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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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THE PROPERTIES OF SPRAYS PRODUCED BY BATTERIES OF IMPINGING JETS

by

D. J. Rasbash

Summary

The entrained air velocity, mass median drop size, drop size distribution and drop velocity of sprays falling on a given area, and produced by a battery of impinging jets, have been related to the diameter of the jets, the pressure at the jets and the rate of flow of spray to the given area. A theoretical formula has been derived for predicting the entrained air velocity in the sprays which agrees fairly well with the formula actually obtained. The application of the theoretical formula to predict the entrained air velocity and reach of sprays from single pressure nozzles is discussed. It was also found that the rate of reduction in drop size with increase in pressure, decreased as the pressure increased.

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Fire Research Station,
Boreham Wood,
Herts.

LIST OF SYMBOLS

Symbol		Dimensions
a	velocity of drops in excess of entrained air stream	LT^{-1}
A	velocity of entrained air stream	LT^{-1}
$\bar{A}$	root mean square of velocity of entrained air stream over area B	LT^{-1}
B	area through which spray and its entrained air stream passes	L^2
c	discharge coefficient of jets	ж
D	mass median drop diameter of spray	L
g	acceleration due to gravity	LT^{-2}
G	percentage of drops present with diameter greater than y	ж
h	distance from nozzle	L
J	jet diameter	L
K	arbitrary constant in equation 16	Ɨ
n	drop size distribution factor	ж
P	pressure	$ML^{-1}T^{-2}$
R	rate of flow per unit area receiving spray	$ML^{-2}T^{-1}$
R_n	rate of flow from nozzle	MT^{-1}
t	time taken by drops to pass through distance n	T
V	velocity of drops at nozzle	LT^{-1}
x	exponent of P in equation 16	Ɨ
y	drop size	L
$\bar{y}$	drop size constant	L
ρ	density (a - air, w - water)	ML^{-3}
α	angle of impingement of jets	ж
θ	cone angle of spray	ж
μ	viscosity of liquid	$ML^{-1}T^{-1}$

ж dimensionless

Ɨ dimensions such that equation 16 balances.

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INTRODUCTION

In work on the extinction of liquid fires with water sprays (1) an apparatus was developed for producing sprays of controlled properties at a fire area 30 cm diameter. During the course of the work the entrained air velocity, drop size distribution and drop velocity of many sprays produced by these batteries were measured. The results of these measurements have now been analysed and related to the pressure, the jet size and the rate of flow at the fire area.

EXPERIMENTAL

The apparatus, and the methods of measuring the spray properties have been described elsewhere (1). It consisted of two batteries of 6 pairs of jets, each pair impinging at an angle of 90°; these batteries were placed 175 cm above the fire area. The number of pairs of jets in use could also be varied by blocking jets not required. For a given size of jets and pressure at the batteries, sprays with varying rates of flow to the fire area and different spray patterns at the fire area could be obtained by varying the number of pairs of jets used and the position of the batteries relative to the area. In most of the tests carried out with this battery the sprays gave an approximately even pattern at the fire area; the results given in this paper will refer only to sprays of such pattern. The jet sizes used were 1/64, 1/32, 3/64 and 1/16 in.

RESULTS

ENTRAINED AIR VELOCITY

The velocity of the air current entrained with the spray (the entrained air velocity) was measured in a plane 30 cm above the combustion vessel (145 cm below the batteries). Measurements were made on 47 sprays which had rates of flow at the fire area between 0·4 and 6 $g/(cm)^2(min)$ and which were produced within pressures of 5-85 lb/in^2.

A regression analysis on these results showed that the entrained air velocity depended significantly on the rate of flow and pressure but not on the jet size. Equation (1) accounted for 95·4 per cent of the total variance.

$$\log A = 0{\cdot}327 \pm 0{\cdot}033^{*} \log P + 0{\cdot}475 \pm 0{\cdot}063 \log R + 1{\cdot}812 \quad .....(1)$$

where A = entrained air velocity (cm/s)
P = pressure (Lb/in^2)
R = rate of flow to the fire area ($g\ cm^{-2}\ min^{-1}$)

It was also found that the somewhat more complicated equation (2) could account for a slightly higher percentage (97·9) of the total variance.

$$\log A = 0{\cdot}296 \log P + 1{\cdot}173 \log R - 0{\cdot}397 \log P \log R + 1{\cdot}876 \quad .....(2)$$

Equation (1) may also be written in the form

$$A = 64{\cdot}9P^{0{\cdot}327}\ R^{0{\cdot}475} \quad .....(3)$$

or

$$A = 10{\cdot}7P^{0{\cdot}327}\ R^{0{\cdot}475} \quad .....(3a)$$

if A is measured in ft/sec and R in $lb\ ft^{-2}\ sec^{-1}$.

