CRANFIELD INSTITUTE OF TECHNOLOGY

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Ph.D. THESIS

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AIRBLAST ATOMIZATION : the effect of linear scale on the mean drop size

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SUMMARY

Stationary prefilming-cup airblast atomizers, in which the fuel is first spread into a thin cylindrical sheet and then exposed on both sides to high velocity air, have several important advantages over other common methods of fuel injection in their application to continuous combustion systems.

This thesis reports the results of a detailed programme of research on airblast atomization directed primarily to the investigation of the effect of atomizer linear scale, or size, on the mean drop diameter of sprays and, to the provision of a comprehensive picture of the performance of thin-sheet airblast atomizers over a wide range of working conditions. Three geometrically similar atomizers giving cross-sectional areas in the ratio of 1 : 4 : 16 were used; covering the range of prefilming cup diameter, D, from 19.05mm. to 76.20 millimeters, and were capable of handling various liquids at flow rates from 0.003kg/s up to 0.225 kg/s, at fuel pressures below 33 x 10^4 N/m^2 (about 50 p.s.i.).

It was found that atomizer scale has an appreciable direct effect on atomization quality. The Sauter mean diameter of low liquid viscosity sprays increases with the 0.44 power of atomizer linear dimension (D), while for liquids of high viscosity this effect is slightly higher. Analysis of the experimental data showed that the SMD of sprays produced by 'thin-sheet' atomizers of diverse designs could be predicted by the following dimensionally consistent expression:

$$\frac{SMD \times 10^3}{\phi} = 73 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(1 + \frac{W_\ell}{W_a}\right)^{1.0} \left(\frac{\sigma_\ell}{\rho_a V_a^{2.0}}\right)^{0.6} D^{0.4}$$

$$+ 0.3 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(1 + \frac{W_\ell}{W_a}\right)^{1.2} \left(\frac{\eta_\ell}{\sqrt{\sigma_\ell \rho_a}}\right) D^{0.5}$$

or alternatively, predictions could be obtained from the following dimensionless expression:

$$\frac{SMD}{D} = 0.063 \frac{(1+f)^{1.1}(1+0.004C_a)}{(W_e)_a^{0.55}} \cdot \left(\frac{\rho_\ell}{\rho_\alpha}\right)^{0.1} \phi$$

where: f is the liquid/air mass ratio = W_ℓ/W_a, C_a is the Capillarity Number = $\eta_\ell V_a/\sigma_\ell$; $(W_e)_a$ is the Weber Number = $\rho_a V_a^2 D/\sigma_\ell$, ρ_ℓ and ρ_a are the densities of liquid and air, respectively, and ϕ is the 'spray-finess factor' which is a function of atomizer geometry only.

The ability of the above expression to predict values of SMD to a reasonable order of accuracy over the following range of conditions has been demonstrated:

Liquid flow rate:	from 0.003 to 0.225 kg/s
Liquid surface tension:	from 0.026 to 0.074 N/m
Liquid absolute viscosity:	from 0.001 to 0.044 NS/m^2
Air to liquid ratio:	from 0.5 to 5.0
Atomizing air velocity:	from 60 to 190 m/s
Atomizing air density:	corresponding to air pressure levels from normal atmospheric conditions to 8.5×10^5 N/m^2.
Sauter mean diameter:	from 25 to 125 microns.

All SMD measurements were carried out using the monochromatic light scattering technique. It was shown that in the close proximity of the airblast under investigation, droplets have a distinct tendency to discretionary exist with distance along the sprays axis on the basis of their size. The mean drop diameter varied in a fairly regular manner, decreasing rapidly from an initially large size immediately outside the atomizer to a minimum value at some very short distance away, (in the order of 1.75 x D), and then gradually increasing at a much slower rate with increase in distance from the atomizer.

In addition, the discharge coefficient of the liquid tangential multi-slot arrangement was found to be 0.65, and independent of the slot's offset diameter, for values of flow Reynold's Number between 3,200 and 24,000 based on flow rate per slot and slot width, for ratios of slot length/width between 4.0 and 7.0.

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NOMENCLATURE

Latin Letters and Abbreviations:

A	=	a constant quantity; or, cross-sectional area of channel.
A^o	=	angstrom, ($1A^o = 10^{-10}$ meter)
a	=	a constant quantity; or, cup radius
A.F.R.	=	atomizing air/fuel mass flow ratio = $\frac{1}{f}$
A.L.R.	=	atomizing air/liquid mass flow ratio = $\frac{1}{f}$
B	=	a constant quantity
C	=	a constant quantity; or, coefficient of
Ca	=	capillarity number = $\eta_\ell V_a/\sigma_\ell$
cp	=	centipoise
cs	=	centistoke
D	=	diameter of airblast atomizer prefilmer; or, offset diameter of the tangential liquid channels (slots) of swirler.
$\bar{D}$	=	most probable droplet diameter
D_∞	=	maximum droplet diameter
$\frac{\bar{D}}{D_\infty}$	=	skewness in the U.L.D.F.
$D_{+\frac{1}{2}}$, $D_{-\frac{1}{2}}$	=	droplet diameters occuring at half the frequency of the most probable droplet diameter
$\frac{D_{+\frac{1}{2}} - D_{-\frac{1}{2}}}{\bar{D}}$	=	spread in the U.L.D.F.
D_{32} or d_{32}	=	volume to surface area mean diameter of spray = $\sum nd^3/\sum nd^2$
d	=	droplet diameter; or, orifice diameter; or, jet diameter

FN = atomizer flow number, UK gallons/hr. $(psi)^{\frac{1}{2}}$

f = mathematical function; or, focal length of lens; or, weight fraction of total airflow in atomizer primary air nozzle (in equation 3.11); or, liquid (fuel) to atomizing air mass flow ratio (in equation 6.7)

G = mass velocity = ρV

g = gravitational acceleration; or, gram

h = height of air annulus of airblast atomizer

$I(\theta)$ = intensity of diffractively scattered light at an angular displacement, θ radians, from the forward direction

K = a function

kg = kilogram

l = characteristic length; length of orifice

m = a constant quantity; or, meter

M.M.D. = mass median diameter of spray, microns $\approx$ 1.2 S.M.D.

Mn = mass number

N = number of tangential liquid channels of a swirler; or, a dimensionless group of properties; or, newton

n = number of drops, in a spray, the diameter of which is d

P = total pressure

ΔP = pressure difference

p = static pressure

psia = pounds per square inch absolute pressure

psig = pounds per square inch gauge pressure

Q = volume flow rate

Re = Reynolds number = $\rho V \ell / \eta$

S	=	liquid sheet thickness at position of disruption (in equation 2.2a)
s	=	seconds
SMD	=	Sauter mean diameter = D_{32}
$\Delta(SMD)_{vi}$	=	increase in the SMD of sprays which can be attributed to increase in the property of absolute viscosity of the liquid
t	=	thickness of liquid film (in equation 2.3)
ULDF	=	Upper Limit Distribution Function
V	=	velocity
W	=	mass flow rate
We	=	Weber number = $\rho V^2 \ell/\sigma$
w	=	width of liquid channel
x	=	photomultiplier traverse distance corresponding to one tenth of the maximum value of $I(\theta)$
Z	=	Ohnesorge number = $We^{\frac{1}{2}}/Re = \eta/(\rho\sigma\ell)^{\frac{1}{2}}$

GREEK LETTERS

α	=	ratio
β	=	angle (solid) of divergence of a monochromatic collaminated light beam; or, rate of growth of interfacial waves
η	=	absolute viscosity
θ	=	angular displacement
λ	=	wavelength, Angstroms
μ	=	micron, ($1\mu = 10^{-6}$ meter)
ν	=	kinematic viscosity
π	=	natural constant
ρ	=	density
σ	=	surface tension
τ	=	shear stress
ϕ	=	Spray fineness factor, a function of the geometry of the interacting fluid streams provided by the airblast atomizer design
Ω	=	circulation constant

SUBSCRIPTS

a	=	air
av	=	average
c	=	contraction; or, core
cr	=	critical
d	=	droplet
D	=	discharge
e	=	effective; or, exit
g	=	gas
h	=	head
l	=	liquid
ℓv	=	low-viscosity liquid
m	=	mean
o	=	orifice; or, jet
s	=	slots; or, swirler
r, rel	=	relative
vi	=	viscous; high-viscosity liquid
x	=	state (x)
y	=	state (y)
1	=	state (1)
2	=	state (2)
∞	=	limiting value

SUPERSCRIPTS

*	=	critical; or, maximum
′	=	modified; in new frame of reference
a,b,..,m,n	=	constant quantities; power indices.

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CHAPTER 1

INTRODUCTION

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1.1. SUMMARY

The combustion of low volatility liquid fuels occurs in most combustion systems through the process of atomization, as in industrial furnaces and boilers, liquid propellent rocket motors and in the land, marine, and aircraft installations of the gas turbine engine. In general, finely atomized sprays and uniformly distributed fuels are pre-requisites to the attainment of satisfactory performance in the main aspect of combustion and to satisfy legislation limiting the emission of exhaust pollutants. Atomizers of diverse capacities are required for the various applications.

The present investigation deals with the effect of the linear scale, or size, of thin-sheet airblast fuel injectors on the mean drop size of sprays produced. The concern here is with prefilming atomizers employing two atomizing airstreams, representative of the design of injector that is well-suited for application to the various combustion units outlined herein. This investigation has been carried out as part of a continuing study of the airblast atomization of liquids, following previous work of Rizkalla (Ref. 79), Lorenzetto (Ref. 54) and Rizk (Ref. 77), to establish a general design basis for airblast fuel injectors.

1.2. Some Background Considerations for the Investigation:

Pressure atomizers have been the most commonly used fuel injector. They are being replaced by airblast systems in which fuel, usually in the form of either a very thin sheet of about 10 to 100 microns in thickness, or a thin circular jet, flowing under relatively low pressure is shattered into fine drops by the action of high velocity air.

It is now recognized that:-

a) Airblast atomizers are particularly well-suited for application to gas turbine engines, especially those operating with high compression ratio. This is mainly because of the good measure of fuel and air premixing that is achieved prior to combustion and, as a natural consequences of the airblast atomization process. The fuel distribution throughout the combustion zone is dictated mainly by the airflow pattern and is not therefore, very sensitive to changes in fuel flow. Thus the airblast atomizer offers distinct advantages in terms of very high volumetric heat release rates, a minimum of exhaust smoke, a low luminosity flame resulting in cooler flame-tube walls, and an outlet temperature traverse that remains sensibly uniform under all operating conditions, with benfit to the life of turbine blades and nozzle guide vanes.

b) An advantage of the airblast system is that because the amount of energy available for atomization is independent of fuel pressure, quantity, or viscosity, the injector has a potential multi-fuel capability with no strict limitation on turn down ratio. With pressure atomizers such limitations are responsible for the poor performance achieved with small-capacity injectors handling heavy fuels. In consequence, small-capacity airblast atomizers offer an attractive solution to the problems encountered in small-volume combustion units in the light of the present trend towards the use of economical low grade fuels, which are also not suitable for use with vaporizing systems.

c) In rocket motors which admit both fuel and oxidizer to the combustion chamber in the liquid phase, the twin-fluid atomizer, as the airblast is sometimes referred to, provides the most effective means of control over the rate of mixing of the propellants throughout the combustion volume and, hence, over the heat release pattern.

Atomization quality depends mainly on the liquid and airflow properties, but is entirely controlled by the process of transfer of kinetic energy from the compressible flow to the liquid stream. Numerous flow configurations are possible for achieving the maximum physical contact between the air and the liquid, that is desirable for the production of fine sprays, and for obtaining optimum droplet dispersion patterns. Atomization is most effective when the fuel is spread into a thin continuous film of uniform thickness prior to its disintegration, and then subjected to high velocity air on both sides, as in the airblast systems employed in this investigation, which are described in detail in Chapter 4.

Thin-sheet airblast atomizers are known for producing fine sprays that other types of spraying devices cannot produce except under extreme operating conditions. Even under the most arduous conditions of relatively low atomizing velocity, such as those encountered in modern low pressure loss gas turbine combustion chambers, prefilming atomizers are capable of producing well-atomized sprays that are at least comparable in size with those produced by pressure swirl atomizers, as demonstrated by Lefebvre and Miller (Ref. 48).

The manner in which sprays are formed from thin liquid sheets by the disruptive action of high velocity gas is varied and not yet exactly known. However, sufficient theoretical work on several idealised cases, and recent experimental investigations on flat sheets, have established a distinct relationship between the mean drop diameter of the spray and the sheet thickness, as discussed in some detail in Chapter 2. The results of all investigations indicate that the mean diameter is roughly proportional to the square root of the sheet thickness.

Uniform film thickness is essential if good atomization quality is to be achieved, as explained by Gretzinger and Marshall (Ref. 29). Prefilming techniques are many. Swirl chambers from which the liquid is discharged radially over a flat surface, spinning cups, and the so-called vortex cups, are some examples. An effective way which involves no moving parts is to impart a swirling motion to the fuel by discharging it over the inside surface of a stationary cup through a number of tangentially machined slots located at its upstream end.

Needless to say, knowledge of the spray drop-size distribution is useful, since many properties of a burning spray depend on the existence of drops of varying size. However, once a spray having a given drop-size distribution is formed, a number of factors will almost immediately serve to change the distribution due to the complex airflow pattern in the combustion zone. In dealing with actual problems of spray combustion, it is usually agreed that, for many practical purposes it is sufficient to consider only the mean drop diameter, which is the main concern of the present work.

It is also relevant to note here that certain secondary and transient effects, other than the main factors affecting atomization, such as air-friction, droplet coalescence, secondary atomization, evaporization and re-circulation, influence the mean drop diameter of the sprays at large distances from an airblast atomizer, as reported by Fraser (Ref. 24) for example. However, in spite of the voluminous amount of spray-data compiled by various investigators, there is a dearth of information regarding variation of the mean diameter in the vicinity of the spraying device where combustion usually occurs and where drop-size data are most needed. This is due to the extreme difficulties encountered in obtaining representative drop-size samples close to the atomizer by the normal drop sizing techniques.

1.3. Scope of the Present Investigation:

Small-capacity as well as large-capacity airblast atomizers of the stationary, prefilming-cup type, in which high velocity air impinges on both sides of a thin cylindrical shell of fuel, are now finding increasing demand for application to a number of combustion systems which use kerosine or viscous low grade fuels.

Considerable research work, both theoretically and experimentally, has been directed towards the study of airblast atomization process and the effect of the many variables involved. However, from the designers' standpoint, the stationary cup atomizer has not received the detailed experimental study needed to establish the influence of atomizer linear scale on the mean drop diameter. From a study of the published literature, the most pertinent of which is reviewed in Chapter 3, it is clear that the results of work done on the effect of scale of thin-sheet atomizers are not only completely at variance, but also appear to be in contradiction with the results of investigations dealing with the effect of film thickness on atomization quality.

These shortcomings provided the incentive for the present investigation into the effect of atomizer scale on the mean drop size of sprays, and to improve prediction of the mean drop diameter produced under varied working conditions. Four atomizers are used, of which three are geometrically similar, but scaled up to give cross-sectional areas in the ratio of 1 : 4 : 16. They are capable of handling liquids of various viscosity at flow rates as high as 225 UK gallon per hour and as low as 3 UK gallon per hour. Examination of the variation of mean drop diameter with distance across the spray axis in the proximity of the atomizer was also carried out.

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CHAPTER 2

Background Considerations on the Disintegration of Liquid Jets, Sheets and Shattering of Droplets

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2.0. Essentially, any atomization process can be considered as the disruption of the consolidating influence of surface tension by some external or internal or inertial forces. When opposed, the action of the surface tension can result in instabilities in the liquid that may permit the bulk liquid to break up into drops. On the other hand, shear stresses set up within the liquid by the action of liquid viscosity tend to resist changes in the system geometry and therefore attenuate the disruption process.

The phenomenon of liquid atomization is complex and varied and depends upon numerous factors whose influence have not yet been fully quantified. However, an insight into the different roles and degrees of influence of the significant factors involved is a prerequisite to any research into this field. The available literature is extensive but only the most useful and relevant references have been selected.

2.1. The Disintegration of Liquid Jets and Sheets

Lord Rayleigh (Ref. 76), in a mathematical analysis, established the conditions to cause the collapse of a continuous invicid liquid jet issuing at low velocity from a circular orifice. He showed that disturbances of the jet can grow in amplitude due to the effect of surface tension and ultimately cause the collapse of the liquid column. The growth rate reaches its greatest magnitude when the wavelength equals 4.51 times the diameter of the undisturbed jet (d_o) and consequently the average drop size may be calculated to be equal to $1.89d_o$. Tyler (Ref. 90), experimenting with jets of mercury confirmed the theoretical values predicted by Rayleigh.

Although this simple case does not represent the practical atomization processes where the actual liquid jet is both viscous and turbulent as well as subjected to the influence of the ambient gas, nevertheless, Rayleigh is credited for developing the earliest theory on the mechanism of jet disintegration which provided the background for consideration of more complicated conditions.

Weber (Ref. 91), extended Rayleigh's analysis to include the effect of liquid viscosity and air friction on the instability of simple liquid jets. He calculated the jet break-up length, and showed that it increased with increase in liquid viscosity, but decreased when there is an additional effect of air friction.

Haenlein (Ref. 30), experimentally studied the break up of liquid jets while varying viscosity and surface tension using high speed photography. His experimental values are in excellent agreement with Weber's theoretical predictions. Haenlin reported four distinct regimes of jet break-up, namely:

1. drop formation due to jet oscillation without the influence of air;

2. drop formation due to jet oscillation with the influence of air;

3. wave formation and break-up assisted by air friction; and,

4. complete disintegration of the jet immediately at the orifice edge.

Ohnesorge (Ref. 68), studied the effects of the main physical properties of the liquid viz. density, viscosity and surface tension, the jet size in terms of the orifice diameter, and the relative jet velocity on the mechanism of atomization. He distinguished three different stages of jet disintegration, which were later confirmed by the Japanese workers Nukiyama and Tanasawa (Ref. 67), and concluded that jet stability was a function of the flow Reynolds number. The tendency of the jet to disintegrate was expressed by the dimensionless Z - number. He condensed his findings in a chart referred to as the 'Ohnesorge-chart'.

Castleman (Ref. 10), proposed the 'ligament theory'. He analysed high velocity disturbances of the liquid jets and included in his investigation some high speed photographic observations made by other investigators, such as Sauter and Scheubel. Castleman envisaged a process of jet disintegration which he described as 'a portion of the large mass is caught at a point where the surface is ruffled by the airstream, and being anchored at the other end is drawn out into a fine ligament. This ligament is quickly cut off by the rapid growth of a dent on its surface, and the detached mass being quite small is swiftly drawn up into a spherical drop'.

Castleman's theory, therefore, considers that the most important factor in the process of atomization is the effect of the relative motion between the outer jet layer and the air which, combined with air friction, causes the irregularities in the previously smooth liquid surface and the production of the unstable ligaments. As the air speed increases, the size of the ligaments decreases, their life period becomes shorter, and upon their collapse much smaller drops occur in accordance with Rayleigh's theory.

Castleman claims that the droplet sizes approach a limiting value of the order of several microns (5 to 6 microns for water) below which the drop diameter may not go, however great is the relative velocity between the liquid and the air. For droplets of the size of 5 microns, the calculated life-time would be 1.5×10^{-5} seconds and the breaking up of the ligament into droplets would occur in a distance of 10^{-8}cm. which could make these ligaments not visible even with high-speed photography. His theory does not distinguish between 'air' atomization and 'solid' (or airless) injection, and reports that both cases have similar physical background.

Littaye (Ref. 53), disagrees sharply with Castleman about a limiting value for the droplet size, and distinguishes between the air atomization and solid injection. On the other hand, Lee and Spencer (Ref. 45), produced excellent photographs of the process of spray formation in support of the ligament theory. They confirmed ligament formation as an intermediate step in the detachment of a small drop from a large mass of liquid, and that the ligament appears to decrease in size and length as the relative velocity is increased.

In a later study, Briffa and Dombrowski (Ref. 7), examined sprays produced from flat liquid sheets by the action of a relatively low velocity airstream. The air flow parallel to the sheet at velocities ranging from 0.23 to 1.55m/sec. Photographs taken for the spray, in the vicinity of the nozzle, show the sheet disintegrating due to aerodynamic action through rapidly growing waves produced on the sheet, which subsequently break down at the crests. Fragments of the sheet then quickly contract into ligaments and break down into drops.

Mayer (Ref. 61), drawing upon the theoretical results of Jeffreys (Ref. 38), analyzed the growth of capillarity waves produced by high velocity gas flowing across a liquid surface. According to Ref. (61), with given fluid properties and air velocity, all wavelengths exceeding a certain minimum value will grow at an exponential rate characterized by a time modulus dependent on the wavelength and fluid properties. Mayer envisaged that at a certain value of the wind-induced wavelength, the crest of the wave is shed as a ligament from which droplets are formed whose diameter is proportional to the wavelength, and proposed the following expression for the mean drop diameter obtained under primary atomization:

$$d_m \propto \frac{\eta_\ell^{2/3} \, (\sigma_\ell \, \rho_\ell)^{1/3}}{\rho_g^{2/3} \cdot V_g^{2/3}}$$

York, Stubbs and Tek (Ref. 98), in an effort towards better understanding of the influence of some of the factors involved in the mechanism of disintegration of liquid sheets, investigated the disintegration of a plain continuous sheet, of finite thickness, moving relative to a surrounding fluid such as air. Their study involved a mathematical analysis of the interfacial instabilities of a sheet of invicid liquid; supported by photographic examination of the disintegration of liquid films produced from swirl nozzles. The break up mechanism proposed was that of disturbances at the interface which immediately set up an unbalanced opposition of forces. This was explained as follows: considering the vicinity of protuberance on the interface, two sets of forces become effective, namely:

1. the uniform tension on the perturbed interface acts to squeeze the liquid back to the original boundary to reinstate the original equilibrium;

2. the air or gas flowing at a constant relative velocity along the interface, experience a local decrease in pressure corresponding to an increase in the local velocity. This local depression tends to oppose the restoring action of the surface tension of pulling the liquid locally further away from the equilibrium plane and therefore increasing the amplitude of the disturbance. The velocity difference between the gas flow and the liquid sheet speeds up the growth of these perturbations and eventually the liquid film disintegrates and is swept away in the gas stream.

The results of this investigation elaborate on the influence of the Weber number and the air to liquid density ratio on the disintegration of the liquid sheet. These were expressed in graphical forms in terms of the nondimensional parameters:

Rate of growth number = $\frac{\beta a}{\lambda}$;

Wavelength to sheet thickness ratio = $\frac{\lambda}{a}$;

The Weber numbers: $We_\ell = \frac{a\rho_\ell V^2}{\sigma}$; $We = \frac{\lambda \rho_a V^2}{\sigma}$;

and, $We = \frac{a\rho_a V^2}{\sigma}$

where: β = rate of growth; $2a$ = thickness of liquid sheet; λ = wavelength of disturbance; ρ_a and ρ_ℓ = air and liquid densities respectively; σ = interfacial tension; and, V = relative velocity.

From their graphical plots it was concluded that:

1. At a given Weber number and for a fixed density ratio, the growth rate has a decided maximum value, particularly at higher Weber numbers, such that decreasing the interfacial tension, decreases the Weber number and increases the growth rate correspondingly.

2. The wavelength (λ^*) corresponding to maximum growth rate is inversely proportional to both the density ratio (ρ_a/ρ_ℓ) and the Weber number.

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2. At a constant value of the density ratio, variation in the film thickness alone causes only slight variations in the wavelength corresponding to maximum growth rate. For air and water (ρ_a/ρ_l = 0.001), a hundredfold variation in the sheet thickness changes the wavelength (λ^*) by only 10%; and for a density ratio of 1.0. such as one liquid flowing over another, a hundredfold variation in the sheet thickness changes (λ^*) by only twofold.

Of special interest to the present study was the development of an equation for predicting roughly the size of sprays from swirl nozzles. In this case, the liquid sheet is of conical shape, and photographic examination showed the disturbances to grow and the sheet break up into rings.

According to York et al., the liquid contained in the rings can be estimated as a ribbon cut out of the sheet, with a thickness equal to that of the sheet at the break up distance, and of a width equal to one wavelength. From Rayleigh's analysis, the wavelength of cylindrical instability, which is the length of a cylindrical section separating into drops of radius (r), is about nine times the radius of the cylinder. As these rings eventually break up into drops, the drop size may be approximately calculated from the typical successive disintegrations, recognising that a range of drop sizes is actually produced, and the proposed equation is:

$$r \simeq 1.06 \quad 2a\lambda^* \quad = 1.06\left(\frac{2a\ We_l^*\sigma}{\rho_a V^2}\right)^{\frac{1}{2}} \quad \ldots \quad (2.1)$$

They concluded that in spite of the many assumptions involved in their analysis, the results are reasonable and verifiable at least qualitatively.

If the previous analysis is acceptable, it can also be applied to the case of a plain sheet which would disintegrate into rod-like portions having similar dimensions to the rings. As it has been shown that the value of (λ^*) does not vary significantly with variations in the sheet thickness (2a), it follows that the drop size should be roughly proportional to the square root of the liquid film thickness.

Dombrowski and Johns (Ref. 19), also considered that instability of thin liquid sheets resulting from interaction with the surrounding gaseous medium gives rise to rapidly growing surface waves. According to Dombrowski and Johns, disintegration occurs when the wave amplitude reaches a critical value and fragments of the sheet are torn off, which rapidly contract into unstable ligaments under the action of surface tension, and drops are produced as the ligaments break down according to theories of varicose instability. With liquid sheets disintegrating in multiples of half or full wavelengths of the so-called sinuous, and, or, dilation aerodynamic wave instabilities, the results of the analysis in Ref. (19) also leads to the conclusion that the mean drop diameter is, most likely, proportional to the square root of the sheet thickness.

Dombrowski and Fraser (Ref. 18), provided more insight into the manner of liquid sheet disintegration and the basic mechanism of ligament and drop formation, by using an improved photographic technique and a specially designed source of lighting combining high intensity with very short duration. They established that ligaments are principally caused by perforations in the liquid sheet. It was also found that the history of the perforations determine the stage of growth at which these ligaments disintegrate. If the holes are caused by air friction, the ligaments break up very rapidly and thus may be very difficult to observe, as previously remarked by Castleman. If, however, the holes are caused by other means, such as turbulence in the nozzle or suspensions of unwettable particles, the ligaments are broken more slowly by the surface tension. According to Dombrowski and Fraser, the life history of the perforations as regards their position of occurrence in the sheet also has an important effect on the drop size, and it appears that if the holes could be made to occur at the same position from the nozzle, then the drops would be of more uniform size.

Using a large variety of liquids to establish the influence of the liquid density, viscosity and surface tension, they reported that:

(a) the effect of the liquid density on the sheet disintegration is insignificant;

(b) the combined effect of high density and surface tension, as in the case of mercury sheets, gives films that are highly resistance to disturbance by air friction; and,

(c) liquid sheets with high surface tension and viscosity are most resistant to disruption.

Fraser, Dombrowski and Routley (Ref. 23), later investigated the mechanism of disintegration of liquid sheets subjected to impingement by high-velocity airstream at 90°, and related the size of the drops so produced to the thickness of the sheet and other operating variables. They used a special type of airblast system in which flat circular liquid sheets were produced from a spinning cup, while the atomizing airstream was admitted from an annular gap fitted axially symmetrical to the cup.

Photographic examination showed circumferential waves initiating at the position of impact of the airstream in the sheet, and the liquid sheet was observed to break down into drops through formation of unstable ligaments. It was also observed that the sheet does not break up upon immediate impact with the air, but is deflected away from it. Fraser and colleagues concluded that the instability leading to disruption seems to result from the cocurrent flow. This appears in conformity with the findings of Hrubecky (Ref. 36), who reported that finest sprays are produced when the liquid and air streams flow in parallel.

Fraser and his colleagues correlated their experimental data with an expression for the drop size based on a theory of sheet instability due to Dombrowski and Johns, and proposed the following semi-emperical equations for predicting the Sauter mean diameter of sprays, in terms of the sheet thickness,

$$SMD = 6 \times 10^{-4} + \frac{1.4\sigma^{\frac{1}{2}}\nu_r^{0.21}}{\rho_g^{\frac{1}{2}}V^2}\left[1 + \frac{0.065}{M_r}\right]\left[\frac{S}{V_t^2(0.5V_r^2 - V_r + 1)}\right]^{\frac{1}{2}} \quad \ldots\ldots (2.2a)$$

and in terms of the liquid volumetric flow rate,

$$SMD = 6 \times 10^{-4} + \frac{0.59\,\sigma^{\frac{1}{2}}\nu_r^{0.21}}{\rho_g^{\frac{1}{2}}(ad+a^2)^{\frac{1}{4}}}\left[1 + \frac{0.065}{M_r}\right]\left[\frac{Q}{V_t^3(0.5V_2 - V_r^2 + 1)}\right]^{\frac{1}{2}} \quad \ldots (2.2b)$$

In both equations the symbols are in c.g.s. units, where:

S = liquid sheet thickness at position of disruption;

ν_r = liquid kinematic viscosity relative to water;

M_r = air to liquid mass flow ratio;

V_t = cup peripheral velocity;

V_r = gas to liquid velocity ratio = V_g/V_t;

ρ_g and V_g = gas stream density and velocity respectively;

d = diameter of cup at lip; and,

a = width (radial) of air annulus at cup lip.

