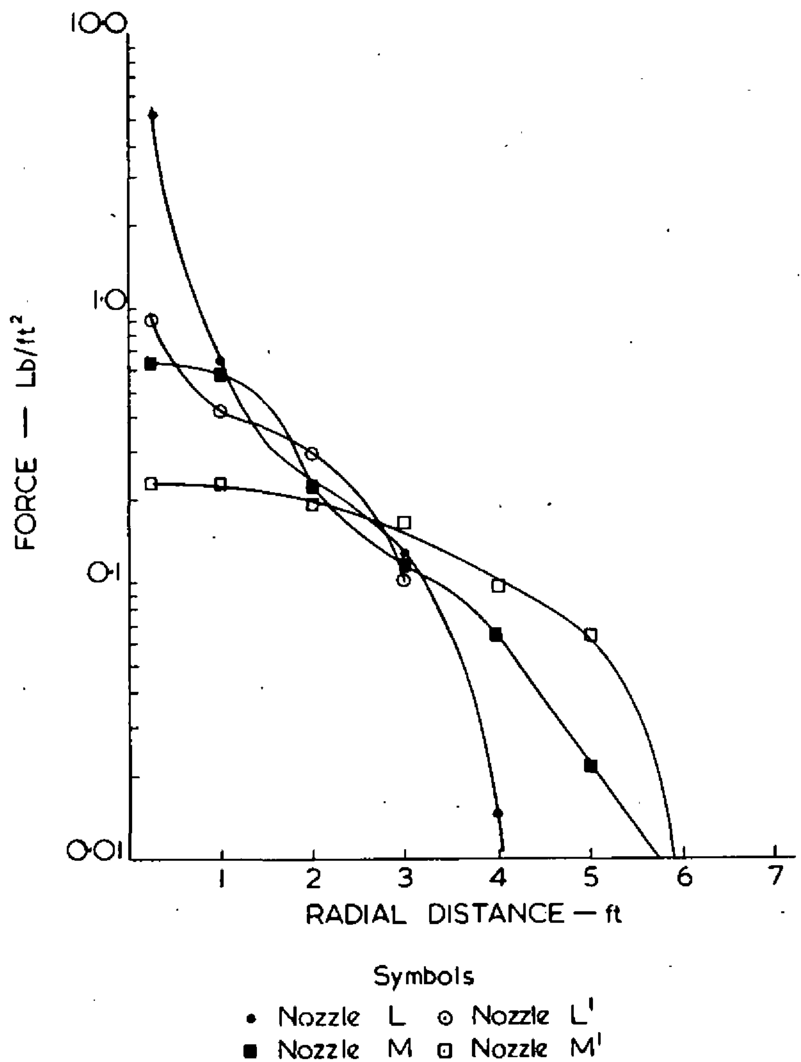
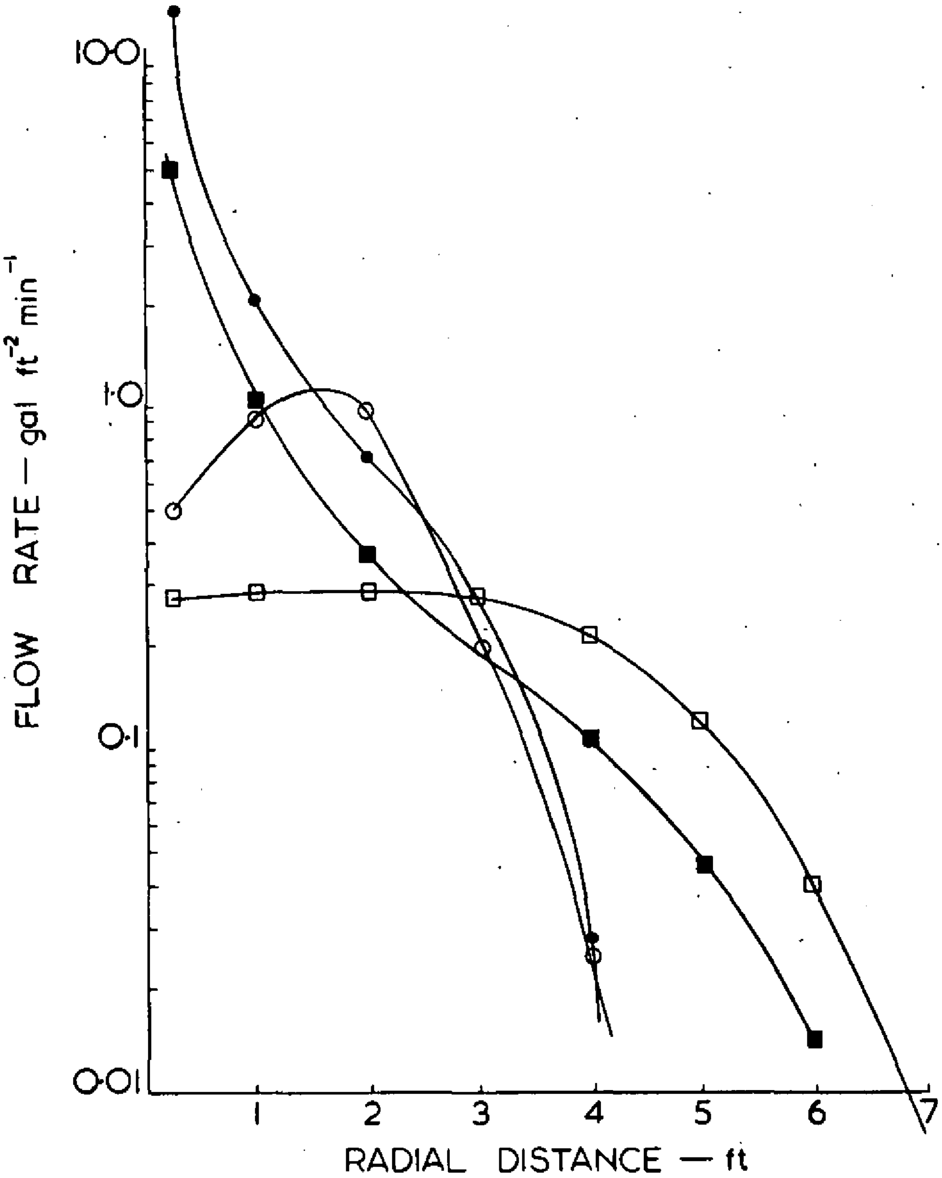