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*95 per cent confidence limits on regression coefficient.

MASS MEDIAN DROP SIZE

The drop size measurements were carried out at the combustion vessel. Eighty-four measurements were made on sprays within the same range of rates of flow to the fire area and pressures mentioned in the previous section. Each measurement was based on a count of 2500 to 10000 drops. A regression analysis on these measurements showed that equation (4) accounted for 94·5 per cent of the total variance.

$$\log D = 0{\cdot}367 \pm 0{\cdot}052 \log J - 0{\cdot}646 \log P + 0{\cdot}110 (\log P)^2 + 0{\cdot}140 \log R + 0{\cdot}160 \qquad \ldots\ldots(4)$$

where D = mass median drop size (mm)
J = jet diameter (in. x 64).

DROP SIZE DISTRIBUTION

It was found that most of the sprays obeyed the Rosin Rammler law (Equation 5) fairly well.

$$2{\cdot}3 \log \frac{100}{G} = \left(\frac{y}{\bar{y}}\right)^n \qquad \ldots\ldots(5)$$

where G = percentage of volume of drops present as drops of diameter greater than y

$\bar{y}$ = a linear size constant

n = a distribution factor

The exceptions were sprays with the larger jet sizes (3/64 and 1/16 in.) at the lower pressures (5 and 10 $lb/in.^2$); these sprays usually contained a smaller amount of very fine drops than predicted by the Rosin Rammler law.

The coefficient n in equations (5) may be taken as representing the homogeneity of the spray; the larger the value of n the more uniform in drop size was the spray. n varied between 2·0 and 3·0; the value increased as the pressure increased and the jet size decreased, but was independent of the rate of flow to the fire area.

DROP VELOCITY

With twelve of the sprays an estimate of the drop velocity was obtained for those drops in the spray up to 0·40 mm diameter, at a point 30 cm above the centre of the fire area (2, 3). The relative downward velocity, a, of the drops to the entrained air stream increased as the drop size increased as shown in Figure 1. Within the accuracy of the estimation the rate of flow to the fire area and the pressure did not affect the value of a.

DISCUSSION

ENTRAINED AIR VELOCITY

Derivation of formula for entrained air velocity

The entrained air velocity of the spray arises from the transfer of the initial momentum of the drops to the surrounding atmosphere due to the form drag between the drops and the air. The form drag is that part of the drag which arises from the pressure difference between the leading and trailing surfaces of the drop and accounts for the major part (about 90 per cent) of the resistance to the drops in their passage through the air. An estimate of the entrained air velocity and an indication of the way in which it should depend on the rate of flow and the pressure may be obtained using a momentum balance. Thus if at a horizontal plane h ft directly below a battery of impinging jet nozzles pointing downwards there is an entrained air velocity of A ft/sec and a rate of flow of water of R Lb ft^{-2} sec^{-1}, and if the velocity of the water drops relative to the air stream at the plane is $\underline{a}$ ft/sec then the momentum flux at the plane will be given by

$$\rho_a A^2 + R(A + a) \text{ poundals/ft}^2$$

This may be equated to the sum of (1) the momentum flux of the same rate of flow of water at the jets and (2) the momentum flux induced by the action of gravity; (1) is equal to RV where V is the initial velocity of the water spray leaving the jets in a direction perpendicular to the plane and (2) is equal to R gt where t is the time taken for the spray to travel from the jets to the plane.

Thus

$$\rho_a A^2 + R(A + a) = R(V + gt) \qquad \ldots\ldots(6)$$

In the derivation of equation 6, skin friction at the drops is neglected and it is assumed that all the form drag results in the transfer of downward momentum to the air stream. An approximation to t may be obtained by assigning a mean velocity to the drops as they fall from the jets to the plane, equal to $\frac{V + A + a}{2}$; from this t may be calculated to be $\frac{2h}{V + A + a}$. Substituting for t in equation 6 and rearranging gives.

$$\rho_a A^2 + R\left(A + a - \frac{2gh}{V + A + a}\right) = RV \qquad \ldots\ldots(7)$$

By equating the downward momentum of the water jets before and after break up then the expression in equation 8 may be obtained.

$$V = C\sqrt{4{\cdot}6\ gP}\ \cos\frac{\alpha}{2} \text{ ft/sec} \qquad \ldots\ldots(8)$$

Here α is the angle of impingement of the jets and C the discharge coefficient at the jets; separate experiments showed that with the jets used in the experiments C varied with the jet size and pressure between 0·75 and 0·90.