Although the design features of the airblast system used by Fraser et. al. differ from the fixed prefilming cup type used in the present study, the fact that the spinning cup was used only to produce circular liquid films of controlled thickness, while the atomizing action was caused solely by the concentric airstream, provides some degree of physical similarity between the interaction of the liquid sheets and airstream in both types.

The previous relationship suggest that the SMD of sprays produced from liquid sheets subjected to the atomizing action of high velocity gas is in proportion to the square root of the sheet thickness at position of disruption. It was also concluded that the air to liquid mass flow ratio has little effect in reducing the SMD for values larger than 1.50. The equations set a limiting value of 6 microns for the SMD below which it would not decrease in agreement with Castleman.

The authors made some useful comparisons between their correlation and that for sprays obtained from an airblast atomizer of the internal-mixing, fixed prefilmer type (due to Fraser, (Ref. 22)), as well as with the Nukiyama and Tanasawa equation for the atomization of solid cylindrical liquid jets. They reported that the prefilming type atomizers are superior to solid jet atomizers in producing finer sprays, and that the controlled production of thin liquid sheets is an essential prerequisite to finer atomization. It was also concluded that the optimum position of the airstream exit plane, in relation with the liquid sheet, for the production of the smallest droplet sizes, is that where the velocity of impaction would be maximum.

A very recent contribution providing more insight and better understanding of airblast atomization phenomena was made by Rizk and Lefebvre (Ref. 77, 78). Their main objective was to study the influence of the liquid film thickness and ambient air density on the airblast process of spray formation. The research was carried out using two airblast atomizers specially designed to produce flat liquid sheets, which were then atomized by high velocity airstreams acting on both wides of the sheet. In one atomizer, the sheet thickness was varied and controlled by varying a two dimensional rectangular slit from which the flat liquid sheet issued.

The mechanism of sheet disruption and drop formation was examined by very high speed flash photography of 0.2 microsecond duration, which also provided their drop size distribution data. They found that the drop size closely obeyed the Rosin-Rammler and the upper limit distribution functions. The values of the SMD of the sprays entering their empirical correlation were, however, established by the method of light scattering. A large variety of liquids and solutions, covering a very wide range of density, surface tension and viscosity were used to examine their individual influence.

They confirmed the process of ligament formation and established that thicker liquid sheets result in thicker ligaments which, in turn, disintegrate into larger drops. This finding highlights the importance of spreading the liquid into very thin sheets for better atomization quality. They also found that the thickness of the sheet depends on both the air and the liquid properties. High values of liquid viscosity and/or liquid flow rate result in thicker films, while variations in the surface tension appeared to have no effect on the thickness of the sheet. They observed, however, that sheets of low surface tension liquids disintegrated more readily by the action of the airflow and the resulting ligaments were shorter. On the other hand, sheets of high viscosity liquids produced long thick threads.

Additional work was carried out to assess the effect of the ambient air pressure on the quality of sprays obtained from low as well as high viscosity liquids. They concluded that increase in the ambient pressure had a beneficial effect on the atomization quality, especially for liquids of low viscosity.

From correlation of their experimental data, taking into consideration all the results of their investigation, they proposed the following dimensionally correct equation for predicting the value of the Sauter mean diameter in terms of the liquid film thickness and the air and liquid properties:

$$SMD = 0.5 \left(\frac{\sigma_\ell^{0.6}\ \rho_\ell^{0.25}}{\rho_a^{0.85}\ V_r^{1.2}} \right) (t)^{0.4} \left(1 + \frac{W_\ell}{W_a} \right)^{0.85}$$

$$+ 0.107 \left(\frac{\eta_\ell^2}{\sigma_\ell \cdot \rho_\ell} \right)^{0.45} (t)^{0.55} \left(1 + \frac{W_\ell}{W_a} \right) \quad .... \quad (2.3)$$

where, t is the thickness of the liquid film

Miesse (Ref. 62), proposed that the atomization phenomena of liquid streams can be sufficiently described by two independent dimensionless groups, namely the Reynolds number and the Weber number, as they include all the significant parameters affecting the atomization process. He added that use of the Ohnesorge number, Z, could facilitate correlation of the experimental data.

That is:

$$Re = \frac{\rho V h}{\eta},$$

$$We = \frac{\rho V^2 h}{\sigma},$$

$$Z = \frac{We^{\frac{1}{2}}}{Re} = \frac{\eta}{\sqrt{\rho h \sigma}},$$

where h, is the thickness of the liquid stream. Miesse also outlined that shattering of a liquid droplet by a high velocity airstream occurs when the kinetic energy of the airstream exceeds the surface energy of the droplet, and the criterion of this secondary atomization could therefore be expressed in terms of a critical Weber number which, according to Ohnesorge, is related to the Reynolds number by the equation:

$$We\ critical = \frac{42500}{Re^{0.4}} \quad ...... \quad (2.8)$$

According to (Ref. 62), the mean drop diameter, D, of a spray formed from the disintegration of a flat sheet of liquid jet is likewise characterised by the Weber number, given by the relation:

$$\frac{D}{h} = \frac{f(Re)}{We^{2/3}} \qquad \ldots\ldots\ldots (2.9)$$

where f(Re) for flat sprays was found essentially constant, while for liquid jets it was found to be a linear function of the Reynolds number.

2.2. Shattering of Liquid Droplets

When a liquid drop travels through a gaseous medium, pressure and shear distributions are set up on its surface by the aerodynamic drag. As a result the drop deforms into a new stable shape. However, a critical situation arise if no shape is sufficient for the surface tension to compensate the pressure variations, and, in consequence, the drop bursts into smaller drops.

Very little information has been published on the process of high-speed breakup of drops occuring in liquid sprays, a process frequently referred to as the stage of secondary atomization. However, the critical conditions leading to the shattering of a single liquid drop have been examined by several investigators.

Lane (Ref. 42), made a remarkable series of flash photographs showing the various sequential stages involved in the process of disruption of a single water droplet subjected to an air flow. This work gives a clearer insight into the action of aerodynamic forces in effecting the atomization of liquid droplets.

For the case of a steady airflow, the photographs show clearly that a drop is first flattened under the influence of the airstream, to form a circular membrane anchored to an outer thicker ring that contains about 70% of the mass of the original drop. The membrane is progressively blown out into a 'hollow bag' which eventually bursts into a shower of small drops. The bursting proceeds as a wave back towards the ring, which when struck, throws off small droplets and then itself breaks into larger drops.

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This demonstrates that in airblast atomization the fine droplets result from the breakup of thin stretched membranes and that a comparatively small fraction of the original liquid mass contributes to the finest droplets in a spray.

Lane found that for a given size of droplet, the onset of disruption, i.e. splitting of the membrane, did not occur unless the relative air velocity was greater than a critical value. For a drop of relatively large diameter of 2.6mm, the minimum air velocity for splitting was about 23m/secs.

Hinze (Ref. 35), distinguished three basic types of globule deformation and six types of airflow pattern around the globule that may cause it to deform and ultimately disintegrate into small drops. Preference for a given type of deformation and breakup depends not only on the flow pattern, but also on the physical properties of the two fluids, namely their density, viscosity, interfacial tension and drop size.

The basic types of break up are:-

(a) the globule becomes flattened, forming an oblate ellipsoid, which may deform into a torus, and after stretching breaks up into many smaller drops;

(b) the globule becomes more elongated, forming a prolate ellipsoid, which may further elongate into a cylindrical thread (cigar-shaped deformation) and then bursts into droplets; and,

(c) the surface of the globule may deform locally, forming bulges and protuberances (bulgy deformation), and ultimately parts of the globule become bodily separated. This type is brought about by the dynamic pressures occurring in an irregular air flow.

According to Hinze, the factors controlling deformation and breakup comprise two dimensionless groups: a Weber group, N_{We}, and a viscosity group, N_{Vi}.

Hinze considered a generalised form of the Weber group as:

$$N_{We} = \frac{\tau}{D\sigma_{\ell}}$$

where: D, is the drop diameter; and, τ, is a stress (e.g. viscous stress or dynamic pressure) acting on the surface of the globule, set up by the surrounding continuous phase. Breakup then occurs when the Weber number exceeds a critical value at which the surface tension cannot counteract the deformation caused by the external forces. The value of the critical Weber number differs according to the type of deformation and airflow pattern. For the case of a globule of low viscosity liquid subjected to a paralled airflow, Hinze reported that the critical Weber number is approximately equal to 13. In this case, the Weber number was given its original notation, i.e.

$$N_{We} = \rho_a V_r^2 D/\sigma_\ell$$

Hinze also proposed that the critical Weber number for a high viscosity liquid can be obtained from its corresponding value for low viscosity liquids by multiplying the latter by a factor function of the viscosity group:

that is, $$(N)_{We} = C(1 + N_{vi}), \quad \ldots\ldots (2.4)$$

where, $$N_{vi} = \frac{\eta^2_\ell}{\rho_\ell \sigma_\ell D}$$

When N_{vi} approaches zero, the function C assumes the value of the critical Weber number for non-viscous liquids and decreases to zero.

Wallis (Ref. 92), states that the experimental data of Hinze can be expressed quite closely by the equation:

$$N_{We} = 12 \left[1 + \left(\frac{\eta_\ell^2}{\rho_\ell \sigma_\ell D} \right) \right]^{0.36} \quad \ldots\ldots (2.5)$$

for values of the viscosity group $(\eta^2/\rho_\ell \sigma_\ell D)$ less than 5.

Ranz (Ref. 73), pointed out that the critical Weber number is approximately equal to: 20, when the velocity is applied slowly; and, 13 when the velocity is applied suddenly, as in a shock front. Ranz also indicated that atomization ceases, because of viscosity, when the group $(\eta^2/D\rho\sigma)$ is greater than 4.

Quantitative expressions for the mass rate of aerodynamic atomization from flat liquid surfaces and from droplets subjected to high relative gas velocities are also presented by Dickerson and Schuman (Ref. 15). Aerodynamic atomization is intimately related to the propagation of capillary waves over the liquid surface. These waves originate from small disturbances on the surface, are caused to grow in amplitude by the aerodynamic forces, and eventually crest and disintegrate into myriad of microdroplets. Dickerson and Schuman developed a theoretical expression for the rate of mass loss from flat surfaces based on the existence of capillary waves, and explained that when liquid droplets are subjected to high velocity gas, a sound theoretical analysis would be excessively and interactably complicated because of the geometric problems involved with the dynamics of capillary waves on the curved surfaces. They conducted a series of experiments and proposed the following empirical expression relating the droplet mass loss rate in terms of a mass number, Mn; to a modified Reynolds number and the Weber number referred to the drop diameter:

$$Mn = 3.53 \times 10^{-5} \times (R\acute{e})^{2.8} \times (We)^{-0.42} \quad ..(2.7)$$

where:

$$Mn = m./DA_d \rho_d;$$

$$R\acute{e} = D.V_r.\rho_g^{\frac{1}{2}}.\rho_d^{\frac{1}{2}}/\eta_d;$$

$$We = \rho_g.V_r^2.D/\sigma_d;$$

Mn = mass loss rate (g/sec); D = droplet diameter (cm); A_d = droplet surface area (cm^2); ρ_d and ρ_g = density of droplet liquid and gas stream respectively (g/c.c.); η_d and σ_d = droplet liquid viscosity (c.poise) and surface tension (dyne/cm), respectively; and, V_r is cm/sec.

As only one liquid, i.e. kerosine RP-1, was used in developing the equation (2.7) its application should be restricted to liquids of similar physical properties. Dickerson and Schuman used an interesting technique, in which the gas flow behind a shock wave, in a shock tube, was the means of subjecting a single droplet to the atomizing action of high-velocity gas. As the droplet was accelerated and atomized it was simultaneously photographed by a high-speed camera (14,500 frames/sec) as well as a high speed streak camera, from which the mass rate of aerodynamic atomization was measured.

Wolfe (Ref. 98), derived the following relationship based on a large number of assumptions, for predicting the average diameter of drops, $D_{av.}$, resulting from aerodynamic breakup of a liquid drop of diameter D, when exposed to a relative velocity V_r:-

$$D_{av.} = \frac{5.14\ D\ \eta_\ell\ \sigma_\ell^{\frac{1}{2}}}{V_r^{4/3} \rho_\ell^{1/6}\ \rho_g^{1/3}}; \quad \ldots\ldots (2.6a)$$

which may be rearranged to the following form:

$$\frac{D_{av.}}{D} = 5.14 \left[\frac{\rho_\ell}{\rho_g}\right]^{1/6} \left[\frac{\sigma_\ell}{D\rho_g V_r^2}\right]^{\frac{1}{2}} \left[\frac{\eta_\ell}{DV_r^2\rho_\ell}\right]^{1/3} \ldots (2.6b)$$

Further experimental investigation, employing high speed motion pictures (26,000 frames/sec), on the mechanism of aerodynamic breakup of droplets, were made by Wolfe over a wide range of variables. The drop sizes employed in the tests varied from 0.5 to 3.0mm. in diameter, the relative gas velocity to which the drops were subjected varied from 17 to 150m/secs, while the ranges covered by the liquid properties were: density from 0.76 to 13.6 gr/c.c., viscosity from 0.89 to 170 centipoise, and surface tension from 22.3 to 487 dynes/cm. The highest values of the surface tension and density were obtained from drops of mercury.

The observed sequences of drop disintegration demonstrated a characteristic type of breakup referred to as 'shear' or 'stripping', in which case the high velocity airflow around the periphery of a flattened drop shears off into thin sheets and ligaments that are carried away and subsequently undergo secondary breakup into a shower of smaller droplets. This 'erosion' process continues until the original drop is reduced to a shower of fine droplets, as long as there is sufficient relative air velocity. The onset of breakup was shown to occur more rapidly with increase in the relative velocity, while the effect of increasing viscosity was to inhibit the drop deformation and retard its splitting. In addition, Wolfe observed that the hollow-bag type of droplet breakup was restricted to small drops subjected to low relative air velocities.

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CHAPTER 3

Review of Literature on the Characteristics of Sprays produced by Airblast Atomizers

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Review of Literature on the Characteristics of Sprays produced by Airblast Atomizers

Numerous factors govern the quality of sprays produced by airblast atomizers. Several empirical relations between the mean drop diameter, or drop-size distribution, and the operating variables have been established through spray analysis at various values of the atomizer design variables and the gas and liquid properties. Many of the correlations apply specifically to one design of the atomizer and fluids employed. Others are claimed applicable to various designs and, or, over a wide range of working conditions.

3.1. Nukiyama and Tanasawa

Perhaps the earliest fundamental studies in airblast atomization, based on a comprehensive collection of experimental data were the result of the notable investigation by Nukiyama and Tanasawa (Ref. 67) who studied what happens to a liquid fuel when injected through a small orifice into the venturi of a piston engine carburettor. The basic design features of the atomizers used are illustrated in Figure (1).

From photomicrographic studies of the sprays, a mechanism for airblast atomization was suggested in which the liquid jet may undergo three stages of liquid disintegration. These were distinguishable on the basis of the shape of the disintegrating liquid jet, and were referred to as:

(a) 'dropwise' atomization;

(b) 'twisted ribbon' atomization; and,

(c) 'filmwise' atomization.

At low air to liquid relative velocity, bead-like swellings and contractions of continuously increasing amplitude are produced in the liquid jet, which then break up into drops. As the relative velocity was increased, another stage of atomization was distinguished, wherein the jet flutters and takes the form of a twisted ribbon, a portion of which is caught up by the airstream and drawn into a fine ligament to be torn off and break up into droplets. At higher relative speed, the twisted ribbon is flattened out into a thin cobweb-like film, and into several smaller and thinner films with further increase in velocity, finally to disintegrate into a spray of fine droplets.

Nukiyama and Tanasawa determined the droplet-size distribution and the Sauter mean diameter from microphotographs of the droplets sampled onto small oil-coated glass slides. They proposed the following empirical distribution function to express the size distribution:

$$\Delta n = 0.5\ n\ b^3\ X^2 \exp(-bX).\Delta x \quad \ldots\ldots \quad (3.1)$$

where n = total number of droplets in the sample;

X = mean diameter of a number of droplets 'Δn' of diameters laying in the size band Δx;

and, b = a size parameter, mainly a function of the liquid density, surface tension and the relative air velocity.

They established that the mean drop of sprays are mainly a function of: the relative air to liquid velocity; the air to liquid volumetric flowrate ratio; and the liquid physical properties, namely, the density, absolute viscosity and surface tension. Mean drop size data obtained from spraying gasoline, water, oils, and solutions of alcohol and glycerine in distilled water, were correlated satisfactorily by the following empirical equation which gives the Sauter mean diameter as a function of the operating variables:

$$\mathrm{SMD} = 585\ \frac{\sqrt{\sigma_\ell}}{V_r\sqrt{\rho_\ell}} + 597\left(\frac{\eta_\ell}{\sqrt{\sigma_\ell\rho_\ell}}\right)^{0.45}\left(1000\ \frac{Qa}{Q_\ell}\right)^{1.5} \quad \ldots. \quad (3.2)$$

The above equation is dimensionally inconsistent; the dimensions of the various variables are as given between brackets: SMD (microns); relative velocity, V_r, (m/sec); liquid surface tension, σ_ℓ (dynes/cm); liquid density ρ_ℓ (gr/c.c.); liquid absolute viscosity, η_ℓ, (poise); air and liquid volumetric flow rates, Q_a and Q_ℓ, (c.c./sec).

Equation (3.2) is probably the best known and most widely quoted relationship in airblast atomization. According to Nukiyama and Tanasawa, it should be valid over the following ranges of variables:

Liquid density,	-	from 0.8 to 1.2 gr/cm^3
Liquid Viscosity,	-	from 0.010 to 0.300 poise
Liquid surface tension,	-	from 30 to 73 dynes/cm
Relative velocity, V_r	-	subsonic

However, an opinion shared by some investigators, e.g. Marshall (Ref. 59) and Rizkalla (Ref. 79), is that the separate effect of each of the liquid physical properties on the quality of airblast sprays was not well established. Rizkalla commented that owing to the difficulties of separating the three dominant liquid properties, no rigorous conclusions were reached in determining the individual effect of each property. Furthermore, Lefebvre (Ref. 80), points out that the effect of the atomizing air properties of density, pressure and temperature were neglected; and therefore equation (3.2) cannot be used for gas turbine combustion chambers applications, since these operate over wide ranges of air temperature and pressure.

Here, it was observed that the R.H. side of equation (3.2) is made up of two terms, indicating that the relative air velocity appears to have an independent influence to that of the liquid absolute viscosity on the values of the mean droplet size. For relatively large values of Qa/Q_ℓ, e.g. $Qa/Q_\ell > 5000$ (which corresponds to a value of ALR of about 6 for most practical low viscosity fuels), the viscosity term in the equation contributes very little to the predicted mean drop size.

When applying dimensional reasoning to the Nukiyama and Tanasawa Equation, the R.H. side terms were found lacking a dimension of length raised to the power of 0.5. This implies that for the equation to become dimensionally correct, it may only be sufficient to introduce an additional parameter having the dimension of length. One such choice could be the diameter of the air nozzle or liquid orifice, as a representative of the atomizer scale. However, from their tests with different sizes and shapes of nozzles and orifices, Nukiyama and Tanasawa concluded that the size and shape of the air and water nozzles have essentially no effect on the mean drop size. This is readily seen from their equation as the atomizer dimension does not enter their expression.

3.2. Wigg

Wigg (Ref. 95), measured the mean drop size of water sprays produced from N.G.T.E. airblast atomizers. Comparing his results and also those obtained by a number of other investigators, with the values of mean drop size predicted by the Nukiyama and Tanasawa equation for similar conditions, he concluded that the Japanese formula predicts too high a drop size and overestimates the effect of the liquid to air mass flow ratio on the mean drop diameter of sprays.

From theoretical considerations of the airflow kinetic energy expended in effecting atomization, and relating it to the energy required to overcome the viscous forces involved in the process of rapid disintegration of the liquid phase, Wigg developed a parameter (X) which takes into consideration the effect of the liquid viscosity (η), liquid mass flow rate (W), air to liquid mass flow ratio (W/A) and the relative air to liquid velocity (V) on the value of the mass median diameter. According to Wigg, the parameter (X), could be used to correlate, and therefore to compare, the mean drop size of sprays produced from different airblast systems. Consequently, Wigg correlated the results obtained from a number of different atomizers spraying wax, and proposed that the MMD for sprays having little or no recombination or coalescence may be predicted by the following equation:

$$MMD = 2300\, X$$

where,

$$X = \frac{\eta^{0.5}\, W^{0.05} \left(1 + \frac{W}{A}\right)^{0.5}}{V} \qquad \ldots\ldots \quad (3.3)$$

and, for sprays with considerable recombination, the MMD was found to be larger and may be given by the expression:

$$MMD = 2300 \; \frac{1 + 2\left(\frac{W}{A}\right)^{0.7}\left(1 + \frac{W}{A}\right)^{0.5}}{V} \qquad \ldots\ldots \quad (3.4)$$

where: MMD is microns; η is centipoises; W and A are gr/sec; and V is m/sec.

In an effort to investigate the effect of the atomizer linear scale on spray characteristics, Wigg tested three airblast atomizers of the type shown in Figure (2.a). The atomizers were of identical design but scaled up to give flow areas in the ratio 1 : 4 : 8. Previously, Radcliffe and Clare (Ref. 74), and Golitzine (Ref. 28), reported considerable scale effect on the droplet size. Wigg recorrelated their results, and, together with those obtained from the three scaled-up NGTE atomizers, concluded that atomizer scale is of little influence and appears to affect the mean drop size only through its influence on the liquid mass flow rate.

Later, (Ref. 96), Wigg applied dimensional analysis to drop size data obtained from several sources, to include the effects of liquid surface tension, liquid density, and a characteristic linear dimension of the atomizer (h) into a more expanded relationship for predicting the mean drop size of sprays. Correlating the droplet size data, he proposed the following dimensionally correct equation for sprays having no recombination:

$$MMD = 190\ N$$

where,

$$N = \frac{\nu_\ell^{0.5}\ W_\ell^{0.1}\ (1 + W_\ell/W_a)^{0.5}\ {}^{0.1}\ \sigma_\ell^{0.2}}{\rho_a^{0.3}\ V} \quad \ldots.\ (3.5)$$

and for sprays having appreciable coalescence of the drops, the expression is:

$$MMD = 200\ N\ \left[1 + 2.5\ (W_\ell/W_a)^{0.6}\ W_\ell^{0.1}\right] \quad \ldots..\ (3.6)$$

which is dimensionally inconsistent.

However, this study suffers from certain drawbacks. First, the range of variation of liquid and air properties was fairly narrow and, therefore, the effect of the air density and liquid physical properties were not well established.

Secondly, there is obvious ambiguity as regards the effect of atomizer scale on the mean drop size. The dimension (h) of the atomizer is the height of the air annulus. As Wigg put it: 'in an extreme case one can imagine the outer layer of air in a very large annulus having no effect at all on the atomization'. It is therefore difficult to accept the chosen dimension as an accurate representative of the atomizer scale which may influence the drop size.

Thirdly, as Wigg himself claimed, a large part of the data was obtained by different people sampling in different ways and that in every set of results there was considerable scatter.

Fourthly, there are reasonable doubts about the procedure adopted by Wigg in sampling and sizing the drops of his sprays, and whether the values of the MMD so obtained were truly representatives of the sprays. As an example, for each set of measurements, the spray was sampled at two different locations at a considerable distance from each other. When sizing, all drops of diameter less than 30 microns were ignored. It is therefore difficult to acknowledge an unbiased nature of sizing in this method, especially since airblast atomizers are characterised by their ability to produce fine sprays.

Nevertheless, there is no doubt that this study did much to elucidate the key factors involved in airblast atomization.

3.3. Marshall and Colleagues

Wetzel and Marshall (Ref. 94), studied the atomization of jets of a molten alloy and a wax. They correlated their data for the spray cooling of the molten wax and suggested the following equation:

$$MMD = 4.2 \times 10^6 \ V_r^{-1.68} \ d_o^{0.35} \qquad \text{.... (3.7)}$$

where: MMD is microns, V_r is ft/sec, and d_o is the diameter of the liquid jet or injection slot in inches.

Their equation shows a rather large effect of the relative air velocity, and an increase in the mean drop size associated with liquid orifices of large diameter. However, they indicated that the effect of the orifice size had not received sufficient investigation in their experiments.

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Gretzinger and Marshall (Ref. 29) investigated the characteristics of airblast atomization on the mean drop size and drop-size distribution using two types of atomizer that provided different spray patterns. One was a 'converging airblast nozzle' which is basically similar to those of Nukiyama and Tanasawa, but the liquid is first brought in contact with the atomizing airstream at the throat of the air nozzle. The other was an 'impingement type air nozzle', in which the liquid is in the form of a cylindrical shell subjected to the action of the air at one side only; both fluid streams are directed radically outward by a conical shaped impinger body. To measure drop sizes they developed a special technique whereby they dried the sprays of an aqueous solution of a black dye and sized samples of the dried dye particles, collected on oil coated slides, by a light microscope. The frequency distribution so obtained, for the dried particles, was then converted to those of the original spray from mass balance considerations, and the spray quality was then expressed in terms of the MMD.

The results were obtained for sonic condition at the air nozzle throat, by using different sizes of liquid orifices and air nozzles, and the following equation was developed to predict the value of the sprays MMD:

$$MMD = 2600 \left(\frac{W_\ell}{W_a} \cdot \frac{\eta_a}{G_a L} \right)^{0.4} \qquad \ldots\ldots (3.8)$$

for the convergent airblast nozzle; and,

$$MMD = 122 \left(\frac{W_\ell}{W_a} \right)^{0.6} \left(\frac{\eta_a}{G_a L} \right)^{0.15} \qquad \ldots\ldots (3.9)$$

for the impingement type airblast nozzle, where:

L = diameter of the contact periphery of the air and liquid streams;

G_a = air mass velocity = $\rho_a V_a$, and

η_a = absolute viscosity of the airflow corresponding to sonic conditions.

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Gretzinger and Marshall suggested that their equations should be restricted to sprays produced under similar operating conditions, i.e. with liquids having physical properties close to their aqueous solution (viscosity = 1 c.p., and surface tension = 50 dynes/cm), liquid flow rates of 0.5 to 5 gall/hour, sonic air velocity, and air densities ranging from 0.002 to 0.005 g/cm^3 at the atomizing edge.

An uncommon feature of the correlating equations, (3.8) and (3.9), is that they contain an air viscosity term; however, its specific influence on the MMD was not examined. The equations show that at a given liquid to air mass flow ratio, the value of the mean drop size decreases for larger liquid nozzle diameters. This was interpreted to mean that the liquid, if spread over a larger exit perimeter, results in a thinner liquid film and consequently produces finer sprays as the energy of the airstream would then be more efficiently employed.

Gretzinger and Marshall, also made some very useful observations. High speed photographs of sprays produced by the impingement nozzle showed that the smallest drops were formed on the side of the liquid film in intimate contact with the airstream, while larger drops were formed on the opposite side. In the case of the convergent nozzle, if the liquid flow was pulsating, the sprays were found to have larger than expected mean drop sizes. This was explained on the basis that a pulsating flow would produce films having non-uniform thickness and larger than expected drops would then be formed from the locally thicker parts of the liquid sheet.

Kim and Marshall (Ref. 40), used an airblast atomizer of a versatile design that provided two different configurations for the atomizing airflow: a 'convergent single airflow nozzle', i.e. twin-fluid atomizer; and a 'concentric double airflow nozzle', i.e. triple-fluid atomizer. In the second type, Fig. (3.a), the liquid is in the form of a thin tube injected in between two parallel airstreams. They sprayed melts of wax mixtures over a range of liquid viscosity (1.3 to 50 centipoise), relative air velocity (250 ft/sec to sonic), air to liquid mass flow ratio (0.06 to 40) liquid density (50 to 60 lb/cu.ft), surface tension (30 to 50 dynes/cm) and air density at the atomizing edge (0.058 to 0.150 lb/cu.ft).