FIG. 4. PATTERN OF FORCE ON AN OBSTACLE 7'-6"
BELOW NOZZLE NOZZLE PRESSURE 50 LB/IN²



Symbols

- ● Nozzle L
- ⊙ Nozzle L'
- ■ Nozzle M
- ⊡ Nozzle M'

FIG. 5. SPRAY PATTERN 7'- 6" BELOW NOZZLE
NOZZLE PRESSURE 50 LB/IN^2

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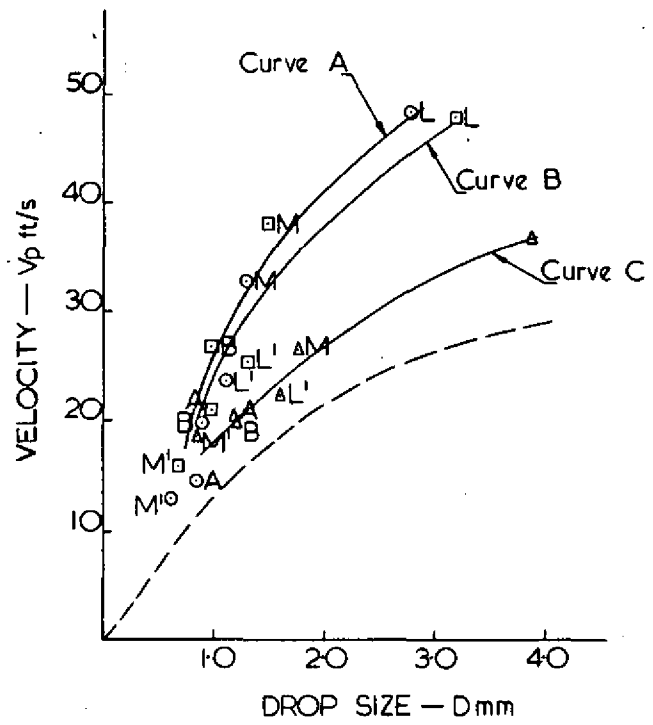


Symbols

Curve A ⊙ = 90 Lbs/in²

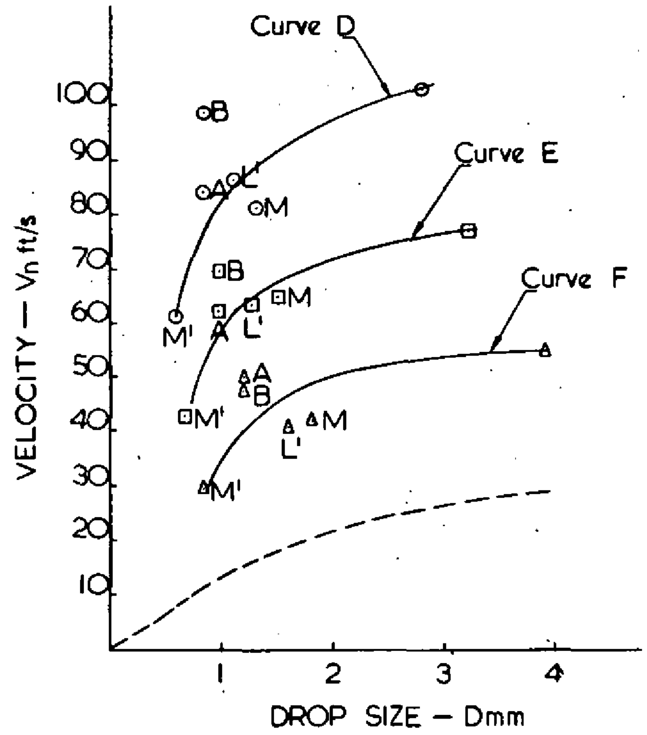
Curve B ⊡ = 50 Lbs/in²

Curve C ▲ = 25 Lbs/in²

Dashed Curve = Terminal Velocity V_t

Capital Letters = Nozzle (Table 1)

FIG. 6. MEAN DOWNWARD VELOCITY V_p OF DROPS IN A PLANE 6 FT BELOW THE NOZZLE



Symbols

Curve D ⊙ = 90 Lbs/in²

Curve E ⊡ = 50 Lbs/in²

Curve F ▲ = 25 Lbs/in²

Dashed Curve = Terminal Velocity V_t

Capital Letters = Nozzle (Table 1)

FIG. 7. MEAN DOWNWARD VELOCITY V_n OF DROPS AT THE NOZZLE