From the information above it was possible to substitute in the factor $R\left(A + a - \frac{2gh}{V + A + a}\right)$ the required values of A, a and V for a number of sprays. All these substitutions showed that this factor was positive and small compared with the corresponding value of RV (about $\frac{1}{5}$). This might have been expected, since in all the tests the value of A was also small compared with the value of V. For simplicity the second term may therefore be omitted from equation 8

$$\text{giving} \qquad \rho_a A^2 \approx RV \qquad \ldots\ldots(9)$$

Combining equation 9 and 8 and inserting the values of α and c gives

$$A \approx 9{\cdot}7\ R^{0{\cdot}5}\ P^{0{\cdot}25} \qquad \ldots\ldots(10)$$

Equation 10 is similar to equation 3a. If the second term were not omitted from equation 7 in order to form equation 10, then the exponent of R in equation 10 would be reduced to less than 0·5 and P increased to greater than 0·25 by amounts which would depend on the values of R, P and a. Under these conditions the exponents in equation 10 would approximate more closely to those in equation 3a.

However, an examination of equation 10 and 3a shows that over the range of pressures studied, equation 10 predicts a value for A which is only 60 to 80 per cent of that given by equation 3a. Because of the assumptions made in deriving equation 10 it would have been expected equation 10 should predict a high result. There are two reasons for this discrepancy. Firstly equation 3a correlates the entrained air velocity with the rate of flow to the fire area whereas in equation 10 the correlation is with the rate of flow at the place where the entrained air velocity is measured. In the tests described this plane was 30 cm above the fire area and separate tests on a few sprays showed that the rate of flow per unit area in this plane was about 1·4 times the rate of flow at the fire area. Thus to make equation 3a and 10 more comparable the coefficient 9·7 in equation 10 has to be multiplied by $\sqrt{1\cdot4}$ giving 11·5. Secondly the measurements correlated in equation 3a were taken at the centre of the spray. Measurements on three sprays produced at 85 Lb/in.^{2} pressure and a rate of flow of 1·6 g cm^{-2} min^{-1} showed that when the measurements were taken nearer the edge of the spray there was a tendency for equation 10 to predict values of A which were higher than the experimental values. It thus appears that air entrained at the edge of the spray finds its way into the centre of the spray; the reason for this is not fully understood.

It was also found that for a given rate of flow and pressure the entrained air velocity did not depend on the jet size, this implies that it was independent of the drop size range covered. A variation in drop size would bring about a variation in the drop velocity (a) in equation 7. It was found that for the sprays studied, the second term of equation 7, which includes the factor a, was small in comparison with the third term; this probably explains why jet size did not appear as a significant factor in the analysis. However, if the sprays were very much coarser and a correspondingly increased then it might be expected that drop size would begin to appear as a significant factor, the entrained air velocity decreasing with increase in drop size.

Entrained air velocity in spray from a single nozzle

In view of the general agreement between equation 10 and 3a, the approach to equation 10 may be used to relate the entrained air velocity in a spray from a single nozzle with the pressure and rate of flow at the nozzle.

Thus, consider a nozzle discharging all its water spray and the entrained air associated with it through an area B situated at some distance from the nozzle. If the rate of flow from the nozzle is R_n and the initial velocity of the drops in the direction of the area is V then the entrained air velocity at the area will be given by

$$B \rho_a \bar{A}^2 = R_n V \qquad \ldots (11)$$

$$\text{or } \bar{A} = \sqrt{\frac{R_n V}{B \rho_a}} \qquad \ldots (11a)$$

Where $\bar{A}$ = root mean square entrained air velocity over the area B, It may be further assumed that V is proportional to $\sqrt{P}$. Thus

$$\bar{A} \propto \sqrt{\frac{R_n P^{0.5}}{B}} \qquad .....(12)$$

V will also vary with the cone angle at the nozzle, the mean value of V decreasing as the cone angle increases. However within the range of cone angles 0 to 90° it is unlikely that V will vary by more than about 20 per cent.