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They found that their drop-size frequency distribution did not comply well with the logarithmic, the square root probability, or the Rosin Rammler functions, but correlated with remarkable accuracy to the modified logistic equation due to Pearl-Reed, and proposed the following expression for drop-size distribution:

$$\phi_v = \frac{1.15}{1 + 6.67 \exp(-2.18\, x^*)} - 0.150 \qquad \text{..... (3.10)}$$

where: ϕ_v = cumulative distribution less than a diameter D (volume basis); and,

$x^* = D/MMD$.

From their data, they developed the following equations to predict the value of the MMD:

$$MMD = 249 \frac{\sigma^{0.41}\, \eta_\ell^{0.32}}{(V_r^2\, \rho_a)^{0.57}\, A^{0.36}\, \rho_\ell^{0.16}} + 1260 \left(\frac{\eta_\ell^2}{\rho_\ell \sigma}\right)^{0.17} \left(\frac{W_a}{W_\ell}\right)^{m} \frac{1}{V_r^{0.54}} \qquad \text{... (3.11)}$$

for the convergent single airblast nozzle; and,

$$MMD = 8140 \frac{\sigma^{0.41}\, \eta_\ell^{0.32}}{(V_r^2\, \rho_a)^{0.72}\, \rho_\ell^{0.16}} + 1240 \left(\frac{\eta_\ell^2}{\rho_\ell \sigma}\right)^{0.17} \left(\frac{W_a}{W_\ell}\right)^{m} \frac{1}{(V_r)^{0.54}} \qquad \text{...... (3.12)}$$

for the double concentric airblast atomizer, where:

A = flow area of the atomizing airstream (sq.inch);

m = -1 at $W_a/W_\ell < 3$, and $m = -0.5$ at $W_a/W > 3$;

$(V^2_{rel.}\ \rho_a)_{av} = f(V^2_{rel.}\ \rho_a)\ pri + (1-f)\ (V^2_{rel.}\rho_a)\ sec$;

$(V_r)_{av} = f\ V_{rel.pri} + (1-f)\ V_{rel.}\ sec$;

f = weight fraction of total airflow in the primary air nozzle;

η_ℓ is centipoise; σ is dynes/cm; ρ is lb/cu.ft; V_r is ft/s; and, MMD is microns.

It was concluded that the most important operating variables in airblast atomization were the dynamic force ($\rho_a\ V_r^2$) of the atomizing airflow, and the mass flow ratio. A recommended operating range of the ALR was suggested to be from 0.1 to 10. Below the lower limit atomization deteriorates, and above the upper limit atomization is done with excess energy expenditure. Equation (3.11) indicates that the mean drop size is affected by the atomizer size (A) in an inverse manner, implying that the MMD is inversely proportional to the nozzle effective diameter raised to the power of 0.72. Consequently, larger atomizers would be expected to produce finer sprays than a geometrically similar but smaller sized one, other factors being equal; which does not seem reasonable and does not agree with the findings of most investigators. Albeit, Kim (Ref. 40), in varying the nozzle size (A) had varied other geometric factors at the same time which altered the geometry of the atomizer at the atomizing plane. Thus, there is reasonable doubt as to whether dimension (A) could be treated as the atomizer scale parameter.

3.4. Lefebvre and Co-workers

Lefebvre and Miller (Ref. 48), used four airblast atomizers of different designs to assess the atomizing capability of airblast systems and the effect of various design features on the quality of water and kerosine sprays. They emphasized the need to have maximum physical contact between the liquid and the atomizing airstream, and estiablished that minimum droplet sizes were achieved when the liquid was spread into a continuous thin sheet and subjected to the disrupting

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action of the air on both sides. The following mechanism of drop formation was envisaged:

1. spreading of the liquid across a pre-filming surface to focus a thin continuous sheet at the atomizing edge;

2. disruption of the liquid sheet by the aerodynamic forces to form ligaments;

3. break-up of the ligaments into drops, and acceleration of the drops;

4. agglomeration of drops by collision, occurring simultaneously with evaporation of drops in the airstream.

The influence of the film thickness on the droplet size was explained by its influence on the ligaments: a thicker sheet will tend to increase the thickness of the ligaments and hence the final drop size.

From drop-size measurements, Lefebvre and Miller confirmed the effect of increasing the atomizing air velocity on reducing the mean drop size, but reported that varying the air to liquid ratio had little effect on the mean drop size. This is reasonable since the ALR in their tests varied from 3.0 to 9.0.

A useful contribution, providing more insight into the influence of the significant liquid and air physical properties on the quality of sprays produced by the process of airblast atomization was made by Rizkallah and Lefebvre (Ref. 79 and 80). They used an airblast atomizer, due to Lefebvre, which is representative of current gas turbine practice. This atomizer was also used in the present study on the effect of scale, and is illustrated in Figure (9). The Sauter mean diameter of the sprays was measured by the method of light scattering, due to Dobbins, Crocco and Glassman (Ref. 17). To establish the separate effect of the liquid viscosity, surface tension and liquid density, they sprayed water, kerosine, and especially - prepared solutions which exhibited wide variations in one property but only very slight difference in the other two main physical properties. The ranges covered in their tests were:

Liquid absolute viscosity:	from 1.3 to 124 centipoise
Liquid surface tension:	from 26 to 73 dynes/cm
Liquid density:	from 0.8 to 1.8 gr/cm^3
Atomizing air velocity:	from 60 to 125 m/sec

Their results were correlated satisfactorily to the following expression:

$$SMD = 521 \; \frac{\sigma_\ell^{0.5} \; \rho_\ell^{0.75}}{V_a} \left(1 + \frac{W_\ell}{W_a}\right) + 0.037 \; \eta_\ell^{0.85}$$

$$(\sigma_\ell \rho_\ell)^{1.2} \left(1 + \frac{W_\ell}{W_a}\right)^{2.0}$$

..... (3.13)

where: SMD is microns; σ_ℓ is dynes/cm; ρ_ℓ is gr/c.c.;

η_ℓ is centipoise; and V_a is m/sec.

The above expression is applicable only to sprays produced at ambient atmospheric conditions, and cannot be applied to those produced under the conditions prevailing inside a gas turbine combustion chamber. Further work, (Ref. 79), was therefore undertaken to investigate the effect of the ambient air temperature and pressure, as a means of establishing the influence of the ambient air density on the mean drop size of sprays of low viscosity liquids, namely water and kerosine. A similar study for liquids having higher viscosity was later made by Rizk and Lefebvre (Ref. 78).

The effect of air pressure was examined at several levels of ambient pressure ranging from 10^5 to 10^6 N/m^2, at a constant level of atomizing air velocity and ambient temperature. They found that the SMD was inversely proportional to the ambient pressure. The results obtained are shown in Figure (8). The air temperature was varied between 296°K and 424°K; and the SMD was found to increase linearly with increase in ambient air temperature. It was concluded that for liquids of low viscosity, the SMD of sprays was inversely proportional to the ambient air density.

Taking into account the effect of all the variables studies, Rizkallah and Lefebvre proposed the following empirical expression, which is dimensionally correct, for predicting the Sauter mean diameter:

$$SMD = A \; \frac{(\sigma_\ell \rho_\ell t)^{0.5}}{V_a \rho_a} \left(1 + \frac{W_\ell}{W_a}\right) + B \left(\frac{\eta^2_\ell}{\sigma_\ell \rho_a}\right)^{0.425} \times (t)^{0.575}$$

$$\times \left(1 + \frac{W_\ell}{W_a}\right)^{2.0}$$

where (t) is the liquid film thickness at the atomizing lip.

To evaluate the constant quantities A and B, it is necessary to carry out film thickness measurements. As this was not made Lefebvre made a reasonable assumption that: for geometrically similar atomizers of different sizes, the film thickness would be proportional to the prefilmer diameter. From the data obtained from their atomizer, having a prefilmer diameter of 38mm. the previous equation became S.I. units:

$$SMD = 6.5 \times 10^{-4} \left(\frac{\sigma_\ell \rho_\ell}{V_a \rho_a}\right)^{0.5} \left(1 + \frac{W_\ell}{W_a}\right) + 1.2 \times 10^{-4} \times \left(\frac{\eta_\ell^{\,2}}{\sigma_\ell \rho_a}\right)^{0.425} \left(1 + \frac{W_\ell}{W_a}\right)^{2.0} \quad \ldots\ldots (3.14)$$

which was reported to be accurate within 5% over a wide range of operating conditions. Equation (3.14) appears to be in agreement with the findings of Nukiyama and Tanasawa as regards the liquid viscosity assuming a role independent to that of the air velocity. In addition it was also concluded that in the design of airblast atomizers for use with light hydrocarbon fuels, the air to liquid mass flow ratio should ideally exceed a value of 2.0. and that little improvement in the quality of atomization is gained by raising the ALR above a value of 5.0.

Lorenzetto and Lefebvre (Ref. 54 and 55), carried out an extensive comparative study of the quality of sprays produced by the process of airblast atomization from plain liquid jets and those produced from thin liquid sheets. They used an airblast system of a versatile design, which is similar in principle to the Nukiyama and Tanasawa systems, where the liquid is injected in the form of a discrete cylindrical jet into a coaxial, coflowing, high-speed airstream, but the liquid is arranged to encounter the airflow at the throat of the air nozzle, as illustrated in Figure (4.a). Measurements of the Sauter mean diameter were made by an improved light scattering optical set-up, which is also used in the present investigation and described in the following chapter. A large variety of liquids were used, covering a wide range of liquid density, surface tension and viscosity.

With the exception of the effect of the liquid density on the mean drop size, all the plots of experimental data exhibited similar trends as the corresponding curves for thin-sheet type atomizers, obtained previously by Rizkalla and Lefebvre, but to different degrees of influence for the various parameters involved. It was observed, for example, that the atomization quality does not seem to improve for values of ALR in excess of 7.0, and starts to decline when the ALR falls below 4.0, and deteriorates rapidly at air to liquid ratios below about 2.0. The liquid density was found to have an effect on the SMD opposite to that reported for prefilming type atomizers. The mean drop size was found to increase with decrease in liquid density, but this effect became of little significance with increase in the atomizing air velocity or the air to liquid flow ratio.

The effect of the size of plain-jet atomizers was also studied, by using four geometrically similar airblast systems in which interchangeable liquid injectors of diameters 0.397, 0.794, 1.191 and 1.588 millimeters were used with a common air nozzle. In addition, to separate the influence of the liquid flow rate on the quality of sprays from that of the air to liquid flow ratio, ten air nozzles were used having throat diameters ranging from 5.84 to 25.4 millimeters.

Lorenzetto and Lefebvre reported that, for liquids of low viscosity, while the liquid injection orifice size (D) had virtually no effect on the mean drop diameter, the liquid flow rate (W_ℓ) has an independent effect. The SMD was found to increase with increase in the liquid mass flow rate, with other factors held constant. For higher viscosity liquids, the liquid orifice size had a significant influence in the direction of increasing the SMD when a larger size orifice was used; and the SMD appeared to vary roughly in proportion with the square root of the orifice diameter. Their experimental data correlated well with the following dimensionally inconsistent expression:

$$SMD = 0.27 \; \frac{\sigma_\ell^{0.32} \; W_\ell^{0.135}}{\rho_\ell^{0.37} \; V_r} \left(1 + \frac{1}{AFR}\right)^{1.7} + 0.06186 \times$$

$$\frac{\eta_\ell^{0.72} \; D^{0.53}}{\sigma_\ell^{0.5} \; \rho_\ell^{0.5}} \left(1 + \frac{1}{AFR}\right) \quad \ldots\ldots \quad (3.15)$$

in S.I. units.

All the data were obtained at atmospheric pressure and room temperature conditions. To obtain a dimensionally correct relationship an air density term was introduced and the following equation was proposed to predict the value of the mean drop size of sprays produced by plain jet atomizers.

$$SMD = 0.95 \frac{\sigma_{\ell}^{0.33} W_{\ell}^{0.33}}{V_r \rho_{\ell}^{0.37} \rho_a^{0.3}} \left(1 + \frac{1}{AFR}\right)^{1.7} + 0.127 \eta_{\ell} \times$$

$$\left(\frac{D}{\sigma_{\ell}\rho_{\ell}}\right)^{0.5} \left(1 + \frac{1}{AFR}\right)^{1.8} \quad ..... \quad (3.16)$$

which is reported to be accurate within 8% over a very wide range of the variables, and in favourable agreement with the Nukiyama and Tanasawa correlation, especially towards the low range of droplet isze.

3.5. Other Important Work on Airblast Atomization

Lewis, Goglia and others (Ref. 50), proposed that the validity of the SMD prediction expression of Nukiyama and Tanasawa, equation (3.2), could be extended to include liquids of viscosity up to 50 centipoises and atomizing air velocity up to sonic speed. They employed several types of compressed gas as the atomizing media and reported that, at constant gas to liquid ratio, when the gas density was reduced to one seventh of its original value the SMD increased by a factor of about two, despite a slight increase in gas velocity.

Weiss and Worsham (Ref. 93), proposed that the droplet diameter range found in an airblast liquid spray depended on the range of excitable wavelengths on the surface of the liquid sheet. The short wavelength limit was due to viscous damping while the long wavelengths were limited due to inertia. On that basis, they concluded that the mean drop diameter depended on the density and velocity of the air, and on the liquid properties as follows:

$$\begin{aligned} MMD \;&\alpha\; V_r^{-4/3} \\ &\alpha\; \sigma_\ell^{1/3} \\ &\alpha\; \rho_a^{-2/3} \\ &\alpha\; \eta_\ell^{2/3} \end{aligned}$$

Their experimental study of the atomization variables concentrated on sprays obtained on injecting molten wax from simple cylindrical tube injectors of inside diameter (D), into a hot high velocity airstream. The results were summarized by the following proportion:

$$MMD \quad V^{-1.34} \alpha \; D^{0.16} \; \nu^{0.08} \; \eta_\ell^{0.34} \quad (1 + 0.05/\rho_a)$$

and written dimensionlessly as:

$$\frac{MMD.\rho_a \, V_r^2}{\sigma_\ell} = 0.60 \left(\frac{V_r \, \eta_\ell}{\sigma_\ell}\right)^{2/3} \left(1 + 10^3 \, \frac{\rho_a}{\rho_\ell}\right) \times \left(\frac{D \, \rho_\ell \, \sqrt{\nu \sigma_\ell \eta_a}}{\eta_\ell^2}\right)^{1/6}$$

where v is the liquid injection velocity.

These relationships confirmed the air velocity response but gave slightly different indices for the other factors, that is approximately:

$$MMD \;\alpha\; V^{-1.34} \; \sigma^{0.42} \; \rho_a^{-0.7} \; \eta_\ell^{0.34} \qquad .... \; (3.17)$$

Godbole (Ref. 26), investigated the effect of ambient air pressure on the quality of water and kerosene sprays over the range of pressure from 14.7 to 150 psia. The sprays were produced by the atomizer shown in Fig. (6), which is also employed in the present study. He found that the sprays became coarser as the ambient pressure was increased up to about 20 to 30 psia, above which the mean drop size of the sprays reduced according to a power law with an index of about -0.6 for the pressure; which is in good agreement with the result of Weiss and Worsham. Godbole also confirmed that the SMD was inversely proportional to the atomizing air velocity, and reported that there was no significant reduction in the SMD for values of the ALR above 2.5, but greatly increased below a value of about 1.50.

Hrubecky (Ref. 36), atomized water by high velocity air using various methods of injection, liquid nozzle positions and orientation. He found that the highest degree of atomization was achieved when the liquid was injected in the region of maximum velocity of the airstream; also, minimum drop sizes were obtained when the liquid was injected parallel to the airflow. Efficient atomization by the airblast process was confirmed, and drop sizes of the order of 5 to 7 microns were obtained at sonic air velocity with an air to liquid volumetric ratio of 5000.

Fraser and others (Ref. 23), recommended airblast atomizers for spraying viscous liquids that are difficult to disintegrate. In which case they proposed using a prefilming type nozzle to produce small drops at lower working pressures and velocities.

Bryan (Ref. 8), tested the performance of several airblast atomizers and found that significant improvements in the starting and atomizing characteristics were achieved through the combined action of prefilming the liquid and the application of airstream on both sides of the sheet. Best results were obtained from the atomizer shown in Fig. (6), where the liquid was spread across the inside surface of a divergent prefilming cup.

Radcliffe and Clare (Ref. 73), tested two similar airblast atomizers but of different sizes, shown in Fig. (2.b), in which the airflow was given a rotary motion; to assess their capability for atomizing liquids of high viscosity. They reported that the main factor controlling the drop size was the ALR; and when this was 0.1, the SMD of the spray was about 100 microns for fuels of viscosity ranging from 20 to 40 centipoise.

Of particular interest was their finding that the droplet size increased approximately in proportion with the square root of the linear dimensions of the liquid orifice and metering section.

Another study of the effect of the atomizer scale was made by Golitzine, Sharp and Badham (Ref. 28). They used three scaled up airblast nozzles of similar design, in which the liquid was injected coaxially into the airflow at the throat of an air nozzle. They reported that larger atomizers produced coarser sprays than smaller nozzles, at fixed values of the ALR and atomizing air velocity, but did not quantify this trend.

CHAPTER 4

EXPERIMENTAL TECHNIQUE AND APPARATUS

- The Spray
- Outline of the Experimental Programme
- The Geometrically Similar Airblast Atomizers, and Modification to the Original Design
- Atomizing Air System
- Liquid System
- Mean Drop Size Measurement
- Liquid Discharge Characteristics of Swirlers

CHAPTER 4

Experimental Technique and Apparatus

4.1 The Spray

The atomization process produces a range of drop sizes, and practical atomizers therefore cannot usually form homogeneous sprays, but poly-dispersions having finite values of minimum and maximum droplet diameter. Undoubtedly, knowledge of the drop-size distribution can be helpful in predicting certain combustion characteristics which depend on the frequency of occurrence of various drop sizes. However, fuel sprays are highly dynamic systems and once a spray of a given drop-size distribution has been produced, a number of factors may almost immediately serve to alter it as the droplets are carried along in the airstream.

Thus, the virtue of considering the drop-size distribution should not be over estimated as it may suffice to take into consideration only a mean drop size that is representative of the entire spray when dealing with many of the problems of spray combustion. For instance: Ingebo, Ref. (37), in a detailed study of iso-octane sprays, showed that good predictions of the evaporation rate of sprays can be obtained from equations using a mean drop size in place of the complete drop-size distribution. Kumagai, Ref.(41) also reported that Probert, Ref.(71) and Tanasawa, (Ref.88), computed the percentage of burned fuel from known drop size distributions, finding that the predicted change of evaporation characteristics were not significant for a range of size distirubtion having a fixed value of the mean diameter.

Hence, a useful property to describe the atomization quality and the effectiveness of an atomizer to perform over a range of conditions is the mean drop size. Many useful mean drop sizes have therefore been proposed having different physical meanings. The aim in all cases is to treat the actual spray as though it were composed of uniformly sized drops.

In this context, the Sauter Mean Diameter (SMD) is generally considered as the most suitable from the standpoint of liquid spray combustion as it is most relevant to mass transfer and reaction rates in high velocity conditions, as shown by Shapiro et al, Ref.(84) for example. The mist containing droplets of uniform diameter (SMD) will have almost the same rate of evaporation or combustion as the actual mist at each instant. Hence, the SMD is employed throughout this investigation, its values being determined experimentally by the well-established light-scattering technique, as explained in article (4.6). For completeness, the SMD can be defined as the diameter of a drop having the same volume-to-surface ratio as the actual spray.

4.2 Outline of the Experimental Programme

It is possible to draw the general conclusion for airblast atomizers of the prefilming type that the mean drop size produced is primarily a function of:

(a) the liquid physical properties of absolute viscosity (η_ℓ), surface tension (σ_ℓ), and density (ρ_ℓ);

(b) the atomizing-air velocity (V_a), and density (ρ_a);

(c) The air and the liquid mass flow rates (W_a) and (W_ℓ) respectively;

(d) the thickness of the liquid film (t);

and, (e) the geometry or design of the airblast atomizer (ϕ).

For a different size of airblast atomizer of similar geometry employing a stationary prefilmer cup with tangential liquid ports, it is reasonable to assume that liquid film thickness is proportional to the atomizer linear dimension, since the liquid flow rate is proportional to the square of the atomizer linear size. In fact this is a simple matter to justify for a liquid swirling inside a cylindrical cup, from fundamentals of fluid flow in curved paths, after making some appropriate simplifying assumptions as given in Appendix (A).

Hence, it may be hypothesised that the atomizer linear scale can affect the mean drop size through its influence on liquid film thickness. It follows that the atomization qualify may be expressed by the following equation:-

$$SMD \ \alpha \ f\,(V_a^{\,a},\ \rho_a^{\,b},\ W_a^{\,c},\ W_\ell^{\,d},\ \rho_\ell^{\,e},\ \sigma_\ell^{\,f},\ \eta_\ell^{\,g},\ D^h \text{ and } \phi);$$

where, (D) is the prefilmer diameter, or the airblast atomizer linear dimension affecting the film thickness.

The effect of the atomizer linear dimension can be resolved by employing airblast systems made to the same design, but of various sizes, and comparing the quality of sprays produced under specified conditions. Because mechanisms of airblast atomization are varied and not completely understood there is no assurance that the same mechanism, or group of mechanisms, would take place with different liquid film thicknesses even with other variables fixed. It is therefore necessary to assess the degree of influence of the significant variables on atomization quality over the range of atomizer sizes under consideration, with values of the power indices for each parameter being determined experimentally. To do so the parameters must be varied independently of one another in order to separate the effect of each on the atomization quality.

Subsequently, because of the large number of variables involved, the investigation was carried out in accordance with the experimental programme as described below:

(a) It is essential to ensure that all sprays are sampled in a reasonably similar state of development achieved by the principal factors controlling the atomization quality. However, as previously explained, sprays are of a dynamic nature whose quality may change with distance from the atomizer discharge plane due to many factors which influence the history of the droplets during their flight other than the principal variables involved in the actual atomization process. Consequently, it is necessary to measure the mean drop diameter in the proximity of the airblast nozzle and to establish its pattern of variation with distance in order to determine the most appropriate spray sampling section for any particular atomizer.

It is therefore necessary to measure the SMD across the sprays axes at small intervals of distance; typically 3 to 6 millimeters depending on the atomizer size and variation pattern, over a distance of up to about 30 centimeters from the discharge plane.

(b) Four airblast atomizers were employed, as follows:

(i) Almost all the experimental data were obtained using three atomizers of the same design, which is representative of the airblast atomizers currently used in modern gas turbines, as described in article (4.4), in order to eliminate the effect of geometry on atomization quality. They were manufactured in different sizes to allow the effect of atomizer linear dimension to be quantified accurately over a wide range of conditions. These were capable of handling liquid flow rates as low as 3 gm/sec. and as high as 225 gm/sec., with liquid feed pressures of not more than 50 lbs/in.sq. (gauge). That is to say, they were capable of producing good quality sprays for kerosine flow rates from about 3 to 225 U.K. gal/hr. The atomizer sizes covered the range of prefilmer diameter from 19.05 mm to 76.20 mm.

(ii) Additional data were obtained employing a fourth airblast atomizer, due to Bryan, Ref.(8), in order to ascertain the effect of geometry on the atomization quality, as explained in Chapter 6 article 5.

(c) All sprays were produced with atomizing air at near normal atmospheric conditions of pressure and temperature. The air velocities covered the range from 60 to 150 m/sec., and were varied in increments of 10 m/sec. This also covered the range of air to liquid ratio from 0.5 to 5.0.

(d) The effect of liquid density on the mean drop size was excluded from the experimental programme because of the very narrow range of variability of this property available with practical liquids, or their solutions, without appreciably changing the other two main properties of absolute viscosity and surface tension. Typically this range is not more than 1.3 fold and is not sufficient to allow this effect to be quantified accurately with confidence within acceptable experimental tolerances.

(e) Finally, the effects of air and liquid densities were resolved by applying the technique of dimensional analysis to the experimental data collected over the entire ranges of variation of all other variables, and comparing the results with findings of other investigators, as given in Chapter 6.

4.3 The Geometrically Similar Airblast Atomizers

Three geomtrically similar airblast atomizers scaled to give flow areas in the ratio 1:4:16 were employed. The design was originally due to Lefebvre, employing a stationary prefilmer cup and two atomizing airstreams, as illustrated by the cross-sectional drawing of the medium size atomizer shown in Fig.(9).

The prefilmer diameters were equal to 19.05 mm, 38.10 mm and 76.20 millimeters; and the atomizers had Flow Numbers of about 1.4, 5.6 and 22.4 UK gal/hr./$(\text{psi})^{\frac{1}{2}}$ respectively, when spraying water. Herein this text, atomizer sizes shall be referred to by LS, LM and LL; or simply as Small, Medium and Large atomizers and, unless otherwise stated, all dimensions refer to the Medium airblast atomizer.

The decision was taken to employ this design mainly because:

(a) it is representative of the airblast atomizers used in modern gas turbines. Mean drop-size data reported in Ref.(79, 80) for sprays produced by a similar design indicated that good atomization quality can be achieved at the levels of air velocity encountered in gas turbine combustion chambers;

(b) adequate quantities of both air and liquids to cover the ranges of atomizing velocity and air to liquid ratio specified for the experimental programme when using the Large airblast atomizer could be provided by existing facilities;

(c) the various parts are of shapes easy to scale and to modify if necessary. In addition, they do not require special materials or manufacturing techniques other than normal toolroom precision standards;

(d) the design offers a good measure of versatility, in that both airflow discharge areas can be varied independently in a simple way, namely by means of interchangeable shroud control rings of different internal diameters and by spacers of appropriate lengths placed against a detachable pintle body.

With this design, effective atomization of liquids is accomplished in a fairly easy manner. As illustrated in Fig. (9), liquid enters the atomizer by the side connection and passes through a number of long circular orifices to an annulus formed in the main body between the central tube and the overlap provided by the prefilming cup. The liquid is given a swirling motion as it is forced through six ports, or slots, each of 0.8 x 0.8 mm cross-section cut into a swirler body as shown in Fig.(11). These channels are equispaced and are tangential to a 28 millimeter diameter which is equal to the upstream diameter of the prefilmer. The cup, Fig.(10), screws firmly and squarely against the matching swirler face, and is of a parallel-sided, cylindrical shape, that diverges towards the atomizing edge into a conical frustrum of 100 degrees included angle where the pre-filmer diameter is equal to 38.10 millimeters. After discharging from the slots, the swirling liquid creates a "well" against the back weir, from which the liquid streams in a spiral motion across the cup inner surface to form a thin continuous cylindrical shell before being discharged at the atomizing tip.

In order to achieve fine atomization, the liquid sheet should be subjected to high velocity air on both sides. Thus two separate airflow paths are provided through the atomizer. One airstream passes through the central air duct, and is deflected radially outward by the pintle body, to maintain good physical contact between air and liquid. The second airstream passes through the outer annular passage enshrouding the main body and strikes the outer surface of the liquid film. The system provides an effective means of controlling the spray cone angle.

In all experiments, the velocities of both airstreams were kept equal so as not to introduce an additional variable, and 66.7 percent of the total atomizing-air mass flow was passed through the shroud annulus. For the Medium atomizer, the total discharge area of the air passages was made equal to 365 mm^2.

4.3.1 Modifications to the Original Design

Prior to carrying out the experimental programme three simple yet important modifications were made to the original atomizer design, as explained below:-

(a) The original design incorporated a pintle body of 100 degrees included angle, equal to that of the prefilmer. This meant that the pintle airflow passed through a divergent passage towards the discharge plane because of the increasing prefilmer diameter along the direction of flow. The original pintle was replaced therefore by another body of modified contour and larger cone angle of 120 degrees, Fig.(12), which ensured that the air passage always converged towards the atomizing lip, giving good physical contact between the air and the liquid and, hence, good atomization quality. Moreover, it eliminated any problems of spray instability associated with airflow separation which otherwise might have impaired the spray quality and the reproducibility of mean drop size measurements.

(b) In the course of preliminary tests conducted with the Medium atomizer, sprays were not discharging evenly across the nozzle, tending to concentrate more towards one side even at water flow rates as high as 30 gm/sec., and to jump across the annular orifice at lower rates, allowing only a very narrow range of air-to-liquid ratio at any level of atomizing velocity. This situation in which the swirler ports were not discharging equally was attributed to the upstream orifices being of a too small diameter in relation to slot size, thus restricting the flow to the later which ran partially full. The orifices were subsequently enlarged to ensure that liquid discharge was metered solely by the swirler ports. Subsequently pulsation-free sprays were obtainable with rates as low as 8 gm/sec.

(c) With the large atomizer it was necessary to chamfer the outer edge of the shroud control ring so as to discourage sprays from depositing liquid on its surface. This effectively prevented drooling at the lower end of the atomizing velocity range.