Relation between entrained air velocity and the reach of a spray

The entrained air velocity of the spray is an important factor governing the throw of a spray projected horizontally; its importance increases as the drop size of the spray is reduced. In equation 12, $\sqrt{B}$ is the linear dimension of the area through which the spray is passing. This dimension will depend on the cone angle, θ and the distance h between the nozzle and the area, in such a way that $\sqrt{B}$ will increase as h and θ increases. The actual value of $\sqrt{B}$ will probably be between 2 tan 11° and 2 tan $\frac{\theta}{2}$ 11° being the angle at which a turbulent jet of air broadens. At a certain distance h_o from the nozzle the entrained air velocity may be reduced by broadening of the spray to that value Ao, which allows the drops to fall out or the spray to be dissipated in the wind conditions prevailing; h_o will then represent the reach of the spray. It follows that

$$\bar{A}_o \propto \frac{R_n^{0.5} P^{0.25}}{B_o^{0.5}} \qquad .....(13)$$

and writing $B_o^{0.5} = ho\, f(\theta)$

gives

$$h_o \quad \frac{R_n^{0.5} P^{0.25}}{f(\theta)} \qquad .....(14)$$

This equation may be compared with a regression equation on the throw of sprays obtained by Thomas and Smart (4).

$$h_o = 0{\cdot}68 \frac{R_n^{0.36 \pm 0.08} P^{0.28 \pm 0.02}}{(\tan \theta /4)^{0.57 \pm 0.18}} \qquad .....(15)$$

(R is measured in gal/min, P in lb/in², θ in degrees and h_o in ft).

It will be noted that the exponent of rate of flow in equation 15 is somewhat smaller than that in equation 14, and that of the pressure is approximately the same. The ratio of the exponents of rate of flow and pressure in equation 15 is not incompatible with the value of 2 predicted by equation 14. Equation 14 may therefore be regarded as giving an alternative approach for determining the way the rate of flow from the nozzle and the pressure at the nozzle might influence the reach of fine sprays from single nozzles, although it may cause an overestimation of the effect of rate of flow.

DROP SIZE

An important feature of equation 4 is that the effect of a pressure increase in reducing the drop size decreases as the pressure is increased.

Thus if the drop size is expressed as a function of the pressure by equation 16,

$$D = KP^{-x} \qquad .....(16)$$

(K = constant, depending on jet diameter, and rate of flow etc).

then the value of x will depend on the value of P. Figure 2 shows x as a function of P; x decreases from 0·5 to 0·2 as the pressure is increased from 5 to 100 Lb/in^2. Equation 4 also shows that the rate of flow at the fire area was a significant factor in determining the drop size. This was probably due to coalescence between drops from the larger number of individual pairs of jets required to give the higher rates of flow.

Fry and Smart [5] have also measured the drop size of impinging jet sprays. The range of jet sizes they used was from 1/16 to 3/16 in. and the pressure range was from 20 to 120 lb/in^2. These authors also varied the angle of impingement from 20 to 90°. Their results are not directly comparable to those obtained in the present tests since they used single pairs of impinging jets, whereas the number of pairs of jets used in the present tests varied according to the rate of flow to the fire area. However, from the value of the rate of flow coefficient given in equation 4 it was possible to apply a correction to the drop sizes obtained in the present tests which resulted in an estimate of the drop size which would have been obtained if only a single pair of jets were used. These corrected drop sizes are plotted in the dimensionless form ($\frac{D}{J}$) against the dimensionless number $\frac{PJ^2\rho}{\mu^2}$ (the latter number is equivalent to half the square of the Reynolds number at the jets), and results obtained by Fry and Smart for an impingement angle of 90° have been included in the graph. All the results fall approximately on a straight line fitting equation 17.

$$\frac{D}{J} = 54\left(\frac{PJ^2\rho_w}{\mu^2}\right)^{-0 \cdot 265} \qquad .....(17)$$

However, it will also be noted that for a given jet size the results fall rather on curves about the straight line than on the straight line itself. This is due to the diminishing effect of pressure as this factor was increased. It would therefore be unwise to use the line given in Figure 3 to predict the drop sizes of sprays at high pressures and low jet sizes except for obtaining a first approximation. It will also be noted that equation 17 predicts exponents of 0·47 and -0·265 for J and P respectively in comparison with an exponent of J of 0·37 obtained from the regression equation 4 and a mean exponent of P of -0·35 obtained from Figure 2. This is a consequence of the fact that these latter regression coefficients are for constant rates of flow at the fire area, whereas those obtained from equation 17 are for rates of flow given by single pairs of impinging jets. There is evidence that an exponent of about 0·5 for J is fairly general. Thus an analysis of all the data of Fry and Smart gives the exponent of J as 0·52 ± 0·18. Moreover, Joyce has stated that for sprays obtained from swirl nozzles the drop size of the spray is approximately proportional to the square root of the orifice size. However, the exponent for P appears to vary not only with P itself as indicated above, but also with other factors in the system. Thus the data of Fry and Smart does not indicate a significant overall effect of pressure although they indicate a significant impingement angle - pressure interaction. At impingement angles of 90° and 70° an increase in pressure decreased the drop size but at lower impingement angles an increase in pressure, if anything, increased the drop size.

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PC.