It is perhaps worth mentioning that from the standpoint of actual application in gas turbines, the atomizers suffer a high air pressure drop. Typically, a pressure difference of about 12 percent of the upstream value is required to achieve an atomizing velocity of about 100 m/sec. at room temperature. This was considered mainly due to the non-streamlined shape of the shroud ring. However, since high pressure drop improves the air-flow distribution across the atomizer, no attempt was made to reduce it in favour of a good spray distribution during the experimental runs.

4.4 Atomizing Air System

A small centrifugal blower of 7 lb/sq.in. (gauge) maximum delivery pressure, adequately supplied the required air quantities at temperatures usually between 0 - 25^{o}C.

Figure (13) shows a schematic drawing of the spray rig layout. The main air supply was divided into two separate lines in order to allow independent control over each of the two atomizing airstreams passing through the airblast atomizer.

Each line was fitted with a bleed-off valve and another valve to control the flow rate to the atomizer. Control valves of different handling capacities were interchanged to achieve good control over the wide range of flow rates required with the various atomizer sizes. The mass flow rates were measured in accordance with British Standard Specifications 1042 using a range of square-edged orifice plates fitted with D and D/2 pressure tappings. PVC pipings and couplings were employed generally for reasons of neatness and accuracy of dimensions, with flexible joints introduced where necessary to cater for thermal effects.

Downstream of the control valves, the supply lines converged into a chamber, but were not allowed to mix, and emerged as a coaxial pipe assembly adapted at its downstream end to fit into the airblast atomizer, as illustrated in Fig.(12). Provisions were made to ensure uniform flow distribution and to reduce any swirl tendencies along the coaxial passages by the usual practices of fitting perforated plates, honeycomb plugs and crucifixes.

With this arrangement, velocities and flow rates of both airstreams could be varied independently, allowing accurate settings to be achieved quite easily. Velocities were monitored at the atomizing edge by means of pitot tubes and the air temperature was recorded by means of a thermometer.

The atomizers were not confined and thus the sprays were free to induce ambient air from around the nozzles and from along their path. These were then discharged to the outside through a long pipe that opened up into a gentle diffuser shape, with coarse grid cloth layers fitted over its outlet to trap most drops, while avoiding any backflow tendencies that could disturb mean drop size measurements.

4.5 Liquid System

The liquids used most extensively throughout the entire programme were water and kerosine. In addition, when liquids of high viscosity were required, a solution of kerosine and a very high viscosity polymer, Hyvis Polybutene No. 05, Ref.(6), was used. This had a viscosity of about 29 centipoises and exhibited very little difference in either surface tension or density from those of kerosine, as illustrated in the following table of liquids physical properties, when measured at a temperature of 20 degrees centigrade.

Liquid	Absolute Viscosity η_ℓ Centipoise	Surface Tension σ_ℓ dyne/cm	Density ρ_ℓ gm/c.c.
(Tap) water	1.00	72.50	1.00
(Commercial) Kerosine	1.34	27.70	0.78
Kerosine + Hyvis 05	29.40	28.90	0.82

Water was fed to the airblast atomizers from a multi-stage pump, while kerosine and the high viscosity solution were supplied from reservoirs pressurised by nitrogen bottles. All liquids were supplied via a fine-element filter; needle type flow control valves and a bank of float type precision flow-meters calibrated for all liquids, covering the wide range of liquid flow-rates. Liquid pressures were monitored on a bank of Bourdon-type pressure gauges with the tappings introduced very close to the atomizers. All calibrations were re-checked systematically during the course of experiments. No pulsations were evident in the liquid feed line during the entire tests.

To cater for variations in liquid viscosity with variations in temperature, the latter was monitored by means of a thermo-meter introduced into the feed line to enable the viscosity to be calculated from previously measure variations of this property with temperature.

4.6 Mean Drop Size Measurements

Methods of measuring the mean drop size of sprays usually fall into two main groups. The first, consists of techniques that result in a size-frequency distribution from which a mean drop size can be computed, while the second group only permits a particular mean diameter to be determined by measuring some known effect of the spray on a chosen property. All methods involve some form of spray sampling, and a large part of the differences in results of some investigators can be attributed to problems in obtaining representative samples. However, without going into details, false information is more likely to arise from sampling techniques that disturb the spray by introducing some form of droplet-collecting apparatus. On the other hand, short duration photography incurs no inter-ference with the spray and can provide very useful and accurate information. However, for studies involving large numbers of measurements, the required analysis of drop sizes becomes extremely time consuming.

Here, all values of spray SMD were determined using an electro-optical system employing the technique of forward scattering of monochromatic light, due to Dobbins, Crocco and Glassman, Ref.(17). This method does not interfere with the sprays and gives accurate assessment of SMD over a very wide range of atomization conditions. It allows measurements to be conducted very close to the atomizer and has the important practical advantage that results are obtained quickly from graphs recorded insitu. It is therefore highly suitable when a large number of readings are required, as in the present investigation.

4.6.1 Principles of the Forward Diffractively Scattered Light Technique

Dobbins et al, Ref.(17), developed their technique on a theory describing the light scattering properties of a poly-dispersion. When a parallel beam of monochromatic light falls on a spherical particle of diameter larger than the wavelength (λ), a diffraction pattern is formed as some of the incidental light is diffractively scattered. The pattern takes the shape of lobes having maximum intensity in the direction of the incident beam, that is the forward direction. The degree of scatter depends upon the particle diameter in a manner such that, the smaller the particle, the larger is the scatter. For a poly-dispersion the cumulative effect is obtained by summing all particles as if each were present alone.

In Ref.(17), a normalised intensity I(θ), is defined as the ratio of the intensity of diffracted light at some small angle (θ), measured from the forward direction, to its maximum value occurring at θ equal to zero. Dobbins et al established that a unique relationship exists between I(θ) and the scattered light angular distribution represented by the dimensionless quantity (π.SMD.θ/λ), for sprays conforming to the upper limit distribution function (U.L.D.F.), within specified limits of spread and skewness.

Roberts and Webb, Ref.(81), extended the validity of the theory to cover very wide ranges of the U.L.D.F. parameters of spread and of skewness, hence making it possible to apply this technique directly to sprays produced under widely varied conditions without prior knowledge of drop-size distribution. They proposed the Revised Mean Theoretical (Illumination) Profile illustrated in Fig.(17), and established that the least standard deviation occurs at approximately one tenth of the maximum normalised intensity in the profile, at which:

$$\frac{\pi.SMD.\theta}{\lambda} = 2.647 \qquad ..... (4.1)$$

Thus, the position in an experimentally determined profile at which one tenth of the maximum intensity occurs, enables values of the SMD to be calculated from equation (4.1) with least deviation from theory.

4.6.2 The Electro-optical System

The set-up is shown in Plate (1) and diagramatically on Figures (18) and (19). The optical components are all aligned to the beam centre line and fixed onto a rigid bench with a built-in test section through which sprays pass perpendicularly to the beam axis. Reference can be made to Appendix C for details of calibration procedure and components' particulars. The intention here is to highlight the important practicalities and apparatus features which enable reliable measurements to be obtained.

In order to investigate the variation of mean drop size across the spray axis with distance from the airblast atomizer the entire optical bench was rigidly mounted onto a heavy manually-operated carriage (removed from a lathe) which was secured to the floor through anti-vibration mountings. With this arrangement the whole optical set-up could be traversed very smoothly relative to the fixed airblast atomizer over distances of up to about 50 centimeters, its position being accurately determined by a precision linear scale incorporated into the carriage. This arrangement enabled SMD measurements to be made at distance intervals of 3 or 6 millimeters quite easily.

To obtain accurate SMD assessments, the beam directed into the spray must be parallel to a very high degree, monochromatic, and of a suitable illumination power that is highly stable. These requirements were achieved to a large extent using a 5 milliwatt laser head used as the source of light of wavelength (λ) equal to 6328 Angstroms.

Because of the property of beams to spread out through some solid angle (β), inversely proportional to the beam diameter (d), a beam expanding assembly, Fig.(20), is fitted to the laser head in order to improve the diffraction-limited characteristic of the laser even further. By expanding the beam diameter the divergence is reduced proportionately to a very small value, typically equal to about 0.1 milliradians. The expanding assembly incorporates a so-called spatial filter; essentially a precision aperture of some 22 micron diameter located at the common focal point of its two-lens systems, to pass only the fundamental laser mode. Thus, a highly collimated monochromatic beam is directed through the spray under investigation.

Some idea about the level of inaccuracy in measuring the SMD attributed to beam divergence only may be gained from equation (4.1) and the relation $\beta = 4\lambda/d$, as proposed by the expression:

$$\frac{\beta}{\theta} = 1.32 \quad \frac{SMD}{d}$$

For this apparatus, the beam diameter equals 4.3 millimeters, hence the error is less than 0.03 percent when the SMD equals 100 microns.

The light scattered by the spray is focused by a receiver lens of focal length (f), equal to 60 centimeters, onto a second 22 microns precision aperture, (fitted to an eye-piece and shutter unit), and passes through to a photomultiplier which measures its energy. This has a high quantum efficiency and responsitivity in the red spectral response and a low, dark-current value. For highest stability, interchangeable neutral density filters may be fitted in front of the photo-tube to keep the anode current below a certain limit. The photo-multiplier and aperture, Fig.(21), mounted on a trolley, can be traversed across the focussed beam to scan its intensity, by means of a very fine pitch screw-jack, and its position may be defined by a dial-type indicator.

The path of the focussed light from the receiver lens is shielded by a metallic tube painted matt black to prevent ghost images forming, and the photo tube is enclosed inside a light tight housing so that its only source of light is the spray diffracted laser coming through the precision aperture. In practice there is no assurance that such shielding alone could prevent stray light from finding its way to the photomultiplier. To allow measurements to be made accurately in conditions where such parasitic effects could appreciably distort the illumination profile, such as when measuring in strong ambient lighting conditions, the system utilizes a chopper unit located on the optical axis before the spray section. This consists of a rotating disc having fan-shaped apertures, a photo-electric cell, and a small white lamp. The unit modulates the continuous laser beam into discrete pulses before it is passed into the spray. In conjunction with a synchronous demodulator the unwanted output of the photomultiplier due to the unmodulated stray light is greatly reduced, resulting in a much improved signal to noise ratio.

The scattered light intensity signal, viz.I(θ), coming from the photomultiplier is amplified and passed to the logarithmic scale (Y-axis) of a log-linear plotter. An oscilliscope and a digital type voltmeter may be used to monitor this signal. Another signal passing to the plotter linear axis (X-axis) comes from an inductive, displacement-type, position transducer linked to the photomultiplier trolley. The transducer gives a very sensitive indication of the traverse position (x) relative to the optical axis. The combination of the X and Y signals allows the profile to be recorded on appropriate log-linear graphical paper.

4.6.3 Readout of the Experimental Illumination Profile

Typical examples of profiles obtained during the course of experiments are illustrated in Fig.(27). They establish a pattern for variation of the mean drop size with distance along the spray axis, as plotted in Fig.(70a).

The profiles show a characteristic spike, due to the proportion of unscattered light, and it is necessary to extrapolate across it to the Y-axis in order to determine the value of maximum intensity, occuring at $\theta = 0 = x$. The position, x, in the profile corresponding to one tenth of the maximum intensity can then be defined. In order to minimise the level of uncertainty in extrapolation, it is important to obtain smooth profiles of reasonable slopes having narrow spikes whose projection is well defined.

Values of the SMD were calculated from equation (4.1). For the prevailing conditions of $\lambda = 6328\ A^{o}$, and $\theta = x/60$, this becomes:

$$SMD = \frac{12.6}{x} \qquad \ldots\ldots (4.2)$$

where SMD is in microns, and x is in inches. Alternatively, values of SMD could be obtained directly from a graphical plot of expression (4.2), as shown in Fig.(23).

Lastly, experience has shown that best consistency of results is obtained when the system settings are fixed over as wide as possible range of conditions under investigation. It is also necessary to allow a warming-up period of about 30 minutes for maximum stability to be achieved. In the present investigation SMD measurements were obtained down to values of about 17 microns and up to about 140 microns, with a very good degree of resolution.

4.7 Liquid Discharge Characteristic of Swirler

No experimental data are available on the rate of discharge of liquids from arrangements of multiple slots of rectangular section, for the liquid swirlers used with stationary cup airblast atomizers. The objective here is to determine the coefficient of discharge of such swirlers at high values of flow Reynolds number, as defined by the simple-orifice equation

$Q = C_D . A. \ (2\Delta P/\rho)^{0.5}$.

From the available literature on liquid discharge characteristics of a single cylindrical tube orifice, discussed in article 4.7.1, it is proposed here that the value of the C_D of swirlers may be described mainly by the Reynolds number of the flow through the slots, the ratio of slot length/width, the slots' offset diameter (or prefilmer diameter), the discharge area of the liquid ports, and the number of slots, that is:

$$C_D = f(R_e,\ \ell/w,\ D,\ A_s \text{ and } N)$$

An important inference drawn from the literature is that, for the purpose of design of low-pressure fuel injectors, the main criterion for choosing plain orifices, having predicatable and stable performance over a given range of flow, is that the orifice should have a length/width ratio greater than 2:1, and preferably not less than 4:1. It should also be of such a size to maintain a well-developed turbulent flow through it.

In consequence, 16 swirlers of various geometry were employed with the test-section described in article 4.7.2, in order to obtain measurements over the range of interest to the designer, namely, Reynolds number from about 3,200 to 30,000, slot length/width ratio from 4:1 to 7:1, swirler flow number from about 2.0 to 20 UK gallon/hour/$(psi)^{0.5}$, and off-set diameter from 12.7 to 50.8 millimeters.

4.7.1 Review of the Main Discharge Characteristics of Cylindrical Tube Orifices.

The mechanism of liquid flow through long orifices of small diameter, and the discharge characteristics of such tubes are well understood. When a liquid is forced through a plate-orifice, the volumetric rate of flow, Q, is related to the discharge area, A, and the pressure drop across the hole, ΔP, by the discharge coefficient, C_D, as expressed by the simple orifice equation:

$$Q = C_D . A . \ (2\Delta P/\rho_\ell)^{0.5}$$

where ρ_ℓ is the density of the liquid discharged.

The extensive experimental data produced by a large number of investigators, e.g. Zucrow (Ref.100), Langhaard (Ref.44), Northup (Ref.66), Spikes et al (Ref.86), Nakayama (Ref.64), Lichtarowicz et al (Ref.51), and many others, has established that the simple orifice equation describes the discharge characteristics of tube orifices to a high degree of accuracy, with C_D treated mainly as a function of the flow Reynolds number, Re, referred to the orifice diameter, and the orifice length/diameter ratio, ℓ/d.

In view of the lack of a satisfactory theory applicable to a wide range of Reynolds number and orifice length/diameter ratio, the variaton of the coefficient of discharge with Re and ℓ/d has been expressed in a number of empirical correlations. For instance, Nakayama proposed that

$$C_D = \frac{(Re)_h^{5/6}}{17.11\ (\ell/d) + 1.65\ (Re)_h^{0.8}}$$

where $Re = C_D\ (Re)_h/(1-m)^{0.5}$, m being the ratio of the area of the orifice to that of the approach pipe. He claimed an accuracy of 2.8% for ℓ/d in the range from 1.5 to 17, and for $(Re)_h$ in the range from 550 to 7000. Among other expressions, Lichtarowicz et al modified the equation of Asihmin (Ref. 3) to read:

$$\frac{1}{C_D} = \frac{1}{0.827 - 0.0085(\ell/d)} + \frac{20}{(R_e)_h}\left(1 + 2.25\left(\frac{\ell}{d}\right)\right) - \frac{0.0015\ (\ell/d)}{1 + 7.5\ (\log 0.00015(R_e)_h^2)} \quad \ldots\ldots \quad (4.3)$$

claiming an accuracy of better than 2% in predicting the experimental data of a large number of investigators for a range of (ℓ/d) from 2 to 10, and for a range of $(Re)_h$ from 10 to 20000.

From consideration of previous work, variation of the coefficient of discharge of plain orifices with Reynolds number and orifice length/diameter ratio may be described as follows.

(a) For the purpose of convenience, the discharge characteristic curve relating C_D and Re may be divided into three regimes. The first corresponds to laminar flow, in with C_D varies linearly with the sqaure root of Reynolds number, e.g. Langhaar proposes that:

$$\frac{1}{{C_D}^2} = \frac{64}{R_e}\left(\frac{\ell}{d}\right) + 2.28$$

The second region corresponds to semi-turbulent or transition flow, where C_D approaches a fairly uniform value towards the higher critical Reynolds number. The third region corresponds to turbulent flow, e.g. $Re > 3000$ where, for most purposes, it is sufficiently accurate to consider that the value of C_D remains constant.

(b) At high flow Reynolds number and low values of the length/diameter ratio, that is $\ell/d < 0.5$ say, the tube passage is similar to a plate-orifice and the coefficient of discharge is comparatively low. It is equal to approximately 0.61 when there is a sharp edged entry, because the liquid jet contracts at the entry and cannot re-expand and fill the passage.

> With increase in the ratio ℓ/d, the jet can expand sufficiently to fill the tube passage. In consequence the contraction coefficient (C_c) increases to unity and, hence, C_D also increases. With further increase in ℓ/d, C_D decreases slightly due to the additional frictional losses.

An important feature of tube orifices of relevance to the design of fuel injectors, is the phenomenon of "flip" or hydraulic-jump, which is usually attributed to liquid cavitation at the entry to the orifice. It has been the subject of research in investigations dealing with stability of combustion in rocket motors, and the design of control mechanisms, e.g. the investigations of Stehling (Ref.87), Northup (Ref.66), Hagerty (Ref.31) and Spike (Ref.86).

The mechanism of hydraulic-jump is attributed to the cavitation area expanding as pressure increases until the tube end is reached and the jet suddently springs away from the orifice walls, contracting into a smooth rod of liquid. This is accompanied by a sudden drop in the rate of discharge, or coefficient of discharge. It appears as a sharp discontinuity or hysteresis in the characteristic curve, initiating at some pressure-drop, or Reynolds number, such that below the critical point the discharge characteristic curves for increasing and decreasing pressures do not coincide. In addition, to the hysteresis effect, if a reversible flip action takes place continuously, excessive pressure oscillations inside the combustor, as well as mechanical vibrations, might occur.

In the context of hydraulic flip, plots of the characteristic curves provided by Bird (Ref.4) show that the Reynolds number at which transition occurs for $\ell/d < 4:1$, lies below a value of about 3000. Similar plots produced by Lichtarowicz et al (Ref.51) indicate that discontinuity occurs at a Reynolds number of between 2000 and 2500. They also show that the decline in C_D diminishes as the ratio ℓ/d is increased to about 2:1, while for higher ratios the characteristic curves are fairly continuous.

4.7.2 Liquid Swirlers and Test-Section

A total of 16 swirlers, in 4 sets, were used. They were made from perspex to the dimensions indicated in Appendix (D) to normal tool-room precision standards. With normal machining methods, variations of up to 0.001 inches in the size of the liquid ports were inherent.

Sets A, B and C had offset diameters equal to 12.7, 25.4 and 50.8 millimeters, respectively. All had 6 equi-spaced, square-section, straight channels milled out of a circular weir, as shown in Fig.(25). With each swirler, the slots were of equal cross-sectional area. The different slot sizes used gave a total discharge area which varied from 1.00 to 9.525 mm^2, covering a range of swirler flow number from about 2 to 20 U.K. gallons/hour/$(psi)^{\frac{1}{2}}$. All swirlers initially had a slot length/width ratio of 7:1. The weir thicknesses were successively milled down to give a length/width ratio of 5.5:1 and 4:1, in order to examine the effect of the slot ℓ/w ratio on the discharge coefficient.

Two swirlers of set D, together with swirler B4, were used to examine the effect of the number of slots on C_D. They had an offset diameter of 25.4 mm, total discharge area of 5.76 mm^2, an ℓ/d ratio of 7:1, and of 3, 6, and 9 slots each.

Figs.(24 and 25) illustrate the test-section employed. As shown, the swirlers screw onto a hollow spindle, or holder, which fits squarely inside the pressure chamber formed by the housing and pressure plate. The latter fits tightly and squarely against the slots' circular weir. To ensure uniform liquid supply to all slots, the area of the annulus leading to the swirlers was made 40 times greater than the largest discharge area used, and the assembly always discharged vertically downward in order to equalize the effect of gravity.

Water and kerosine were employed throughout the entire tests. The rate of discharge was determined by means of precision flowmeters. A pressure tapping inserted into one side of the chamber allowed the pressure drop across the liquid ports to be monitored on pressure gauges covering an appropriate range of full-scale readings. Measurements were made over a range of liquid pressure drop from 10 to 100 psig.

CHAPTER 5

TEST RESULTS AND CORRELATIONS

- Summary
- Variation of the SMD with distance across the spray axis
- Allowable range for variation of liquid flow rate
- Sprays of low viscosity liquid
- Comparison between the present results on the effect of atomizer scale with other works:
  1) Fraser et al; York et al; Hagerty and Shea; Dombrowski et al
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  3) Wigg
  4) Kim and Marshall
- Discharge characteristics of liquid swirlers

CHAPTER 5

TEST RESULTS AND CORRELATIONS

5.1 Summary

Unconfined sprays of water, kerosine, and a high viscosity solution were produced by the three geometrically similar airblast atomizers employing airflows at near atmospheric pressure. Measurements were carried out for each atomizer size with the purpose of evaluating the influence of the dominant factors affecting the mean drop diameter, in order to bring out any distinct effect the atomizer size might have on the influence of each particular parameter, and, eventually, quantify the effect of the atomizer linear dimension on the spray mean drop size.

The large amount of data collected for the various liquids produced with the small and the medium airblast atomizer sizes showed a very good degree of consistency. It was therefore sufficient to employ the large airblast atomizer in a smaller number of tests involving kerosine and the high viscosity liquid, but mostly with water sprays.

Here, the experimental data are analysed. The results are presented for each atomizer size in a manner that is designed to give a clear picture of the effect of the different variables involved. They establish that the atomizer dimension has an influence on atomization quality that is distinct from other parameters, and that mean drop size increases appreciably with atomizer linear scale. Measurements also indicate that in the proximity of the atomizer the mean drop size varies quite appreciably but in an orderly manner. The data confirm that a suitable form for an equation predicting the mean diameter of sprays is one in which the mean drop size is expressed as the sum of two terms: (a) the first term, $(SMD)_{\ell v}$, is dominated by the atomizing air velocity; while (b) the second term, $\Delta(SMD)_{vi}$, is independent of the atomizing velocity but dominated by the air and liquid physical properties, mainly liquid viscosity, and becomes negligibly small in comparison with the former for low viscosity liquids, such as kerosine or water.

5.2 Preliminary Experiments

Two sets of experiments were carried out for each atomizer size prior to carrying out the programme outlined in the previous chapter, in order to (a) establish the variation pattern of the mean drop size with distance from the airblast nozzle, and (b) determine the maximum and minimum limits within which the liquid mass flow rates can vary.

5.2.1 Variation of the SMD with Distance across the Spray Axis

Figures (28), (29) and (30) show plots of the mean drop sizes measured at different distances from the nozzle discharge planes across the spray axis in increments of 3 and 6 millimeters. They relate to water sprays produced by atomizers of different size at a constant air velocity level of 100 m/sec. but for various levels of air-to-liquid ratio. Figure (29) also shows the results of similar tests made with the medium size airblast atomizer at another level of air velocity, viz. 80 m/second. From these graphs it was possible to recognise three regions of variation of the mean diameter with distance across the axis of a spray, distinguishable as follows:-

(a) A relatively large mean diameter exists for a very short distance, of the order of about 0.2 of the prefilmer diameter. This is probably the result of the atomization of the cylindrical liquid shell inside the airblast atomizer by the shearing action of the high velocity pintle airflow only.

(b) Beyond this very small distance interval, the SMD decreases sharply to some minimum size. This is attributed to secondary atomization of the initially large and unstable drops that are shattered during their flight outside the airblast nozzles when impacted by the high velocity shroud air which creates some new upper limit for droplet survival diameter.

(c) Further downstream of the atomizer, the mean drop size increases with distance but at a much slower rate. This increase in drop size may be attributed to one or more of the following factors:

1) <u>Coalescence</u>

Because of the increase in drop concentration per unit volume of the spray caused by the secondary atomization process, droplets will collide more frequently with the result that some coalesce and form larger drops with a corresponding reduction in the number of smaller diameter drops.

2) <u>Discretionary Existence</u>

Drops of smaller diameter decelerate faster and evaporate quicker than larger ones. In sprays, the larger droplets will therefore tend to occur more frequently at larger distances and vice versa. In addition, this tendency towards discretionary existence, (or preferential occurance), is encouraged at further distances from the atomizer because the entraining air velocity falls and, therefore, more drops of larger diameter can survive. The result is an increase in mean drop size with increase in distance downstream of the airblast atomizer.

As illustrated by the graphical plots, the patterns of variation of SMD are basically similar for all atomizer sizes, air to liquid ratios, and atomizing velocities, which suggests that it may suffice to obtain only one such plot for a particular airblast atomizer in order to determine how the mean diameter varies with distance along the spray axis. For the particular geometry of atomizer employed here, the minimum mean diameter occurs at a downstream distance of about 1.5 times the prefilmer diameter. As also shown on the same graphs, of Figures (28) to (30), the ratio between the initially large mean drop size adjacent to the discharge annulli to the minimum mean diameter is about 1.5 on average, while drop size growth to almost the initial values is achieved at further distances of about 7 to 8 times the prefilmer diameter. Further away, reliable measurement of SMD's are, unfortunately, not feasible by the light-scattering technique, since the spray becomes unsteady as it diffuses into the ambient atmosphere.

It was decided for each atomizer size to carry out the drop-size measurements called for in the experimental programme at the position in the spray corresponding to minimum SMD. The mean diameter obtained at these locations represents the combined atomization effects of both airstreams, and sprays produced by the different atomizer sizes would most likely be in similar states of development at these positions than at other locations in the sprays. Fortunately, these positions can be located easily and quite accurately from the SMD variation patterns. Furthermore, the narrowest spikes were found for the illumination profiles obtained at such positions, due to the large reduction in the proportion of undiffracted light associated with increase in droplet concentration at these planes.

Since the mean drop size can vary appreciably in the proximity of an airblast atomizer, it is proposed that atomizer performance data should include a mean diameter variation pattern and a clear reference to the spray sampling plane in order that such information would be more representative of the actual spray.

5.1.2 Allowable Range for Variation of Liquid Flowrate

Experiments indicate that airblast atomizers produce sprays satisfactorily within certain minimum and maximum limits of liquid rates. Figure (31) is an example of typical measurements obtained with two atomizer sizes when spraying water at a constant level of atomizing air velocity. As shown, it is clear that for each size

(a) the mean drop size decreases with decrease in liquid rate as expected, but only to some minimum flow-rate below which the measured mean diameter appears to increase in a disorderly manner. This behaviour is attributed to the situation where the liquid ports begin to discharge unequally. The liquid film thickness ceases to be uniform and consequently larger than expected drop sizes are produced from locally thicker swellings in the liquid sheet. With further reduction in liquid rate, blind areas in the spray become apparent. The spray also becomes intermittent, or pulsating, with liquid emerging as individual streams or lamillae.

(b) on the other hand, mean drop size increases with increase in liquid flow rate up to a limit above which the mean diameter does not increase further at the rate expected, but varies slightly with further increase in flow rate. For all atomizer sizes this limit occurs at liquid rates corresponding to feed pressures of about 65 lbs/sq.inch. This is attributed to some measure of pressure-type atomization taking place due to the somewhat high feed pressures necessary to force large flow rates through the relatively small sizes of the tangential liquid ports.

Thus limits can be set within which the liquid flow is allowed to vary during the experimental programme. In all experiments, liquid rates are not allowed to fall below 3, 12 and 33 grams/second respectively; and feed pressures do not exceed 50 lbs/sq.inch.

5.3 Sprays of Low Viscosity Liquids

The low viscosity liquids used over the entire test range were water and kerosine. The recorded data shown plotted in Figures 32, 33, 35, 36 & 38 illustrate the atomization quality produced by the various atomizer sizes as a function of air to liquid ratio, for several levels of atomizing velocity, ranging from 60 to 150 m/sec, and a range of air to liquid ratio from 0.5 to 5.0.

As illustrated on these graphs, similar trends were established for all atomizer sizes, confirming the beneficial effect of increased air velocity and increased air to liquid ratio on the fineness of the spray, and indicating that the mean drop size increases rapidly for values of air to liquid ratio below about 1.5, while very little improvement can be achieved by raising this ratio above a value of about four. It can also be appreciated from comparison of the different graphs that atomization quality deteriorates with increase in atomizer size.

Since the atomizer geometry was fixed, the effects of air velocity and air/liquid ratio on drop size were not separable during the course of the experiments. In order to evaluate the separate effect of each on the sprays produced by each atomizer size, it is necessary to determine the values of mean diameter corresponding to very high levels of air/liquid ratio, where the effect of variation of ALR on SMD is negligibly small. The procedure employed here was to (a) determine the best fit curves to the data points of the plots previously outlined and (b) extrapolate to an ALR approaching infinity to obtain the asymtotic values of the mean drop size $(SMD)_\infty$ at each velocity level, as illustrated by the logarithmic plots of Figures (39a) to (39e). These graphs also suggest that slopes of the lines of constant velocity are not significantly different from their average value of about 0.986 for all atomizer sizes employed, thus providing an insight into the consistency of the experimental data.

Values of $(SMD)_\infty$ obtained with water and kerosine correlate well with the corresponding values of air velocity for all three atomizer sizes, as illustrated by Figures (40, 41 and 42), suggesting that the relationship between both quantities can be expressed by:

$$(SMD)_{\ell v} \; \alpha \; \frac{1}{V_a^{1.214}}$$

The above power index of 1.214 is in excellent agreement with that reported by Rizk and Lefebvre, and in good agreement with the finding of Kim and Marshall, but somewhat higher than the well-known value of unity proposed by Nukiyama and Tanasawa, as indicated by the correlating equations (2.3), (3.11-12) and (3.2) respectively. In turn, the quantity $(SMD_{\ell v} \times V_a^{1.214})$ were correlated to the corresponding values of (1 + 1/ALR) and, as shown on Figures (43) to (45), both quantities correlated well, suggesting that for all atomizer sizes the mean drop size of low viscosity sprays is directly proportional to (1 + 1/ALR). Hence:

$$(SMD)_{\ell v} \; \alpha \; \frac{(1 + 1/ALR)^{1.0}}{V_a^{1.21}}$$

Since an airblast atomizer loading condition is fully described by both liquid flow rate (W_ℓ) and air to liquid ratio, the effect of the liquid rate was evaluated by introducing this variable in the right hand side of the above equation and correlating the recorded values of (W_ℓ) to the corresponding quantity $(SMD_{\ell v} \times V_a^{1.21}/(1 + 1/ALR))$. This is allowable since (W_ℓ) is an independent variable and its introduction into the relationship can improve the correlation. However, calculations established that the value of the power index on the liquid flow rate is negligibly small, suggesting that it is sufficient to take into consideration only the air/liquid ratio when predicting the mean drop diameter produced by prefilming-type atomizers.

As the liquid property of surface tension (σ_ℓ) is the only significant parameter contributing to differences in mean drop size between kerosine and water under otherwise similar operating conditions, the collected data allowed the relationship between atomization quality and liquid surface tension for each atomizer size to be ascertained without recourse to liquids of diverse surface tension./ It has been well established that increase in surface tension impairs atomization quality because of its consolidating influence on the liquid interface, which resists any increase of its area. This effect is clearly shown for the three atomizer sizes by Figures (46) and (47). Conforming to a power law relationship between $(SMD)_{\ell v}$ and (σ_ℓ), the data points indicate values for the power of the surface tension term equal to 0.533, 0.588 and 0.554 for the small size, medium size and large size atomizers respectively, which are not significantly different from their average value of 0.56 for all three sizes. This result agrees well with the value of 0.5 proposed by theoretical considerations of maximum rate of growth of interface instabilities in thin liqud sheets, and is also in good agreement with experimental findings reported by Nukiyama and Tanasawa (0.5),Lefebvre et al (0.5 - 0.6), Fraser et al (0.5) and Plit (0.58), but higher than the values suggested by Wigg (0.2), Weiss and Worsham (0.34) and by Kim and Marshall (0.41).

It only remains to account for the effect of the atomizer size on the gathered data, and it is proposed that:

$$(SMD)_{\ell v} = C.\frac{\sigma_\ell^{0.56}(1 + 1/ALR)^{1.0}}{V_a^{1.21}} \,.\, D^x$$

where (D) is the prefilmer diameter measured in the plane of the atomizing edge, and the constant of proportionally (C) is a function of the parameters fixed throughout the tests, namely the atomizer geometry, the liquid density and the air density. The effect of the atomizer linear dimension on mean drop size is clearly brought out by Figures (48) to (50), which show that mean diameter increases with atomizer linear scale to the 0.426 to 0.452 power, for the water and kerosine data respectively.

Thus, the results obtained for low viscosity liquids may be summarized by the following expression:

$$(SMD)_{\ell v} = 137.8 \frac{\sigma_\ell^{0.56}}{V_a^{1.21}} \left(1 + \frac{W_\ell}{W_a}\right)^{1.0} D^{0.44} \quad .... \quad (5.1)$$

where (SMD) is microns, (V_a) is m/sec, (σ_ℓ) is dyne/cm, and (D) is millimeters.

5.4 Sprays of High Viscosity Liquid

Here, a high viscosity solution of kerosine and a soluble polymer, of Ref. (6), was used to examine the effect of liquid viscosity on atomization quality. For brevity this solution is referred to simply as "Hyvis". It has an absolute viscosity of approximately 29 centipoise at a temperature of 20^{o}C, and its density and surface tension are very close to the values for kerosine. During all tests, the liquid temperature did not vary sufficiently to have any appreciable influence on the viscosity of the liquid.

Figures 34, 37 and 51 refer to the small and the medium size atomizers respectively. They illustrate the variation in mean drop size of the hyvis sprays with air/liquid ratio for various levels of atomizing air velocity. As shown, the data points exhibit trends similar to those observed with water and kerosine sprays, recalling the beneficial effects of higher velocity and air/liquid ratio on reducing mean drop size. They show also that atomization quality improves little with increase in liquid ratio above about 4.0, but deteriorates very rapidly for ratios below about 1.50, as illustrated in Fig.(51).

Figures (51 to 54) compare the SMD's of hyvis sprays with those of kerosine, for each of the three airblast atomizer sizes. The graphs demonstrate the deleterious effect of liquid viscosity on atomization quality which is attributed to its stabilizing, or dampening, influence on the growth of instabilities created by the disruptive aerodynamic forces.

The data suggest that the increase in spray mean diameter attributed to increase in liquid viscosity, denoted as $\Delta(SMD)_{vi}$, appears to be independent of the atomizing velocity. This implication may be exemplified by plots of the data points shown on Figures (55a, 55b), in which values of $\Delta(SMD)_{vi}$, collected at different velocity levels, seem to fall on the same line for each particular atomizer size. This independence of $\Delta(SMD)_{vi}$ on velocity was confirmed for the range of conditions under consideration here, when the recorded values of $\Delta(SMD)_{vi}$ were treated in the same manner as the mean drop size data of the low liquid viscosity sprays. This may be illustrated by Fig.(56) in which the data points reveal negligibly small values for the power index of the velocity term, inferring that the mean drop size of sprays can be predicted as the sum of the two independent terms, namely $(SMD)_{\ell v}$ and $\Delta(SMD)_{vi}$, i.e.

$$SMD = (SMD)_{\ell v} + \Delta(SMD)_{vi} \qquad ..... (5.2)$$

where $(SMD)_{\ell v}$ is given by expression (5.1).

$\Delta(SMD)_{vi}$ measurements obtained with the small and medium size atomizers correlate well with corresponding values of the loading group (1 + 1/ALR), as shown in Figures (57a) and (57b) respectively, thus confirming a power law relationship between both quantities, and suggesting that $\Delta(SMD)_{vi}$ increases with the 1.247 to 1.144 power of (1 + 1/ALR). Within acceptable experimental limits it is reasonable to consider an average value for the different atomizer sizes of 1.2, in which case the proportionality constants are 12.0 for the small atomizer having a prefilmer diameter (D) of 19.05 mm, and equal to 16.8 for the medium airblast atomizer having D = 38.10 millimeters, as shown in Fig.(58).

Thus, $\Delta(SDM)_{vi} = 12.0 \quad (1 + 1/ALR)^{1.2}$ for D = 19.05 mm;

and $\Delta(SMD)_{vi} = 16.8 \quad (1 + 1/ALR)^{1.2}$ for D = 38.10 mm.

The experimental evidence on the affect of D suggests that $\Delta(SMD)_{vi}$ increases with atomizer linear dimension to the power 0.48. We may therefore write:-

$$\Delta(SMD)_{vi} = C_2 \eta_\ell^d \ (1 + 1/ALR)^{1.2} \ D^{0.48} \qquad ..... (5.3)$$

Substitution in expressions (5.1) and (5.2), the correlating equation becomes:

$$SMD = C_1 \frac{\sigma_\ell^{0.56}}{V_a^{1.21}} (1 + 1/ALR)^{1.0} \ D^{0.44} + C_2 \eta_\ell^d \ (1 + 1/ALR)^{1.2} \ D^{0.48} \qquad ..... (5.4)$$

where the constants (C_1) and (C_2) are functions of atomizer geometry, liquid density (ρ_ℓ), and air density (ρ_a). The absolute viscosity (η_ℓ) is 29 centipoises, and (d) is a power index. For the atomizer geometry employed, (C_1) is 137.8

for the density conditions of equation (5.1). The quantities (C_2) and (d) can be determined by applying the method of dimensional analysis, as proposed in Chapter (6).

It is of interest at this stage to compare expression (5.4) with the prediction equations for SMD proposed in other works, namely equations (2.3), (3.14) and (3.16), due to Rizk, Rizkalla, and Lorenzetto respectively. It is clear that the effect of air to liquid ratio on atomization quality is less pronounced with prefilmer type airblast atomizer than with airblast systems employing discrete, or plain, liquid jets. In this context it can be inferred that in prefilming systems the spray mean diameter is approximately directly proportional to (1 + 1/ALR), while with plain-jet airblast atomizers the power on this term can be as high as 1.8. Another implication is that air/liquid ratio has similar effects on the atomization quality of both low and high viscosity sprays, suggesting that Rizkalla's equation (3.14) over-estimates this effect on the mean diameter "viscosity" term.

5.5 Comparison Between the Present Results on the Effect of Atomizer Scale with Other Work

Before applying dimensional analysis to the experimental data, it is informative to first examine the results already obtained concerning the special influence of atomizer linear dimension on SMD in the light of the findings reported in other relevant works dealing with the influence of (a) film thickness, and (b) atomizer scale, as proposed by Wigg, Ref.(95), and by Kim and Marshall, Ref.(40).

The experimental evidence suggests here that the mean drop size of sprays achieved with prefilming airblast atomizers increases with the 0.45 power of the atomizer linear dimension to a reasonable degree of approximation.

5.5.1 Comparison of Film Thickness

The above result is in very good agreement with findings reported in other investigations which examined the influence of film thickness on spray atomization quality.

Briefly, the literature tells us that the occurence of interfacial disturbances having maximum growth rate is considered the most likely event leading to the formation of drops. However, the exact manner in which sprays are so formed is not yet fully understood. In this respect, visual studies indicate that disintegration of the sheets themselves is exceedingly complex, the following three mechanisms being the most widely accepted possibilities:

(a) the airstream undercuts an interfacial wave and a round, open-ended bubble begins to form which is then drawn out into an attenuating ligament with a thicker tip that eventually breaks off to form a large drop, while the ligament breaks down according to theories of varicose instability; or

(b) a large amplitude wave tends to steepen at its front and curl over under the action of the airflow, forming a breaking or a rolling wave, which is drawn into thin laminae or ligaments that subsequently break up into a shower of drops; or

(c) disintegration of the parent sheet can also occur directly through sinuous and dilation aerodynamic wave instabilities, in which multiples of half or full wavelengths of the sheet are torn off into the airstream to disintegrate into drops.

In spite of the aforementioned uncertainties regarding which mechanism is most dominant, theoretical and experimental work has now established a distinct link between sheet thickness and spray SMD. For instance, the analyses of York, Stubbs and Tek, Ref.(98); Hagerty and Shea, Ref.(32), and Dombrowski and Johns, Ref.(19), all suggest that mean drop diameter is most probably proportional to the square root of the film thickness. In addition, the elegant photographic studies of film disintegration, as carried out by Fraser, Dombrowski and Routley, Ref.(23), show that, for sheets breaking down through the formation of unstable ligaments, the diameter of the latter depends mainly on the sheet thickness. Recently, the investigation of Rizk and Lefebvre, Ref.(78) is notable, in that by using a specially designed airblast system they succeeded in correlating the thicknesses of very thin flat sheets, subjected on both sides to coflowing high velocity airstreams, to the mean drop sizes produced over a very wide range of conditions. They reported that SMD is proportional to the 0.4 power of the sheet thickness for low viscosity liquids, but slightly higher for liquids of high viscosity. (Note: The SMD viscosity term in their equation (2.3) increases with the 0.55 power of the sheet thickness).

Figure (59) compares the findings of the various investigations, and clearly illustrates the remarkably good agreement between the present results on the effect of atomizer linear dimension on mean drop diameter and that previously established for liquid film thickness. Hence, the validity of the hypothesis made earlier, in Chapter 4, that atomizer size affects atomization quality mainly through its influence on film thickness is substantiated.

However, as illustrated by the same graph in Fig.(59) the present results disagree with the findings of certain prominent investigators, namely Wigg, Ref.(95, 96) and Kim and Marshall, (Ref.40). The reasons for these discrepancies are discussed below.

5.5.2 Comparison with Wigg, (Ref.95, 96).

In the important work of Wigg, there appears to be some ambiguity regarding the effect of atomizer scale on mean drop size. On the one hand, it was concluded in Wigg's publications that atomizer scale has insignificant influence on the mean drop diameter, proposing that MMD is proportional to the 0.1 power of the atomizer linear dimension (h). On the other hand, Wigg also stated that atomizer scale would affect the mean drop size through its influence on the liquid flow rate (W), which, substituting for $W \alpha h^2$ in his MMD prediction equation (3.5), would imply that mean drop diameter increases as the 0.3 power of the atomizer size. With either interpretation, both investigations differ as to the degree of influence of the atomizer size.

It is considered that this discrepancy may be attributed to the considerable differences in spray sampling distance, combined with substantial differences in the mean drop-size assessment techniques employed in the two studies.

As mentioned in Ref.(95), sprays were sampled at distances that usually ranged from 4 to 8 feet, and sometimes as far as 15 feet or even 30 feet from the atomizer. Moreover, droplets below 30 microns in diameter were ignored. Hence, knowing the tendency of droplets of different sizes in a given spray to discresionarily exist at different distances from the airblast atomizer, as noted here, and also from the fact that airblast systems are renowned for their tendency to produce fine sprays, it is not difficult to appreciate that Wigg's method indicated sprays as having a more mono-disperse character, biased towards the larger droplet sizes, than had the samples been obtained at closer distances to the atomizer.

This also explains why a less significant role was assigned to the air/liquid group (1 + 1/ALR) which was originally proposed by Wigg himself, in his mean drop diameter prediction formula (3.5), in comparison with all other prediction equations employing the same group, namely the expressions due to Rizkalla, Lorenzetto, Rizk and the present equation (5.4).

5.5.3 Comparison with Kim and Marshall, (Ref.40)

Kim and Marshall reported that mean drop diameter decreases with atomizer air passage cross-sectional area to the 0.36 power, and they introduced this result into their MMD prediction formula (3.11). This implies that the mean drop size decreases with the 0.72 power of the atomizer linear dimension, in contradiction to the findings of the present investigation. Although the results of both investigations are so obviously at variance, the probable reason leading to this disagreement can be identified.

According to Ref.(40) the airblast atomizer employed embodied some design flexibility by allowing the airflow discharge area and the liquid annulus film thickness to be varied. It is clear from their report that, when increasing the cross-sectional area, the film thickness increased as well. However, the film thickness was not increased in proportion to the atomizer linear dimension. In fact, the sheet thickness was reduced far below that required to maintain geometrical similarity.

Thus, in their experiments, any increase in mean drop size to be expected from increase in film thickness was overshadowed by a larger reduction in mean drop diameter, caused by a comparatively greater increase in the air/liquid ratio, combined with an increase in the amount of exposure of the liquid sheet to the airflow, due to the increase in area of contact, accomplished by increasing the diameter of the liquid annulus.

In short, when varying the film thickness, other factors were varied as well which had conflicting effects on the mean drop diameter. Consequently, it is not surprising that the influence of atomizer size was misinterpreted.

5.6 Discharge Characteristics of Liquid Swirlers

Water flow rates were measured over the range of injection pressure from 10to 100 psig, for various discharge areas of the 6-slot swirlers, having offset diameters of 12.7, 25.4 and 50.8 mm, and a slot length/width ratio of 7:1. Similar measurements were also obtained for kerosine and for swirlers having values of the ratio equal to 5.5:1 and 4:1. With each swirler the ensuing jets were constantly examined and photographed at various pressures for any sign of distortion in the discharge pattern formed against the perspex backwall, in order to ensure that liquid discharge occured only through the swirler slots, as illustrated by Plates (12 and (13).

The measurements obtained indicated that, for the swirlers under consideration, the offset diameter has no significant effect on the swirler discharge capacity, as shown by Figs. (60a) and (60b), in which the recorded data for water and kerosine appear to lie on the same graph. The test data also confirmed the linear relationship between the rate of discharge and the square root of the pressure difference, for the square-section, tangential, multiple-channel arrangement.

Figure (61) presents values of the coefficient of discharge plotted against the corresponding values of the flow

Reynolds number. Values of C_D were calculated from the simple orifice equation, $C_D = Q/(2\Delta P/\rho)^{\frac{1}{2}}$, and Reynolds numbers were calculated from the mean velocity of the flow and the physical cross-sectional width of the discharge channels, that is, $Re = Q/A_s w N_s$. As illustrated, almost all the experimental data points lay within a narrow band of about ± 5%, around a value of C_D equal to 0.65. Similar results were obtained with the 25.4 mm diameter swirlers having 3, 6 and 9 discharge channels, as shown on Fig.(62). Thus, for all practical design purposes, the coefficient of discharge may be assumed equal to 0.65, over the range of Reynolds number from about 3200 to 28000.

Figure (63) shows that swirler flow number correlates with the total discharge area, which suggests that values of flow number may be calculated from the following simple expression:

$$FN = 1.908 \frac{A_s}{\sqrt{\rho_\ell}}$$

where FN is U.K. gallons/hour/(psi)$^{\frac{1}{2}}$, A_s is in mm^2, and ρ_ℓ is in g/cc.

It should be noted that the present result of $C_D = 0.65$ is smaller than the value proposed for the coefficient of discharge of single cylindrical orifices, the latter being in the order of about 0.76 on average, as proposed by the modified equation (4.3) of Asihmin. This is to be expected, since, with swirlers, part of the available pressure energy is used to swirl the liquid across the cup, thereby creating a back-pressure against the submerged slot exits.

CHAPTER 6

Dimensional Analysis of the Spray Data and Discussion of the Results

1. Dimensional Analysis.
2. Comparison Between the Experimental Data and Equation (6.5).
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CHAPTER 6

Dimensional Analysis of the Spray Data and Discussion of the Results

It is desired to obtain an equation allowing the Sauter mean diameter of a given spray to be predicted accurately over a wide range of atomizer sizes and specified conditions of the significant variables involved in the atomization process. Since certain relevant factors were not included in the experimental tests, namely the atomizing-air density ρ_a and the liquid density ρ_ℓ, these gaps are filled here by applying the method of dimensional analysis to the experimental results previously described. The influence of airblast atomizer geometry is quantified in the light of the data obtained here, and of those reported in other publications also. The SMD prediction formula thus obtained is shown to be reasonably accurate in predicting the drop-sizes reported in various investigations, over a wide range of operating conditions.

6.1. Dimensional Analysis

Taking into account all the variables which have a significant effect on the airblast atomization process, the mean drop size of sprays produced by a fixed, prefilmer-cup, airblast atomizer can be expressed as:-

$$SMD = f_1(V_a, \rho_a, W_a, W_\ell, \sigma_\ell, \rho_\ell, \eta_\ell, D, \phi)$$

Using the dimensionless groups most meaningful to spray formation, the previous statement can be written as:

$$SMD = f_2\left[\left(\frac{\rho_a V_a{}^2 D}{\sigma_\ell}\right), \left(1 + \frac{W_\ell}{W_a}\right), \left(\frac{\rho_\ell}{\rho_a}\right), \left(\frac{\rho_\ell V_a{}^2 D}{\sigma_\ell}\right), \left(\frac{\rho_\ell V_a D}{\eta}\right), \phi\right] \quad \text{..... (6.1)}$$

where: $\frac{\rho_a V_a^2 D}{\sigma_\ell}$ = Weber number, referred to airflow properties = $(We)_a$;

$\frac{\rho_\ell V_a^2 D}{\sigma_\ell}$ = Weber number, referred to liquid properties = $(We)_\ell$;

$\frac{\rho_\ell V_a^2 D}{\eta_\ell}$ = Reynolds number, referred to liquid properties = $(Re)_\ell$;

$\frac{W_a}{W_\ell}$ = Air to liquid mass flow ratio = ALR;

$\frac{\rho_\ell}{\rho_a}$ = Liquid to air density ratio;

and, ϕ = Dimensionless quantity, function of the airblast atomizer geometry only.

The quantity, ϕ, shall be referred to as the "atomizer spray-fineness factor"; and, being constant for geometrically similar atomizers, its influence on SMD will be deferred, until sub-chapter (6.5).

Use of $(We)_a$ was an almost automatic choice, since it is basically an expression of the ratio of the disrupting aerodynamic force to the consolidating surface tension force. Its influence on the atomization process is well established, as evidenced by the various relationships proposed between $(We)_a$ and the maximum rate of growth of interfacial instabilities and drop survival diameter.

In regard to the effect of liquid viscosity on mean drop size, this may be allowed for by applying a correction factor to $(We)_a$, such as $(1 + K_{vi})$. Here, (K_{vi}) is a dimensionless group representing the influence of liquid viscosity in relation to that of the liquid surface tension, such that its magnitude diminishes with reduction in liquid viscosity. Similarly, the effect of liquid density can be accounted for in (K_{vi}). Hence a suitable form for this parameter would be the product of the powers of $(Re)_\ell$ $(We)_\ell$, as follows:

$$K_{vi} \; \alpha (Re)_\ell^d \; . \; (We)_\ell^e$$

For the case when d = 2e, the parameter (K_{vi}) becomes a function of Ohnesorge Number only, that is $Z_\ell = (\eta_\ell^2/\rho_\ell \sigma_\ell D)^{\frac{1}{2}}$, which is an expression of the relative influence of the shear forces to the capillarity and inertia forces.

Use of the loading group ($1+W_\ell/W_a$) is self explanatory, since it represents well the experimental data, and also because its value approaches unity as the air to liquid ratio increases. Another reason for using this group is because it appears to have an important role in determining the mean drop size, as proposed in the theory of Wigg.

From analysis of the experimental data it became obvious that a suitable form of the equation for predicting the mean drop size would be one in which the SMD is given as the sum of the two terms, $(SMD)_{\ell v}$ and $(\Delta SMD)_{vi}$ as previously defined. It was also found that the influence of ALR on SMD appears to be somewhat different when the effect of liquid viscosity is significant. Accordingly, the following dimensionless form of equation is proposed:

$$\frac{SMD}{D} = f_3 \left[(We)_a^a,\ \left(1 + \frac{1}{ALR}\right)^{b_1},\ \left(\frac{\rho_\ell}{\rho_a}\right)^c \right]$$

$$+ f_4 \left[(We)_a^a,\ \left(1 + \frac{1}{ALR}\right)^{b_2},\ (We)_\ell^d,\ (Re)_\ell^e \right] \quad \ldots\ (6.2)$$

Or,

$$\frac{SMD}{D} = \frac{(SMD)_{\ell v}}{D} + \frac{(\Delta SMD)_{vi}}{D} \quad ;$$

$$\frac{(SMD)_{\ell v}}{D} = A \left(\frac{\rho_a V_a^2 D}{\sigma}\right)^a \left(1 + \frac{W_\ell}{W_a}\right)^{b_1} \left(\frac{\rho_\ell}{\rho_a}\right)^c = f_3; \quad \ldots(6.3a)$$

$$\text{and,}\quad \frac{(\Delta SMD)_{vi}}{D} = B\left(\frac{\rho_a V_a{}^2 D}{\sigma_\ell}\right)^{a} \left(1 + \frac{W_\ell}{W_a}\right)^{b_2} \left(\frac{\rho_\ell V_a{}^2 D}{\sigma_\ell}\right)^{d} \left(\frac{\rho_\ell V_a D}{\eta_\ell}\right)^{e}$$

$$\equiv f_3 \qquad \ldots. \ (6.4\,a)$$

where A and B are constant for any given atomizer geometry.

To obtain good agreement with the experimental data the following values must be assigned in equations (6.3a):

$a = -0.6$, and $b_1 = 1.0$

$$\therefore \quad \frac{(SMD)_{\ell v}}{D} = A\left(\frac{\sigma_\ell}{\rho_a V_a{}^2 D}\right)^{0.6} \left(1 + \frac{1}{ALR}\right)^{1.0} \cdot \left(\frac{\rho_\ell}{\rho_a}\right)^{c}$$

$$\ldots. \ (6.3b)$$

Similarly, in equation (6,4a) the following values must also be assigned:

$a = -0.6$, and $b_2 = 1.2$

also, the power of the velocity term $= 0 = 2a + 2d + e$,
and, the power of the diameter term $= -0.5 = a + d + e$.
Solving for values of (d) and (e) we obtain:

$d = 1.1$, and $e = -1.0$

Therefore,

$$\frac{(\Delta SMD)_{vi}}{D} \; \alpha \; \frac{\rho_a^{-0.6}\,\rho_\ell^{0.1}\,\eta_\ell^{1.0}}{\sigma_\ell^{0.5}\;D^{0.5}}$$

$$\alpha \left[\frac{\rho_\ell}{\rho_a}\right]^{0.1} \cdot \left[\frac{\eta_\ell}{(\sigma_\ell \rho_a D)^{0.5}}\right]^{1.0} \qquad \ldots. \; (6.4b)$$

$$\text{hence,} \quad \frac{(\Delta SMD)_{vi}}{D} = B \left[\frac{\rho_\ell}{\rho_a}\right]^{0.1} \left[\frac{\eta_\ell^2}{\sigma_\ell \rho_a D}\right]^{0.5} \left[1 + \frac{1}{ALR}\right]^{1.2}$$

$$\ldots. \; (6.4c)$$

where, $Z_{\ell,a} = \eta_\ell/(\sigma_\ell \rho_a D)^{0.5}$ = Modified Ohnesorge Number

Some important implications can be drawn from the previous analysis. Firstly, expression (6.4b) indicates that a minimum drop size exists, below which the mean spray diameter cannot fall no matter how high the atomizing-air velocity may be. Further, this minimum size depends to a very small degree on the liquid density, ρ_ℓ, and is mainly directly proportional to a modified Ohnesorge Number ($Z_{\ell,a}$) expressed in terms of the liquid absolute viscosity, liquid surface tension, atomizing-air density and the atomizer linear dimension. Furthermore, since the liquid density and absolute viscosity are two physical properties of the liquid that are independent of each another, it follows that the role assigned to liquid density in affecting the mean drop size must be the same regardless of the order of influence of viscosity, implying that the magnitude of the exponential power (c) in equation (6.3b) should also be very small as proposed in expression (6.4b).

Consequently, the important implication to be drawn regarding the effect of the atomizing-air density is that for all liquids, whether the influence of liquid viscosity on the atomization quality is significant or negligible, the mean drop size appears to decrease with the 0.6 power of the atomizing-air density.

It is now necessary to compare these findings with the experimental results of other investigators who actually varied the atomizing-air density, since all the present experimental data were obtained with airflows at very near ambient atmospheric conditions. We find that the previous conclusion is in excellent agreement with the findings of Godbole (0.6), and of Weiss and Worsham (0.7), and also in fair agreement with that of Rizk and Lefebvre (0.85), (the value of the power of reciprocal ρ_a being given in paranthesis), but much lower than that predicted by Rizkalla (1.0).

This discrepancy with Rizkalla can be explained. Figures (68a) and (68b) show Rizkalla's correlation of the SMD of water and kerosine sprays with the atomizing-air pressure respectively, as given in Ref. (79). According to Ref. (79), the data were obtained at a fixed level of atomizing-air velocity and liquid mass flow-rate. It follows that the air mass flow rate and, therefore, the air/liquid ratio were allowed to vary with air pressure. Naturally, the result of this must be that the correlations reported in Ref. (79) overestimate the influence of air pressure on SMD, since they include the effect of increasing air/liquid ratio, in addition to the effect of the increasing air density.

Refering all recorded values of SMD to a reference ALR and atomizing-air velocity, by application of the relationship SMD $\alpha (1+1/ALR)/V_a^{1.2}$, the corrected values of the mean drop sizes thus obtained are plotted against the corresponding values of atomizing-air pressure, are shown on the same graphs of Figs. (64a) and (64b). They show that the exponent on the air density term is equal to -0.75 and -0.68 for water and kerosine sprays respectively, with an average value of -0.72.