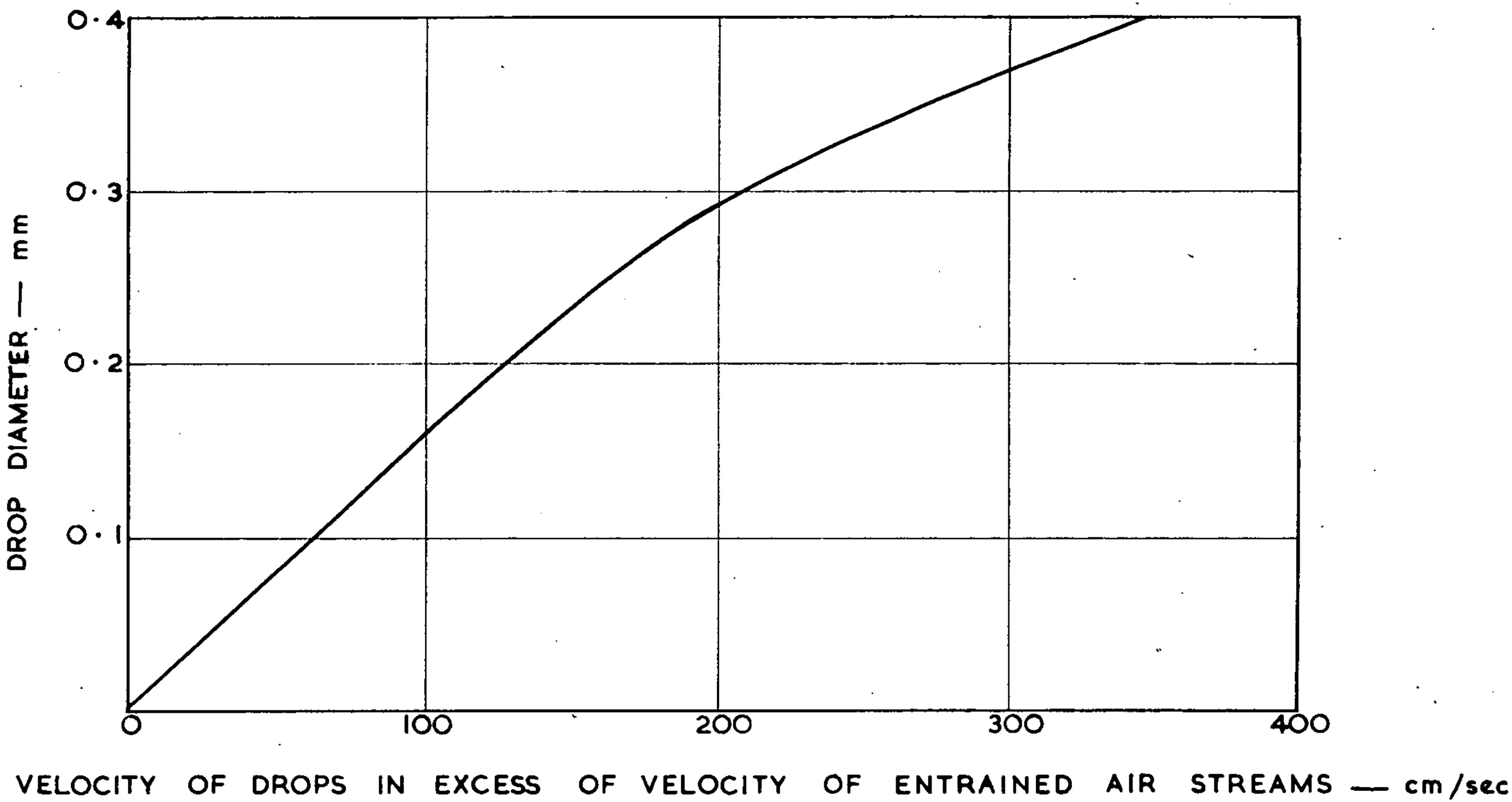

FIG. 1. RELATION BETWEEN DROP SIZE AND DROP VELOCITY IN THE WATER SPRAYS

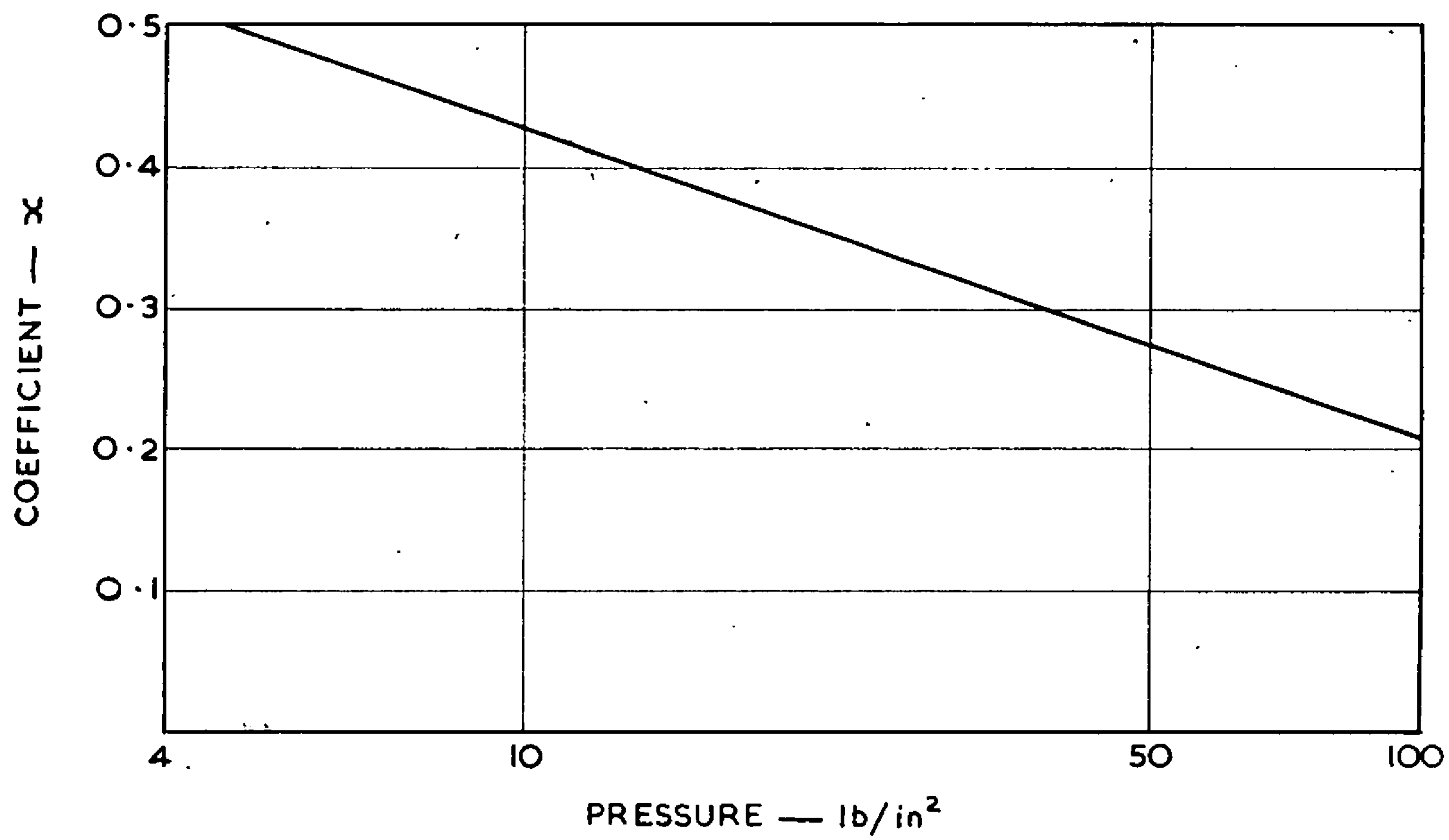

FIG. 2. RELATION BETWEEN PRESSURE AND