The experimental results of the separate investigations have therefore been reasonably reconciled, suggesting an average value of about 0.70 for the exponent on the air density. Taking into consideration the value of 0.6 proposed by the present dimensional analysis, it follows that a value of 0.10 can be assigned to the exponent (c) confirming the inference previously drawn from analysis of the SMD viscosity term.

It is concluded therefore, that liquid density, or liquid/air density ratio, has a very limited influence on the atomization quality of airblast sprays, the mean drop size increasing with $(\text{density})^{0.1}$. The reason for this is most probably due to the very small effect of gravity forces on the growth of interfacial protuberances in thin sheets in comparison with the influences of the aerodynamic, shear and surface forces. The above result is in broad agreement with the photographic findings of Fraser-Eisenklam (Ref. 24), and Rizk-Lefebvre (Ref. 78), showing that, for thin liquid sheets, subjected to high velocity air, liquid density has no appreciable effect on the mode of disintegration, or on the size of the ligaments formed.

The fact remains that the mean drop-size prediction equations of other investigators give values for the liquid density exponent that vary widely, from, say, the value of -0.5 suggested by Nukiyama-Tanasawa to +0.75 suggested by Rizkalla. This is probably due to the fact that in the process of reconciling experimental data covering a wide range of variation of several independent variables, the particular variable (or variables) having only a limited effect on the function can assume a range of exponents without significantly impairing the accuracy of the overall correlation. This is certainly more likely if the experimental range over which the variable was allowed to vary was particularly narrow, as in the case of the density for the commonly used liquids. The available range is normally not more than 1.3 fold, as outlined in the previous section (4.2).

Taking all the previous results into consideration, and with values of the quantities (A) and (B) determined from the recorded data, the Sauter Mean Diameter may be expressed as:

$$SMD \times 10^3 = 73 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(\frac{\sigma_\ell}{\rho_a V_a^{2}}\right)^{0.6} \left(1 + \frac{W_\ell}{W_a}\right)^{1.0} D^{0.4}$$

$$+ 0.3 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(\frac{\eta_\ell}{\sqrt{\rho_a \sigma_\ell}}\right) \left(1 + \frac{W_\ell}{W_a}\right)^{1.2} D^{0.5} \quad \ldots. \ (6.5a)$$

In view of the narrow range of liquid density normally encountered in practice, especially with the hydrocarbon fuels used in gas turbines, the effect of liquid density becomes negligibly small and can be ignored in favour of a somewhat simpler form

$$SMD \times 10^3 = 73 \left(\frac{\sigma_\ell}{\rho_a V_a^{2}}\right)^{0.6} \left(1 + \frac{W_\ell}{W_a}\right)^{1.0} D^{0.4}$$

$$+ 0.3 \left(\frac{\eta_\ell}{\sqrt{\rho_a \sigma_\ell}}\right)^{1.0} \left(1 + \frac{W_\ell}{W_a}\right)^{1.2} D^{0.5} \quad \ldots.. \ (6.5b)$$

The above equations are dimensionally consistent. Further simplification is possible if we ignore the small differences in the effects of atomizer linear dimension and the air/liquid ratio as assigned to the low viscosity and high viscosity terms of the equations, and combine each variable into one average index, as illustrated below:

$$\frac{SMD}{D} = 0.063 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(\frac{\sigma_\ell}{\rho_a V_a^{2} D}\right)^{0.55} \left(1 + \frac{W_\ell}{W_a}\right)^{1.1} \left(1 + \frac{\eta_\ell V_a}{240 \sigma_\ell}\right)^{1.0}$$

$$\ldots. \ (6.5c)$$

which may be re-written as:

$$\frac{SMD}{D} = 0.063 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \frac{(1+f)^{1.1}(1+0.004Ca)^{1.0}}{(We)_a^{0.55}} \ ; \quad \ldots. \ (6.5d)$$

where (f) is the fuel/air ratio, and $\frac{\eta_\ell V_a}{\sigma_\ell}$ is the Capillarity Number (Ca) a dimensionless expression of the ratio of the shear to surface forces. The Capillarity Number has been successfully correlated to the onset of atomization of liquid films, as suggested by van Rossum (Ref. 82), and by Zuber (Ref. 99), to indicate the air velocity below which no atomization occurs.

In the above expressions the effect of the Weber Number, $(\rho_a V_a^2 D/\sigma_\ell)$, on mean drop size is clearly brought out, suggesting that the mean diameter is approximately inversely proportional to the square root of the Weber Number, in good agreement with the theories of growth of interfacial instabilities. Alternatively, this also implies that the mean drop size of spray increases as the 0.45 power of the atomizer linear dimension, which is in good agreement with the experimental measurements achieved. In addition, it is easily appreciated from expressions (6.5d) that the level of inaccuracy in predicting the SMD of sprays that comes from neglecting the effect of liquid viscosity, is directly proportional to the Capillarity Number. For values of Ca <12 it is suggested that the error should not exceed 5 percent. Thus for kerosine sprays, at the levels of atomizing velocity encountered in gas turbines, where Ca is about 4.0, the effect of viscosity can safely by ignored when predicting SMD.

6.2. Comparison between the Experimental Data and Equation (6.5)

The ability of the derived formula to predict values of mean drop size of sprays produced by the various sizes of atomizers employing air flows at near-atmospheric pressure is illustrated by the scatter diagrams of Figures (65a) and (65b), for sprays of low-viscosity and high-viscosity respectively.

The experimental data-points for water sprays show a small tendency towards forming a separate line implying that a slightly higher value was assigned to the influence of liquid surface tension in the drop-size prediction equation. The high viscosity data points usually show a measure of scatter that is larger than that obtained with water and kerosine. This is due to the nature of the tests, in that higher levels of experimental error are encountered when determining values of $(\Delta SMD)_{vi}$ since each value involves the difference of two drop-size measurements.

With the exception of the lowest and higher ends of the SMD range on the scatter diagrams, the agreement is very good between the predicted and the measured mean drop sizes. In general, the accuracy of prediction is high for the range of mean drop sizes between 25 and 125 microns, where almost all of the predicted values lie within ±10% of the experimental data, and improves with atomizing air velocities higher than 60m/sec.

6.3. Comparison of Equation (6.5) with Existing Formula

The predicted effects of various factors on mean drop size have already been compared with the findings of other investigators and discussed in some detail. In this context reference should be made to Chapter (5) for the effect of the atomizer linear scale. From comparison of the derived Equation (6.5) with other well known prediction formulae further aspects were highlighted. The following are noteworthy.

(a) Equation (6.5) has a form similar to the expressions proposed by Nukiyama-Tanasawa (3.2) Rizkalla (3.14), Lorenzetto (3.16), and Rizk (2.3). These suggest, when predicting the SMD of a spray, that the effect of liquid viscosity can be treated independently to that of air velocity, and that a minimum mean diameter must exist regardless of the level of atomizing velocity. In this respect Equation (6.5) differs from that proposed by Wigg (3.5).

(b) The Nukiyama-Tanasawa equation implies that liquid viscosity has practically no effect on mean drop size for values of the air/liquid volumetric ratio above 5000, but Equation (6.5) assigns a higher influence to viscosity and proposes a definite effect of this liquid property on atomization quality, no matter how high the air/liquid ratio may be. This disagreement is probably due to the large differences in the drop-size measurement techniques employed, particularly in regard to the collection and evaporation losses of small diameter drops that is likely to occur with the method of Nukiyama-Tanasawa. This may account for their failure to detect the differences in mean drop size caused by changes in viscosity at high air/liquid ratios where drop diameters are usually very small.

(c) In spite of the similarity with the Lorenzetto Equation and with that of Rizk, it should be noted that in their equation the atomizing air density has no effect at all on the increase in mean drop size attributed to liquid viscosity, viz. $(\Delta SMD)_{vi}$. Equation (6.5) on the other hand asserts that increase in air density, while having a significantly beneficial effect on the quality of sprays of low viscosity liquids, also has a nearly equal effect on reducing the deletrious influence of viscosity on atomization quality.

Here, the disagreement with Lorenzetto was attributed to his neglect of the air density term in his dimensional analysis of his data collected at near atmospheric pressure condition. According to Ref. (54), it appears that Lorenzetto only took into consideration the influence of liquid density in his analysis of the mean drop size viscosity term $\Delta(SMD)_{vi}$.

In the case of Rizk (Ref. 77), the disagreement is considered as most likely due to the comparatively low level of viscosity used in the course of his experiments conducted at high atomizing air pressure conditions, namely a viscosity level of 17 centipoises.

(d) On the other hand, the Rizkalla Equation proposes an influence of air density on high viscosity sprays similar to that given by Equation (6.5), although there is no clear evidence in his original work, Reference (79), of how he arrived to this result.

(e) The equation due to Wigg (3.5) appears to over-estimate the influence of viscosity on mean drop size, in comparison with Equation (6.5), and also with all the aforementioned prediction expressions. This difference with Wigg is probably due to differences in the range of variables examined and to the substantial differences in spray sampling and sizing techniques.

(f) All equations generally give mean drop sizes that are larger than those predicted by Equation (6.5), mainly because in deriving the present formula all SMD measurements were conducted very close to the fuel nozzle at pre-established positions along the sprays having minimum drop diameters, while in most of the other investigations droplet measurements were made at considerable distances downstream of the nozzle. Appreciable growth of SMD is known to occur over large distances downstream of airblast atomizers, as reported by Fraser and Eisenklam (Ref. 24), Shapiro et al (Ref. 84), and by Mani (Ref. 58). The latter from theoretical and experimental considerations of droplet coalescence and deceleration, suggested that the mean drop diameter is proportional to the cube root of the downstream distance, over the range of distance from 1 to 10 feet.

Another reason for discripancies in the prediction of mean drop size may be attributed to differences in design of the airblast systems employed.

6.4. Correlation of the Experimental Data of Other Investigators by Equation (6.5):

As a result of the previous comparison it became clearly desirable to assess the ability of Equation (6.5) to correlate the recorded values of mean drop size for prefilming type airblast atomizers obtained by other investigators, notably: Wigg; Lefebvre et al; Rizkalla; and, Rizk.

(a) Wigg, Ref. (95 and 96):

Sprays were produced by three scaled-up N.G.T.E. atomizers of Fig. (2a) employing a single, high-velocity airstream to strike a thin liquid annular disc perpendicular to its plane. Spray samples were usually collected at distances of 4 to 8 feet from the atomizers.

Figure (66) shows the ability of Equation (6.5) to predict the Mass Median Diameter of water sprays tabulated in Ref. (96), assuming that for the given range of mean diameter the MMD is approximately equal to 1.2 times the SMD. As illustrated, the agreement is fair up to mean diameters of about 100 microns if a constant quantity of about 4.5 times higher than the quantity A=0.145 of Equation (6.5) is used, in order to obtain a reasonable fit to the data points.

(b) Lefebvre and Miller, Ref.(48):

Figure (67) illustrates the ability of the prediction equation to correlate the experimental data reported by Lefebvre and Miller for water and kerosine sprays produced by their atomizer shown in Fig. (4a). They sampled their sprays at a distance of 8 feet on oxide-coated slides. Again, the agreement is reasonably good provided that the predicted values are multiplied by a factor of about 2.90, as indicated on Figure (67).

(c) Rizkalla, Ref.(79):

Figure (68a) compares the mean drop sizes measured by Rizkalla with values predicted by Equation (6.5) for sprays of water and of kerosine; and, Figure (68b) is the same, but for several higher viscosity liquids. As illustrated, both measurements and predictions correlated remarkably well for the low and high viscosity sprays, although data points corresponding to the highest viscosity level of about 76.5 centipoise tend to form a separate line.

The graphs indicate that Rizkalla's measurements are always 1.65 times greater than predicted, in spite of the fact that both investigations employed atomizers that were very similar, and used the same technique of light-scattering and spray sampling at comparatively similar distances from the atomizer. This marked difference is attributed to what might have appeared at the time as minor modifications incorporated into the original air-blast atomizer design, as detailed in Chapter (4). Briefly, the principle aim of the modification was to ensure that the pintle air passage inside the atomizer always converged towards the atomizing lip in order to avoid problems associated with flow separation, while in the configuration employed by Rizkalla the pintle passage diverged towards the lip. The effect of this was studied by conducting a few measurements with water sprays produced by the medium size atomizer testing the configuration of Ref. (79), at flow conditions that were comparable to those reported by Rizkalla. The greatly improved atomization quality achieved with the present geometry underlines the importance of optimizing the air passage shapes in order to achieve the maximum physical contact between the interacting fluids. This suggests that the quantities (A) and (B) in the SMD prediction formula are very sensitive to atomizer geometry.

(d) Rizk Ref. (77):

Rizk used a flat-sheet atomizer as shown on Fig. (5), and employed the light-scattering technique, sampling his sprays at a distance of 14 centimeters from the airblast nozzle.

Once more the predictions correlated well with the measured mean drop sizes for sprays produced over a wide range of conditions, as illustrated by Fig. (69a) for water and kerosine, and by Fig. (69b) for several solutions of different viscosities of up to 44 centipoises. As shown, the calculated mean diameters were always 1.5 times smaller than the recorded sizes produced with a liquid slit width of 0.0089 centimeters of the atomizer.

It is perhaps worth noting on Fig. (69b) that the data points corresponding to a high viscosity level of about 76.5 centipoises again tended to form a separate line, as previously observed in Fig. (68b) with Rizkalla's data. An explanation for this may be that the role assigned to liquid viscosity, that is independent of atomizing velocity, does not hold good beyond a certain range. Or perhaps it may be attributed to the non-newtonian behaviour of liquids, such as kerosine solutions containing a high percentage of the high-viscosity polymer (Hyvis), of which little is known about its effect on drop sizes. In fact, subsequent viscosity measurements, using a Brockwell rotating-cylinder viscometer, confirmed a distinct non-newtonian characteristic for kerosine-hyvis solutions having a static viscosity level of about 79 centipoise, where the viscosity level dropped to about 66 centipoise at 30 r.p.m.

6.5. Effect of the Airblast Atomizer Geometry

In the previous section it was established that airblast atomizer design can have an appreciable influence on the quality of the sprays produced. However, this result is not fully supported by the drop-size data reported in other investigations, since in many of the cases considered the sprays were sampled at large distances from the atomizer and mean drop diameters were assessed by different techniques which could have contributed substantially to the observed differences in mean drop size. Furthermore, some investigators expressed the opinion that differences in atomizer design should not cause significant changes in spray quality, and proposed that their prediction equations for mean drop size were applicable to a wide variety of airblast atomizer design.

Hence, in order to further ascertain that atomizer geometry has a distinct influence on spray mean diameter, it was considered desirable to obtain first-hand information on the quality of sprays produced by another stationary prefilming cup airblast atomizer of a somewhat different geometry to that due of Lefebvre. Consequently, the Bryan Atomizer of Ref. (8), illustrated in Fig. (6) was used to spray water. The SMD variation with distance was first established, as shown in Fig. (70a). Subsequently mean drop-size measurements were obtained over the usual ranges of air velocity and air/liquid ratio, at the position in the sprays corresponding to minimum mean diameter. As expected, the recorded drop sizes correlated well with predictions of Equation (6.5), as illustrated by the scatter diagram of Fig. (70b). This graph also shows that measured values were always about 1.5 times greater than predicted values.

This difference in mean diameter is attributed to the differences in prefilmer shape and shroud-to-pintle airflow ratio employed in the Bryan and the Lefebvre airblast system. Without going into details, the difference in prefilmer divergence can result in different degrees of film-tearing by the primary airstream through its effect on the air passage convergence, and may also cause different modes of film disintegration to take place through its effect on encouraging the liquid sheet to separate from the cup surface and become suspended in the pintle airflow. In addition, difference in shroud to pintle flow ratio is likely to cause different proportions of primary and secondary atomization. Since it remains that both airblast systems are not basically different, it becomes quite clear that airblast atomizer design has a significant effect on the mean drop sizes achieved.

Finally, in view of the good correlations acknowledged between the predictions of Equation (6.5) and the corresponding measured values, covering a wide range of conditions, and obtained by several investigators employing airblast atomizers of varied geometry and using different measuring techniques, it is proposed that the effect of atomizer design can be accounted for in the SMD prediction formula by means of a spray fineness factor (ϕ), which expresses the ratio of the mean diameter produced by the particular atomizer under consideration to the mean diameter expected from a similar size Lefebvre system (of the present configuration) operating under similar conditions. This factor does not, of course, account for differences in atomization quality that can be introduced by differences in sampling distance or drop-sizing techniques. A few experimental points should prove sufficient to determine its value for most prefilming type airblast atomizers. For example the Bryan Atomizer has (ϕ) equal to 1.5, Rizkalla's geometry has (ϕ) equal to 1.65 and if we accept Mani's proposition for the cubic root relationship between mean diameter and distance from an airblast atomizer, (Ref. 58), the value of (ϕ) for Miller's atomizer would be equal to 0.75 approximately, and so forth for other atomizers, as shown in the tabulation below for the purpose of illustration.

Airblast Atomizer Design	Spray Fineness Factor ϕ (approx)
Bryan	1.50
Lefebvre-present study	1.00
Lefebvre-Rizkalla	1.65
Miller	0.75
Rizk	1.25
NGTE (Wigg)	1.50

6.6. Proposed SMD-Prediction Formula:

From all the results obtained, the mean drop sizes produced by prefilmer cup type airblast atomizers can be predicted by the following dimensionally correct equation:

$$\frac{SMD \times 10^3}{\phi} = 73 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(\frac{\sigma_\ell}{\rho_a V_a^2}\right)^{0.6} \left(1 + \frac{W_\ell}{W_a}\right)^{1.0} D^{0.4}$$

$$+ 0.3 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(1 + \frac{W_\ell}{W_a}\right)^{1.2} \left(\frac{\eta_\ell}{\sqrt{\sigma_\ell \rho_a}}\right)^{1.0} D^{0.5} \quad \ldots. \; (6.6)$$

Alternatively, predictions may be obtained reasonably accurately by the following simpler expression:

$$\frac{SMD}{D} = 0.063 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \frac{(1+f)^{1.1}(1+0.004\ Ca)}{(We)_a^{0.55}} \cdot \phi \quad \ldots \; (6.7)$$

where, $Ca = \frac{\eta_\ell V_a}{\sigma_\ell}$, $(We)_a = \frac{\sigma_\ell}{\rho_a V_a^2 D}$, and $f = \frac{W_\ell}{W_a}$

For almost all types of commonly used liquid fuels the effect of liquid density, or the density ratio (ρ_ℓ/ρ_a), on the mean drop size is negligibly small and can be ignored in the above expressions without seriously impairing the prediction accuracy.

In the context of efficiency of design of airblast atomizers, (since the gaseous and liquid streams can be brought to interact in many ways), the parameter ϕ may be regarded as a measure of the relative efficiency of thin-sheet airblast systems under consideration to transfer kinetic energy available with the gaseous stream(s) to the liquid sheet, within the reservations outlined in section 6.5 concerning the effects of drop-size measuring techniques and sampling distances off-course.

CHAPTER 7

Conclusions and Suggestions for Future Work

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7.1. Conclusions

From the extensive test data collected on the performance of several 'thin-sheet' airblast atomizers, and on the liquid discharge capacity of swirler units in which liquid is forced through a number of equal-size, square-section channels arranged tangentially to an offset diameter, certain conclusions are drawn which may be stated as follows:-

(1) For geometrically similar airblast atomizers the spray fineness deteriorates with increase in atomizer scale, such that the mean drop diameter increases to approximately the 0.45 power of the atomizer linear dimension.

(2) The effects of the main variables involved in the airblast atomization process are separate and distinct from those of atomizer linear scale. For thin sheet airblast atomizers covering a wide range of flow capacity, it was found that:

(a) the air/liquid ratio has nearly equal effects on the mean drop diameter of sprays produced from either low or high viscosity liquids, suggesting that for all practical purpose little benefit is gained by using more air when dealing with heavy fuels than is needed for light fuels. In this context, in order to obtain satisfactory spray quality the recommended ALR operating range for all atomizer capacities is from 1.5 to 3.0. Below the lower limit spray quality deteriorates rapidly, and above a value of about 4.0 insignificant improvement is achieved for the higher energy expenditure.

(b) atomizing air velocity has the most dominant effect on the atomization quality of low liquid-viscosity sprays; the mean drop diameter decreases with air velocity to the power 1.2.

(c) liquid viscosity contributes to increase the non-dimensional mean drop size, SMD/D, in increments proportional to a modified Ohnesorge Number, expressed in terms of the atomizing air density, atomizer linear dimension, liquid viscosity and liquid surface tension.

(3) Analysis of the drop-size data for the various atomizer sizes revealed that:

(a) increasing the atomizing air density produces finer sprays. This effect is very nearly the same for both low and high viscosity liquids, the mean drop size decreasing with the 0.6 to 0.7 power of the air density. This suggests the use of compressed air to improve the atomization of heavy fuels, in addition to the common practice of heating up the liquid to reduce its viscosity, and,

(b) mean drop size is proportional to the 0.1 power of the liquid density, suggesting that its effect on spray fineness may often be ignored in comparison to the effects of the other variables, especially for the hydrocarbon fuels normally employed in practice.

(4) In close proximity to the airblast atomizer, the mean drop diameter varies appreciably with distance along the spray axis up to about 7 times the prefilmer diameter, decreasing rapidly from an initially large value immediately outside the airblast nozzle to a minimum, and then slowly increasing again further away, as a consequence of the droplets undergoing secondary atomization, evaporation, air resistance and agglomeration. This suggests that determination of this variation allows a more accurate comparison of the performance data of different atomizers to be made.

(5) For airblast atomizers employing a stationary prefilming cup, with tangential liquid slots, a minimum flow rate exists below which coarser than expected sprays are produced due to loss of uniformity of the film thickness which can impair the atomizer turn down ratio.

(6) Variation in the offset diameter of the liquid discharge ports has no effect on the discharge capacity for ports of square section having length/width ratio in the range from 4 to 7. The coefficient of discharge of the swirler, C_D, as defined by the simple theory of liquid discharge for long orifices, is equal to 0.65 over the range of flow Reynolds Number from 3200 to 24000, expressed in terms of flow rate and slot width.

(7) Taking into consideration all the results obtained from analysis of the spray data, the mean drop diameter (SMD) produced by stationary, prefilming-cup airblast atomizers is given by the following dimensionally-consistent equation:

$$\frac{SMD \times 10^3}{\phi} = 73 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(\frac{\sigma_\ell}{\rho_a V_a^2}\right)^{0.6} \left(1 + \frac{W_\ell}{W_a}\right)^{1.0} D^{0.4}$$

$$+ 0.3 \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \left(\frac{\eta_\ell}{\sqrt{\sigma_\ell \rho_a}}\right)^{1.0} \left(1 + \frac{W_\ell}{W_a}\right)^{1.2} D^{0.5}$$

where ϕ = atomizer spray fineness factor, a dimensionless function of the atomizer geometry.

Over the following range of conditions the above expression should predict the Sauter mean diameter of sprays to a reasonable order of accuracy:

σ_ℓ	=	liquid surface tension	- 0.026 to 0.074 N/m
η_ℓ	=	liquid absolute viscosity	- 0.001 to 0.004 Ns/m
W_ℓ	=	liquid mass flowrate	- 0.003 to 0.225 kg/s
W_a/W_ℓ	=	air/liquid ratio (ALR)	- 0.5 to 5.0
V_a	=	atomizing air velocity	- 60 to 190 m/s

ρ_a = atomizing air density corresponding to air pressure levels from atmospheric to 8.5×10^5 N/m^2

D = prefilming cup diameter - 0.019 to 0.076 m

SMD = Sauter mean diameter - 25 to 125 microns

Predictions based on the above equation correlate well with the test data. The equation appears to have a slight tendency to overestimate the influence of surface tension.

Alternatively, the SMD may be calculated from the following dimensionless expression without seriously impairing the accuracy of prediction:

$$\frac{SMD}{D} = 0.063 \; \frac{(1+f)^{1.1}(1+0.004\ Ca)}{(W_e)^{0.55}} \left(\frac{\rho_\ell}{\rho_a}\right)^{0.1} \phi$$

where: f is the fuel/air ratio; Ca is a Capillarity Number = $\eta_\ell V_a/\sigma_\ell$;

$(W_e)_a$ is a Weber Number = $\rho_a V_a^2 D/\sigma_\ell$; and, ϕ is the 'spray-finess factor' a dimensionless function of atomizer geometry only.

The above expression suggests that the effect of viscosity on the SMD can be safely ignored for values of Ca $\leqslant$ 12.

(8) Comparison between the results obtained in the present study and from previous investigations show that:-

(a) remarkable conformity between the effect of atomizer linear scale on atomization quality and that of the thickness of flat liquid sheets established in other works, notably by Fraser et al (Ref. 23), York et al (Ref. 98), Dombrowski et al (Ref. 19) and Rizk and Lefebvre (Ref. 77,78). This suggests that atomizer linear dimension appears to affect the mean diameter of the spray through its influence on film thickness, and,

(b) that the mean drop diameters calculated from the SMD prediction formula correlated well with the experimental data of both Rizkalla (Ref. 79) and Rizk (Ref. 77) obtained over a wide range of operating conditions. In the case of Rizkalla's data the comparison emphasised the importance of optimizing the geometry of the airflow passages inside the atomizer in order to achieve best atomization quality. Good agreement between predicted values and actual drop-size measurements was also obtained with the test data of Lefebvre and Miller (Ref. 48). With the water spray data of Wigg, (Ref.96), the agreement was fair around the 80 microns sizes. The generally reasonable levels of agreement between predicted and measured values of mean drop diameter obtained by various investigators using different airblast systems suggests that only a small number of data points is needed to define a value for the spray fineness factor, ϕ.

7.2. Suggestions for Future Work:

(1) Detailed investigation should be carried out into the mechanism of liquid prefilming for the stationary cup employing a tangential multi-slot arrangement, in order to establish the influence of flow geometry and liquid properties on the film thickness and its uniformity, and to investigate the effect of film thickness non-uniformity on atomization quality.

(2) The effect of atomizer geometry on mean drop diameter needs more work to define precisely the relative effect of each of the various geometrical variables involved.

(3) Further work is still required to assess the performance of airblast atomizers handling non-Newtonian liquids.

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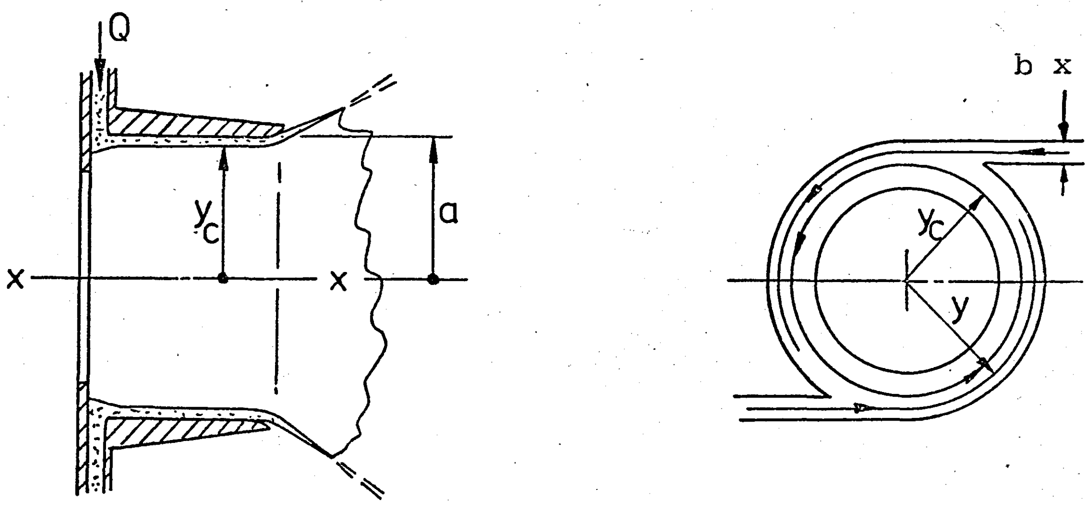
APPENDICES

APPENDIX (A)

An insight into the variation of liquid film thickness with atomizer scale can be obtained from consideration of the fundamentals of fluid flow in curved paths.



The liquid enters tangentially to the prefilming cup inner surface of radius, a. It forms a swirling annulus against the backwall and flows in a spiral motion towards the edge of the cup. Concentric with the liquid tube is an air core at ambient pressure. To simplify matters several assumptions must be made. Here, it is assumed that the liquid flow is irrotational and the liquid behaves as a perfect fluid. No account is taken of the effects of the liquid entry conditions, or gravity, or the high-velocity air core, or turbulence.