COEFFICIENT x IN EQUATION $D = KP^{-x}$

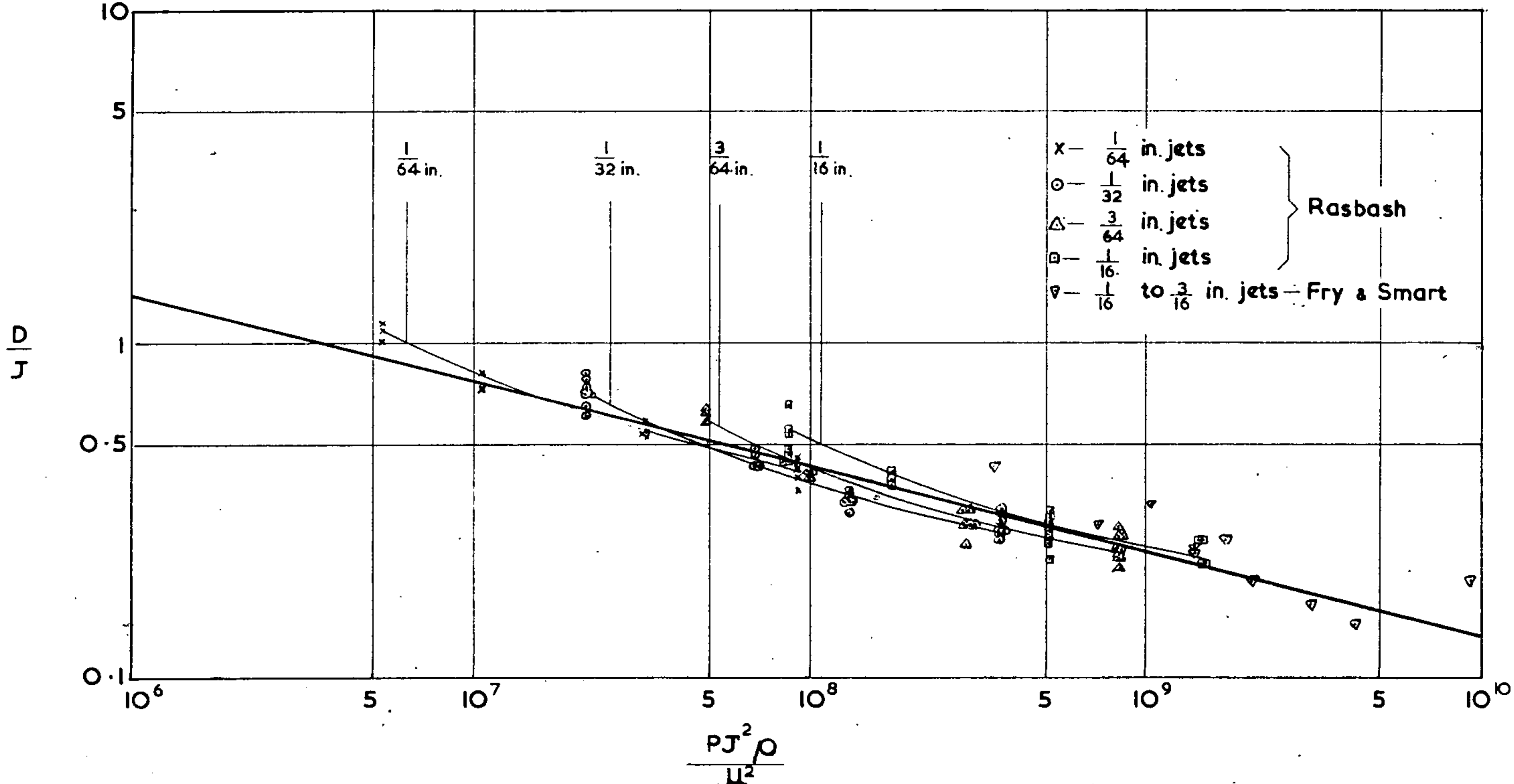

FIG. 3. DROP SIZE OF IMPINGING JET SPRAYS
ANGLE OF IMPINGEMENT 90°

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