The velocity of the liquid at some point, y, from the axis, has a tangential component, V_t, and an axial component V_x. For the free vortex motion in the y-plane, the pressure variation across the liquid cross-section is given, from consideration of the balance of forces in the radial direction, by the following equation:

$$\frac{dp}{dy} = \frac{\Omega^2}{y^3} \qquad \ldots\ldots (1)$$

$$\therefore \quad p = \frac{\rho\Omega^2}{2}\left(\frac{1}{y_c^2} - \frac{1}{y^2}\right) + p_c \quad .... (2)$$

where y_c is the radius of the air-core, and p_c is the liquid pressure at the interface and is assumed to be equal to the ambient pressure.

From Bernoulli's equation, it follows that

$$p + \frac{1}{2}\rho(V_x^2 + \frac{\Omega^2}{y^2}) = p \quad .... (3)$$

$$\text{and } \therefore V_x = \left(\frac{2\Delta P}{\rho} - \frac{\Omega^2}{y_c^2}\right)^{\frac{1}{2}} \quad .... (4)$$

Approximately with $y_c = a$, then

$$V_x = \left(\frac{2\Delta P}{\rho} - \frac{\Omega^2}{a^2}\right)^{\frac{1}{2}} \quad .... (4a)$$

where ΔP is the liquid supply pressure (gauge). Equation (4) implies that the axial velocity is constant over the cross-section and therefore the liquid volumetric flow rate is given by:

$$Q = \pi(a^2 - y_c^2) . V_x \quad .... (5)$$

$$\text{or } Q \simeq 2\pi at\, V_x \quad .... (5a)$$

since $t/a << 1$.

Eliminating V_x between equations (4a) and (5a).

$$\frac{Q}{2\pi at} = \left(\frac{2\Delta P}{\rho} - \frac{\Omega^2}{a^2}\right)^{\frac{1}{2}} \quad .... (4a)$$

To find the value of Ω in terms of the measurable variables, consider the liquid discharging from the tangential slots with velocity equal to that existing in the free-vortex annulus against the weir.

If N is the number of liquid ports, each of size b x b, then the

$$\text{total area of slots, } A_s = Nb^2$$

and $$\frac{Q}{N} = \int_{a-b}^{a} \frac{\Omega}{y} b \, dy = -\Omega b \cdot \ln(1 - b/a)$$

Since the ratio (b/a) is usually much smaller than unity, then $\ln(1-b/a) = -b/a$

$$\therefore \frac{Q}{N} = \Omega\frac{b^2}{a}$$

$$\text{or} \quad \Omega = \frac{Q_a}{A_s} \qquad \text{..... (6)}$$

Substituting in equation (4b) and (6) for Ω, and manipulating, gives

$$t \simeq \frac{A_s}{2\pi a \dfrac{2\Delta P A_s^2}{\rho Q^2} - 1} \qquad \text{..... (7)}$$

As shown in this study, the magnitude of the group $(2\Delta P A_s/\rho Q^2)$ is independent of the prefilming diameter and for low viscosity liquids discharging through the multi-slot arrangement at Reynolds number above 3000 referred to the slot size, the group assumes a constant value given as:-

$$\left(\frac{1}{C_D}\right)^2 = \frac{2\Delta P\, A_s^2}{\rho Q^2} = \left(\frac{1}{0.65}\right)^2$$

Relationship (7) can be re-written as:-

$$t \approx \frac{A_s}{2\pi a \left(\frac{1}{C_D^2} - 1\right)} \qquad \ldots. \ (7a)$$

which, for geometrically similar system means that the liquid film thickness is proportional to the scale.

The accuracy of equations (7) or (7a) has not been tested and should therefore not be used for assessing the magnitude of the liquid film thickness. The exercise was merely to justify the proposition, in Chapter 4, of the proportionality of the film thickness with atomizer scale.

APPENDIX B:

Solutions of the synthetic hydrocarbon polymer, Hyvis Polybutene No. 05 in kerosine to obtain a wide range of viscosity:

Solution	η_1	σ_1	ρ_1
Pure kerosine	1.293	27.67	0.784
30% Hyvis 05	2.868	28.67	0.800
40% Hyvis 05	4.286	28.78	0.809
50% Hyvis 05	6.042	28.87	0.812
60% Hyvis 05	9.789	29.17	0.819
70% Hyvis 05	17.014	30.08	0.823
80% Hyvis 05	33.802	30.16	0.828
85% Hyvis 05	44.104	30.27	0.830
90% Hyvis 05	76.541	30.46	0.833
95% Hyvis 05	123.921	30.70	0.838
Pure Hyvis 05	218.562	30.96	0.840

η_ℓ = centipoise; σ_ℓ = dyne/cm; ρ_ℓ = g/c.c.

APPENDIX (C):

(1) ALIGNMENT OF THE OPTICAL BENCH

Before optimum results can be expected from the Light Scattering Technique all optical surfaces must be clean and the system components must lie on the same optical axis.

(i) Check laser beam parallelism, as follows:

a. Switch on the laser head and allow 30 minutes to stabilize.

b. Adjust position of spatial filter (x,y,z) to obtain a beam of regular cross-section with highest possible intensity against a white sheet of paper placed 18 inches away. In addition, the diffraction rings must have lowest possible intensity.

c. Check (or adjust) beam diameter is 8mm. close to the expanding lens, and that it does not exceed 9mm. at several distances from the lens up to 15 feet away.

(ii) Adjust position of laser head on the bench w.r.t. the small white lamp and chopper vanes.

(iii) Adjust components until beam is retained central in the receiving lens.

(iv) Adjust position of photomultiplier and of apperture to obtain a well focused image against the shutters. Always maintain shutters (and iris diaphragm) closed under conditions of "NO-Spray", to prevent damaging the photomultiplier.

(2) Calibration and Operating Procedure of the Logarithmic Amplifier

Calibration of the X-Y plotter is necessary after installation and should be repeated subsequently each time before use or when it is re-installed in a different axis or recorder main frame.

The calibration and operating procedure is done in the following way:

(a) With the function S/W in the OdB position switch on the recorder and allow 15 minutes warm up period.

(b) Place a sheet of 5 cycles x mm paper on the recorder and check that it is held in position by the vacuum.

(c) By means of the Pen Offset Control move the pen to half scale.

(d) Turn the Range central to its calibrated position, i.e. fully anti-clockwise and switch to Internal Reference.

(e) Switch the Internal Reference switch to 100mV and adjst the sub-panel SET OdB potentiometer with a small screw driver so that pen returns to the OdB-line.

(f) Switch to 10V and adjust the CAL potentiometer to give 10 cm deflection corresponding to 2 decades (2 log cycles) i.e. to 40 dB.

(g) Switch to 0.316 mV and adjust the CAL 0.316 mV potentiometer to give a deflective of -12.5 cm corresponding to -2.5 decades.

(h) When calibration is performed, repeated use of the Pen Offset Control is necessary to ensure that the pen does not exceed full scale deflection in either direction.

(i) Check the full range of Internal Reference sources from 0.316 mV to 10V. The Log Amplifier will now be calibrated with a scale factor of 4 dB/cm over the full dynamic range from 0.316 mV to 10V.

(j) After the required 15 minutes warm-up period the Log Amplifier is ready for use. The Log x mm paper is useful for the indication of the actual magnitude of the compressed input signal.

(k) Switch to OdB. The input from the photo-potentiomultiplier is now disconnected from the Log Amplifier and the pen will have taken up a position corresponding to OdB.

(l) Move the pen by means of the Pen Offset Control to the maximum desired pen deflection e.g. full scale deflection. This will be the OdB position.

(m) Switch to Internal Reference and switch the Internal Reference switch to the level desired for OdB (in this case the highest voltage to be measured).

(n) Switch the highest voltage to be measured and rotate the range control until the pen position coincides with the desired lines on the paper for this voltage e.g. zero scale deflection.

(o) Switch the Input to plot the input function i.e. the photomultiplier output against the traverse distance.

(p) <u>After use</u>, switch to either OdB or Internal Reference and disconnect the input signal line from the input terminals before switching off the recorder.

APPENDIX (D)

LIQUID SWIRLERS

The swirlers are identified by N x w x w and the offset diameter, D, where: N is the number of tangential slots and w is the slot width in inches.

Set (A) : D = 50.8 mm,

Six swirlers as shown:-

A.1 - 6 x 0.016 x .016
.2 - 6 x 0.023 x .023
.3 - 6 x 0.032 x .032
.4 - 6 x .039 x .039
.5 - 6 x .047 x .047
.6 - 6 x .063 x .063

Set (B) : D = 25.4 mm,

Four swirlers, B.1 to B.4, as above for A.1 to A.4.

Set (C) : D = 12.7 mm,

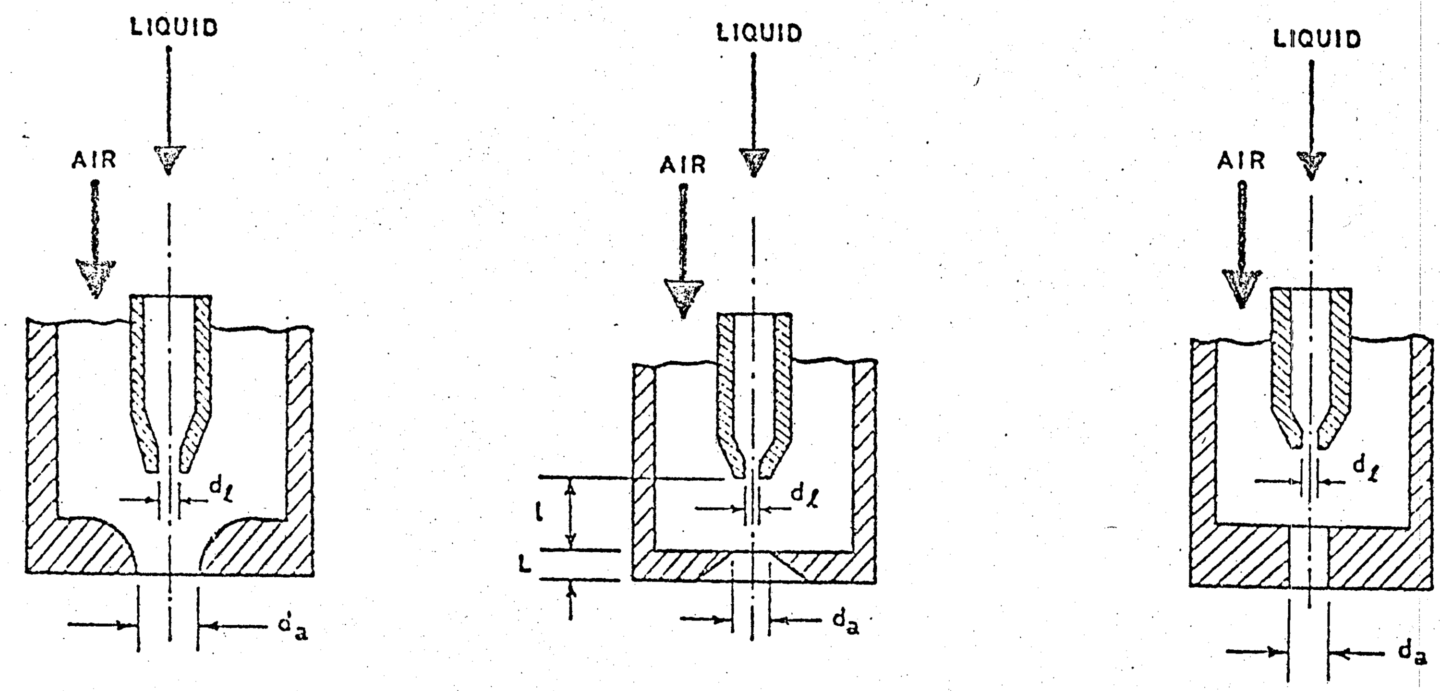
Also four swirlers, C.1 to C.4, as above.

Set (D) : D = 25.4 mm,

Two swirlers only,

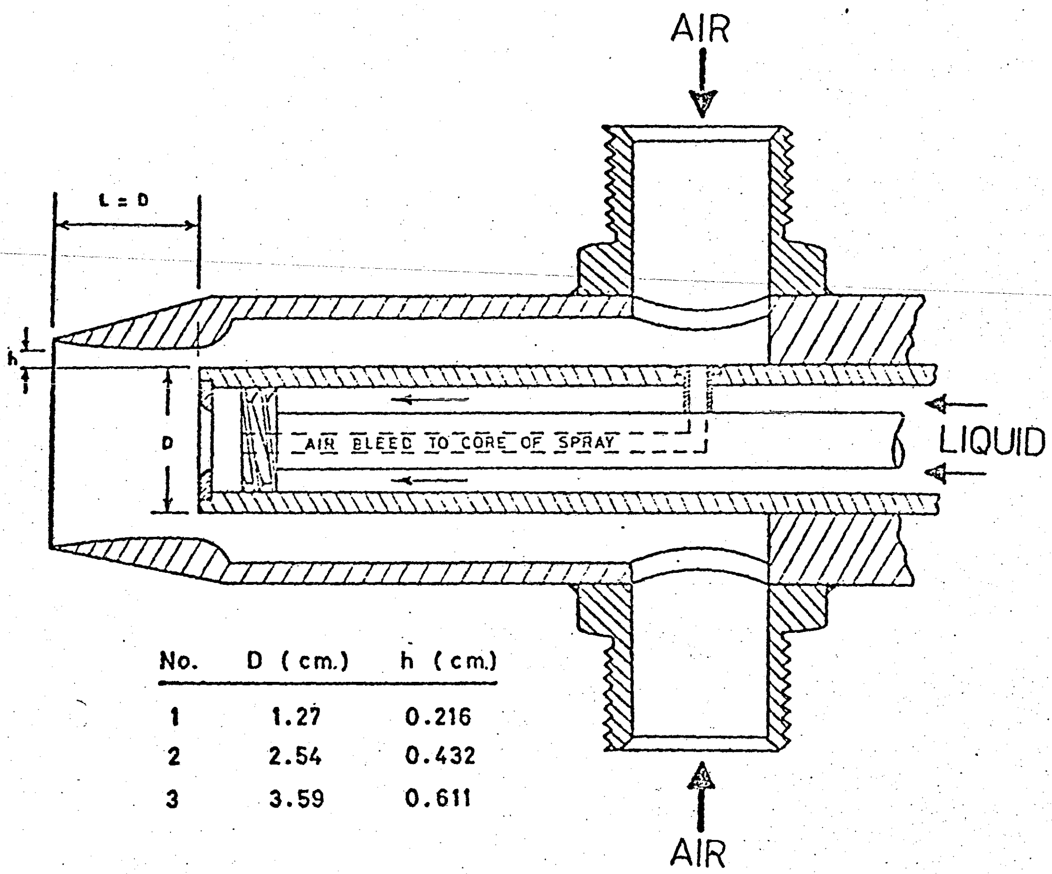
D.1 - 3 x .063 x .048
D.2 - 9 x .032 x .032

FIGURES



(a) Convergent Air Nozzle. (b) 120° Sharp_Edged Orifice (c) Cylindrical Air Nozzle

FIG.1. NUKIYAMA AND TANASAWA ATOMIZERS



No.	D (cm.)	h (cm.)
1	1.27	0.216
2	2.54	0.432
3	3.59	0.611

FIG. 2a. WIGG (N.G.T.E.)

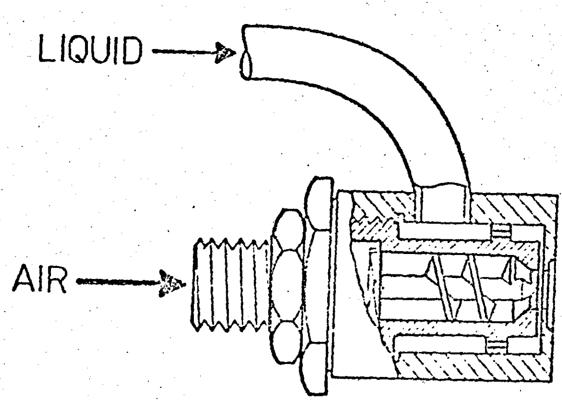


FIG. 2 b. RADCLIFFE - CLARE

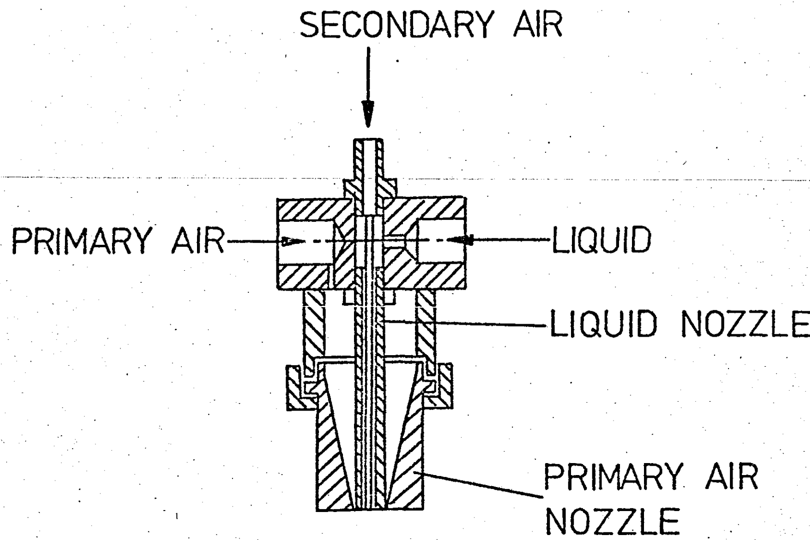


FIG. 3a. KIM-MARSHALL

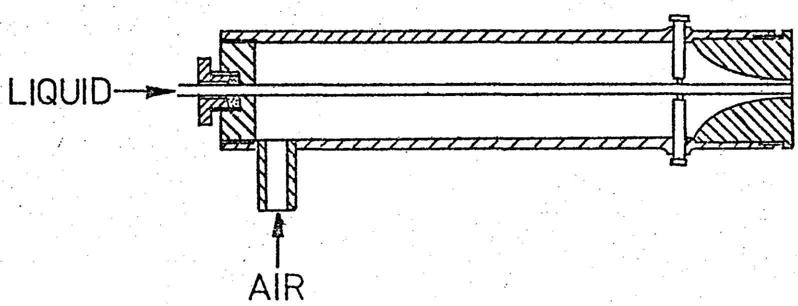


FIG. 3b. GRETZINGER-MARSHALL

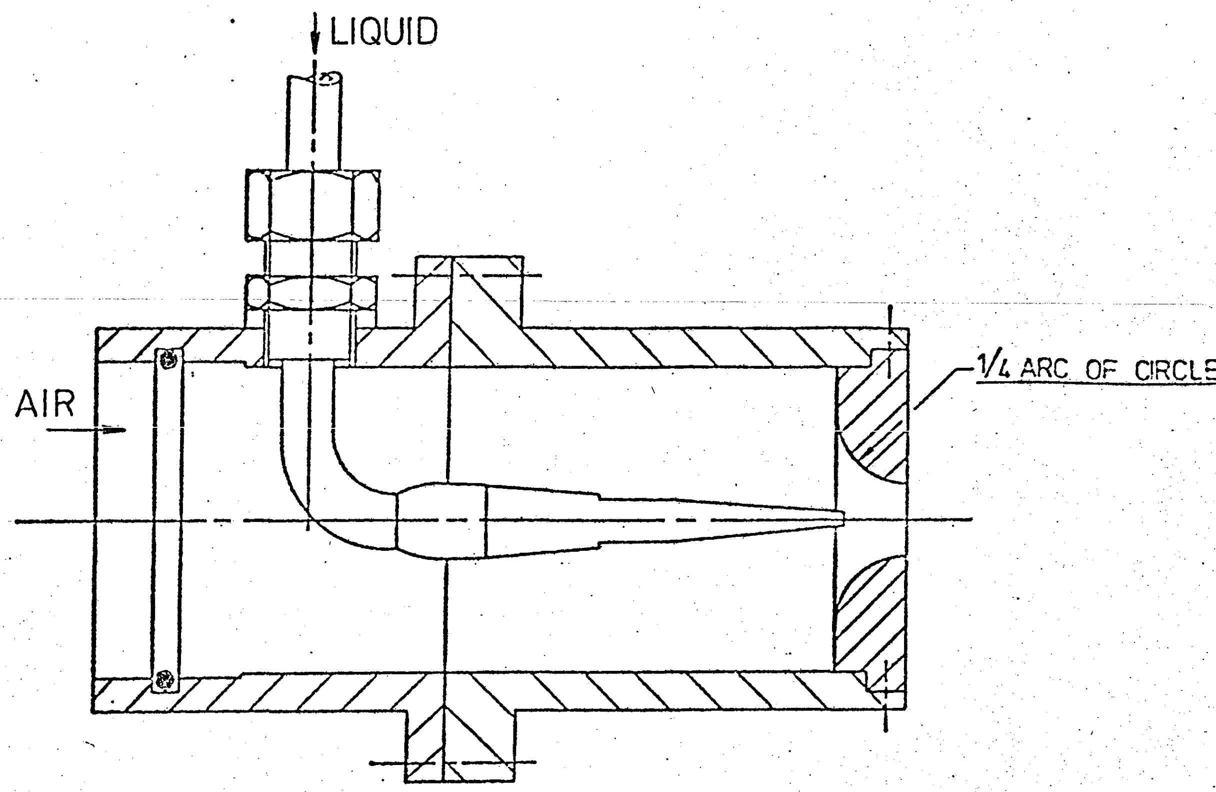


FIG. 4a. LORENZETTO - LEFEBVRE

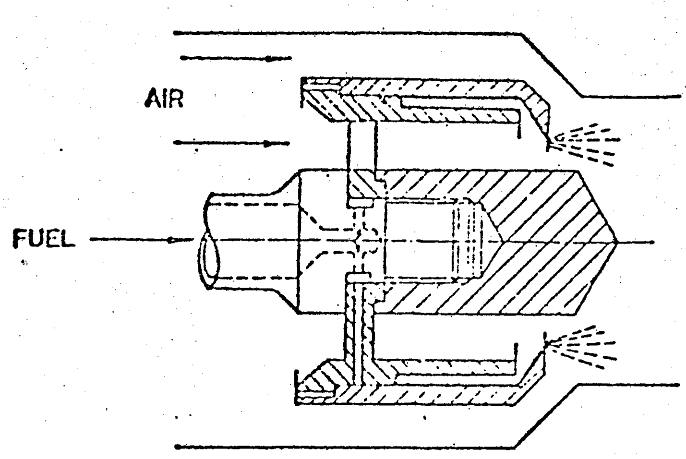


FIG. 4b. LEFEBVRE - MILLER

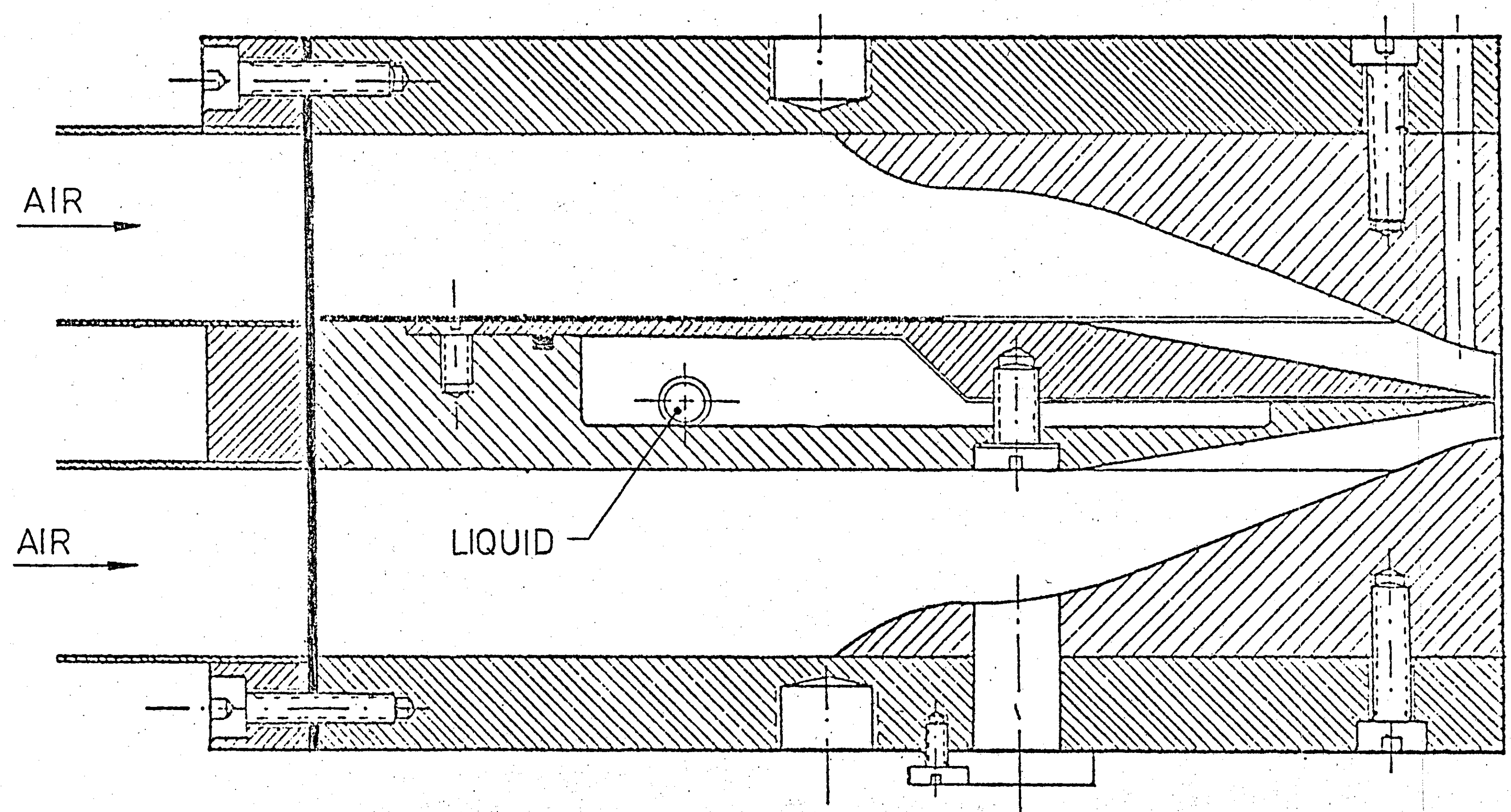


FIG. 5. RIZK - LEFEBVRE

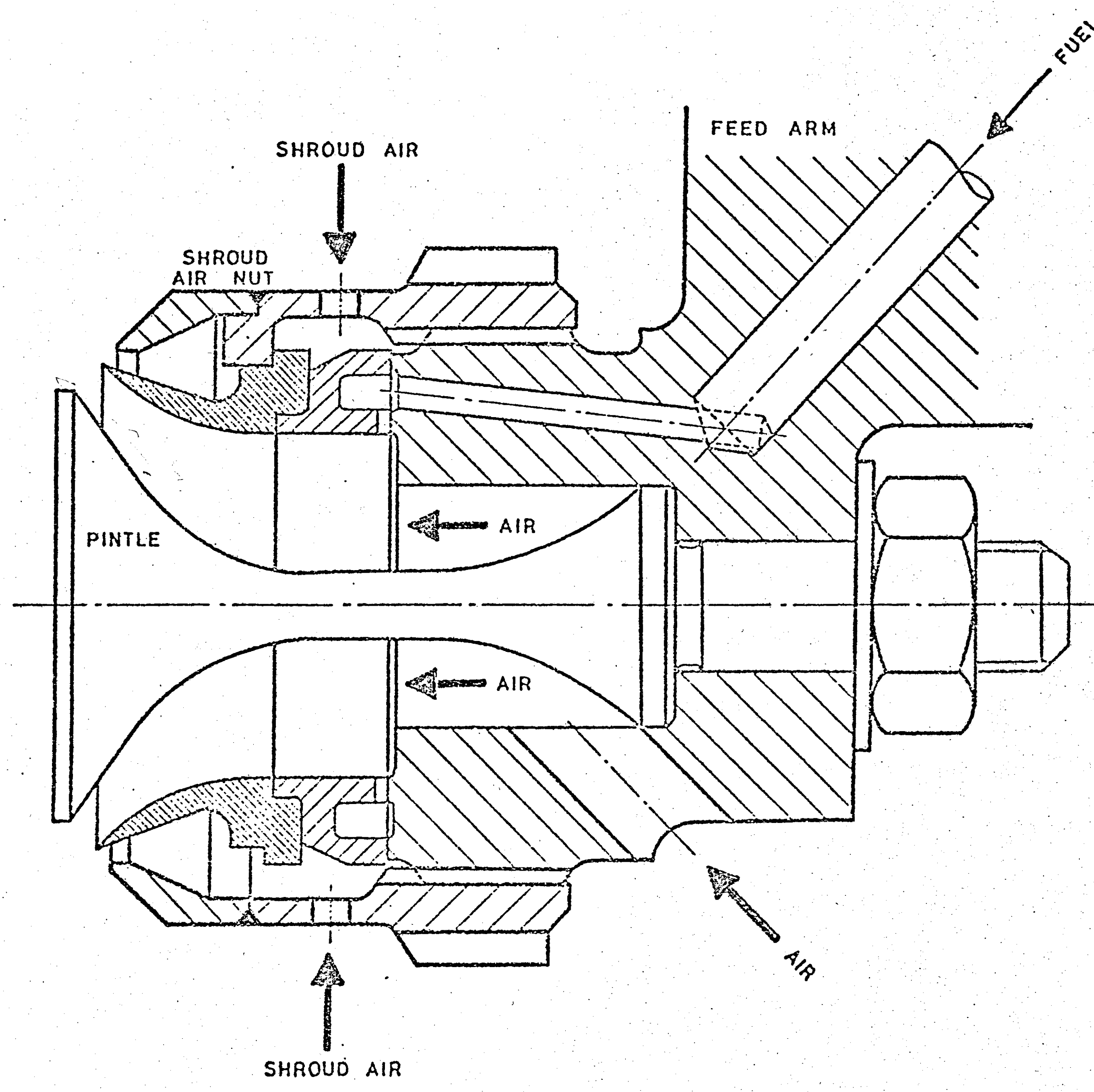

FUEL
FEED ARM
SHROUD AIR
SHROUD
AIR NUT
PINTLE
AIR
AIR
AIR
SHROUD AIR

FIG. 6. BRYAN

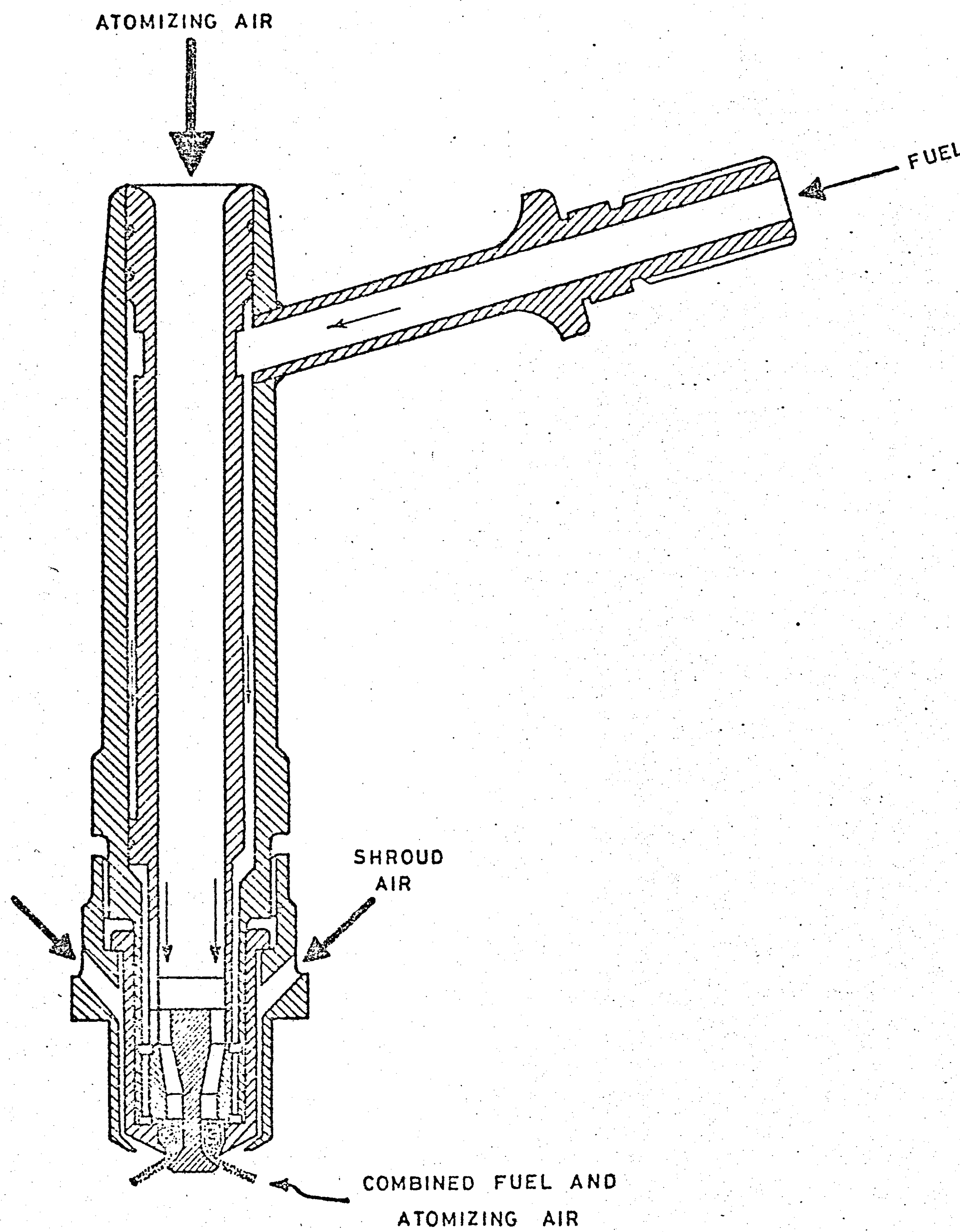


FIG. 7. ROLLS_ROYCE "DART" AIRSPRAY ATOMIZER

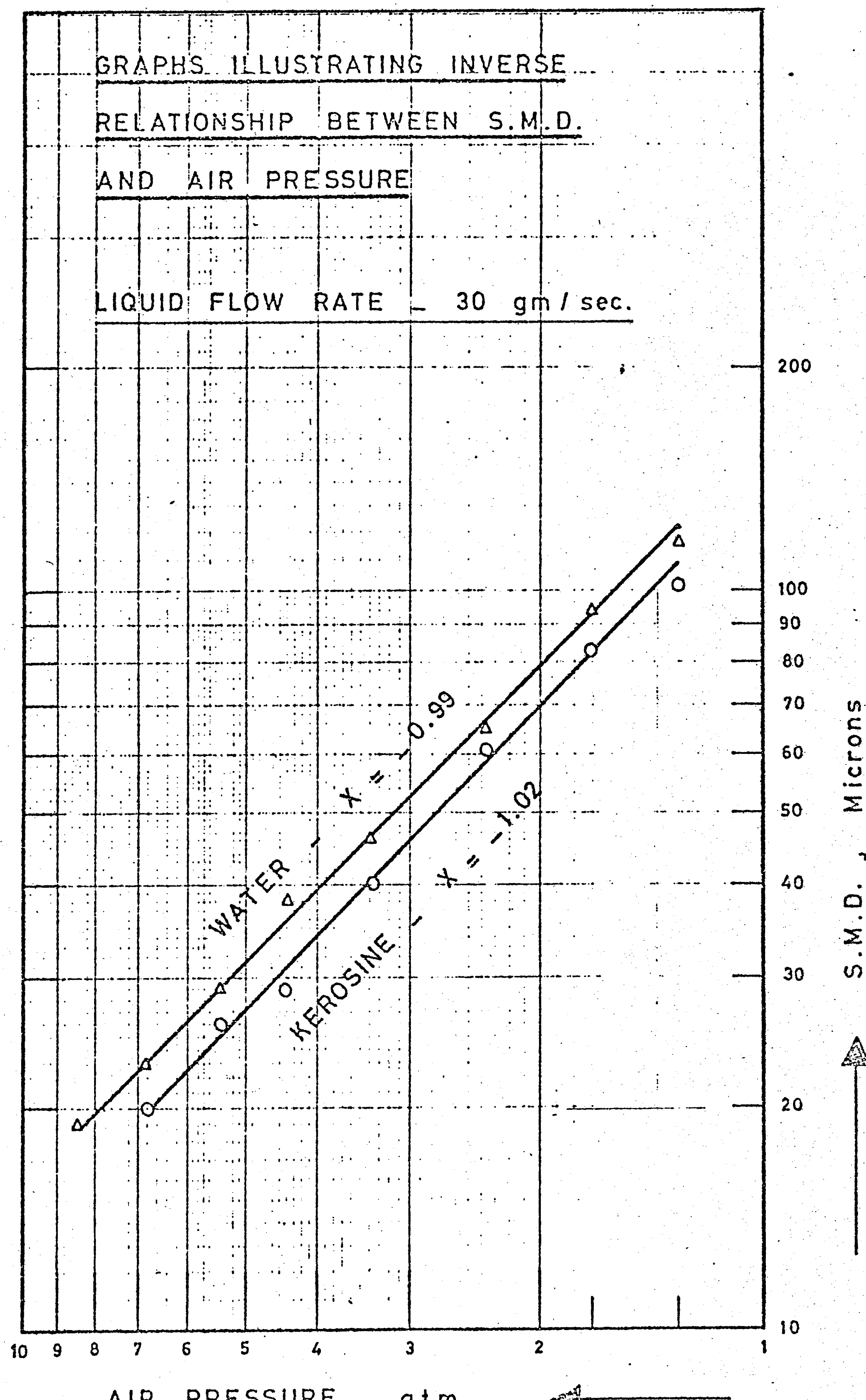


FIG. 8. EFFECT OF ATOMIZING AIR PRESSURE ON SMD – RIZKALLA (REF. 79,80)

X

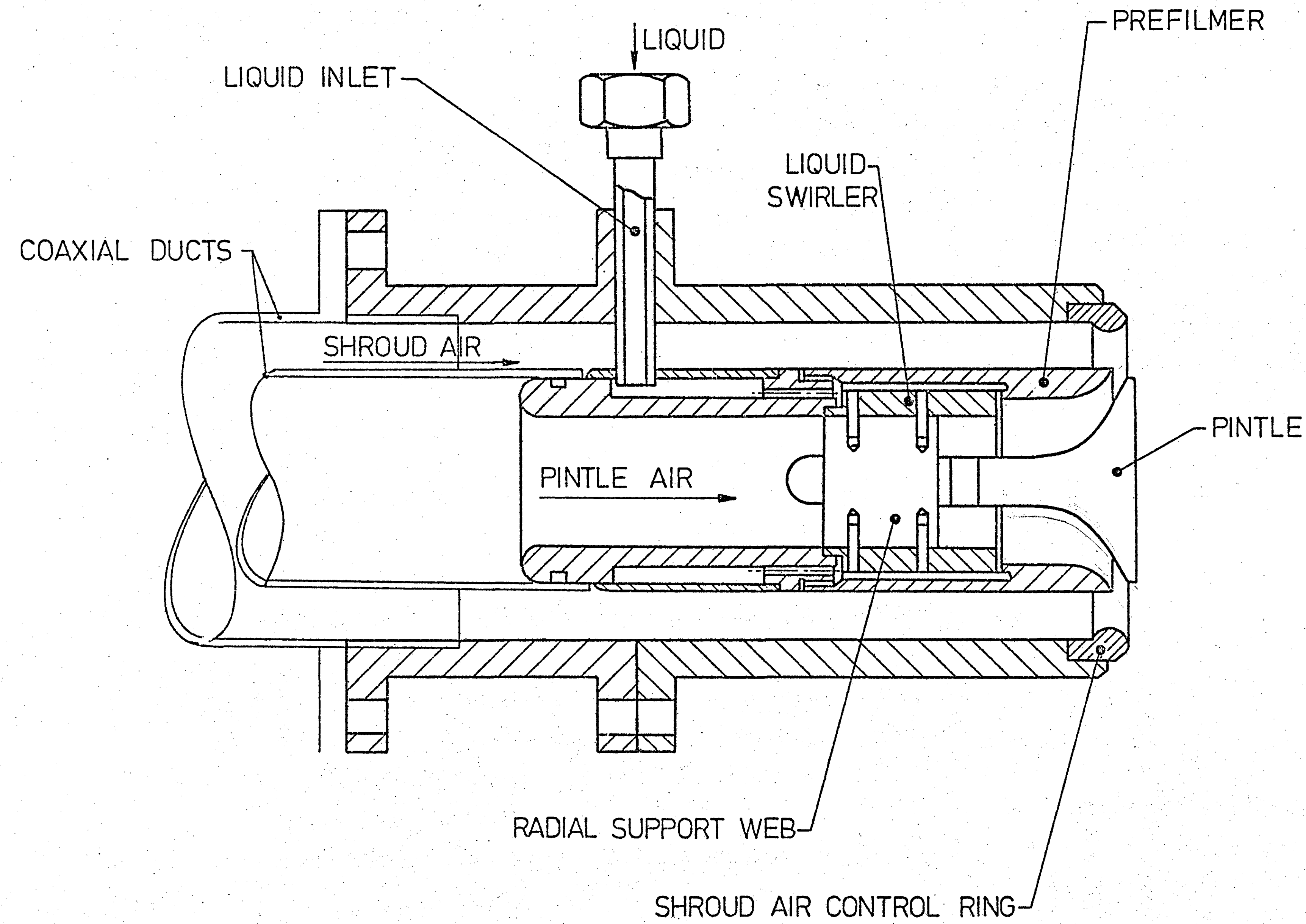
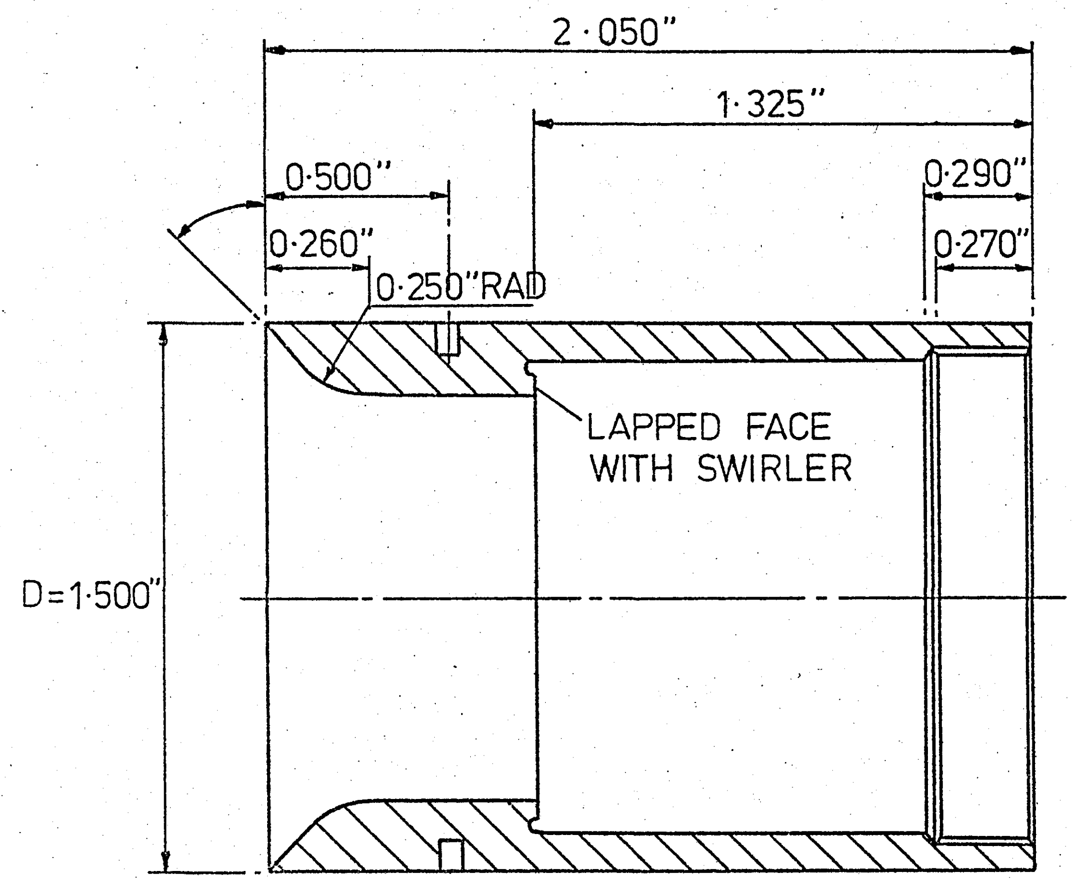


FIG. 9. AIRBLAST ATOMIZER USED IN PRESENT STUDY

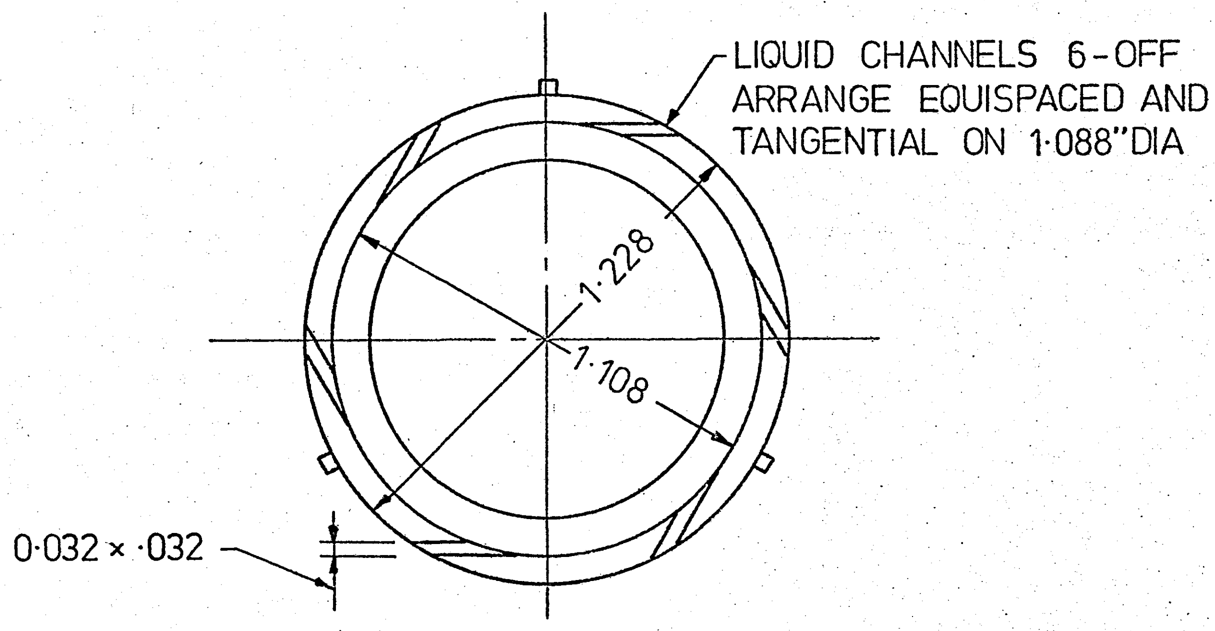


D = PREFILMER DIAMETER

FIG. 10. PREFILMER CUP – MEDIUM ATOMIZER

(DIMENSIONS IN INCHES)

(a) LIQUID SWIRLER



MEDIUM ATOMIZER

(b) SHROUD RING

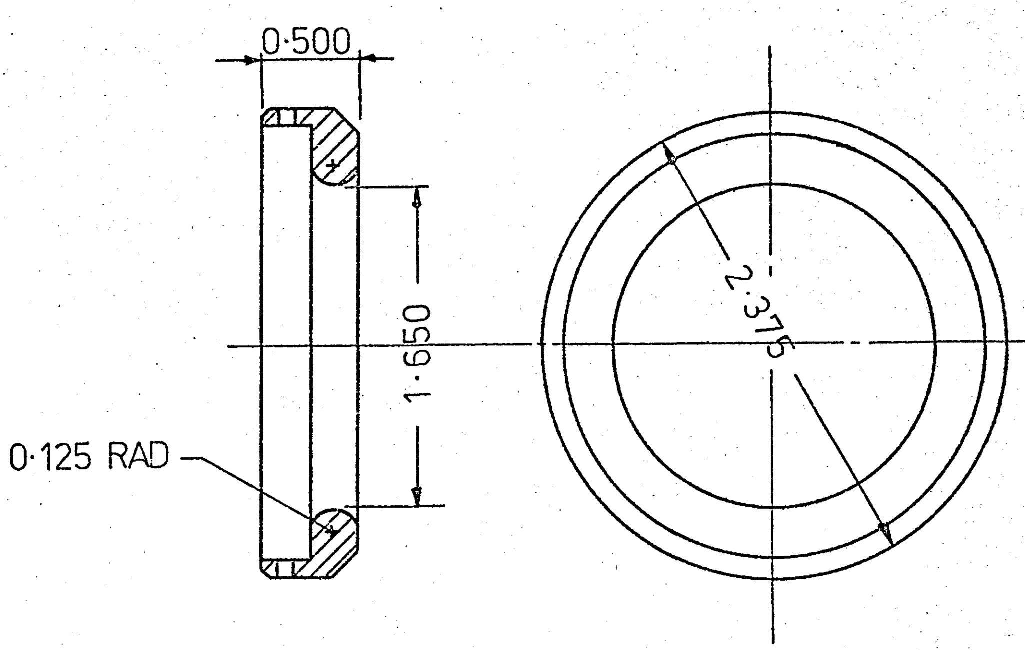


FIG. 11. LIQUID SWIRLER AND SHROUD AIR CONTROL RING

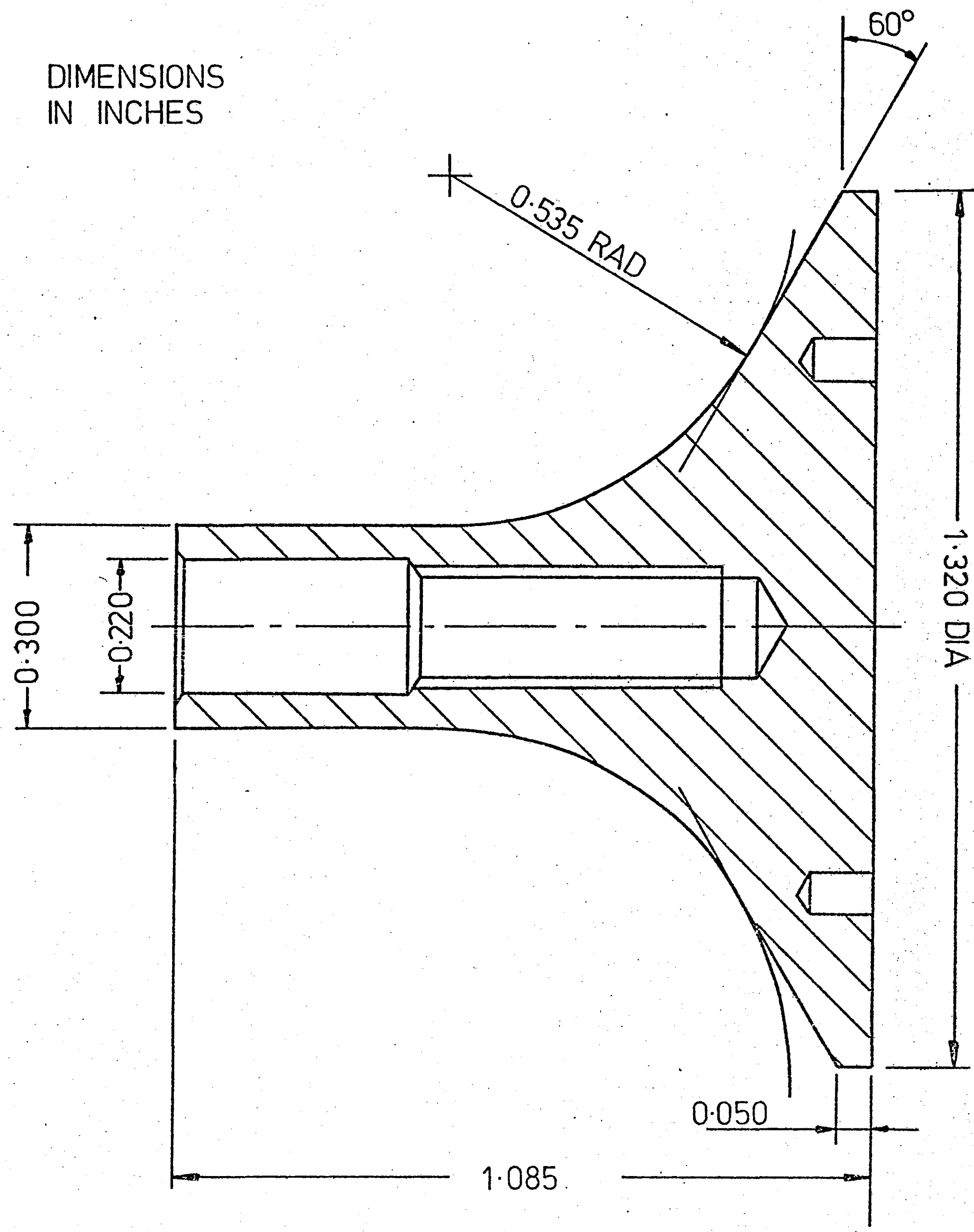


FIG. 12 PINTLE – MEDIUM ATOMIZER

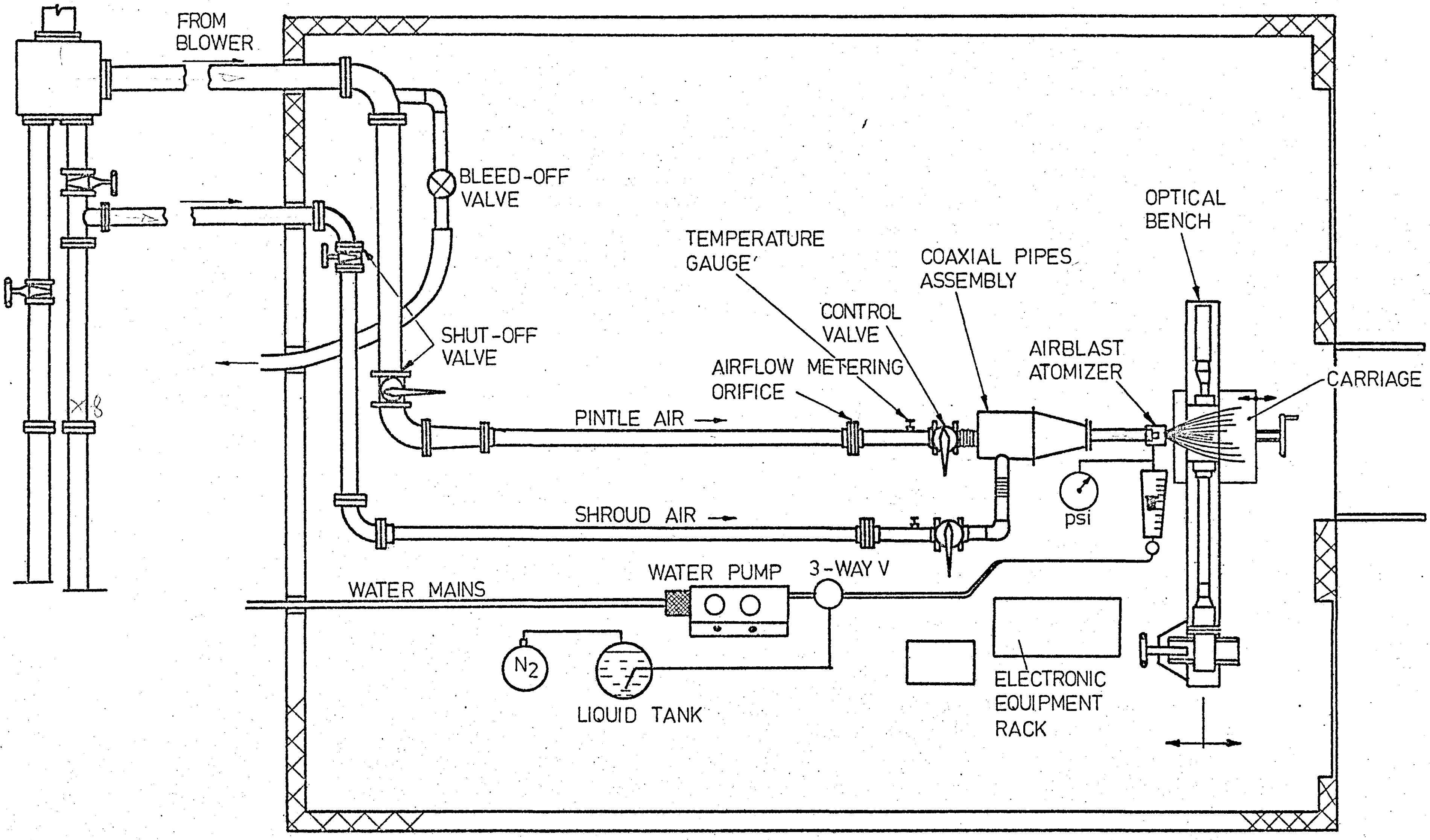


FIG. 13 LAYOUT OF SPRAY TEST RIG

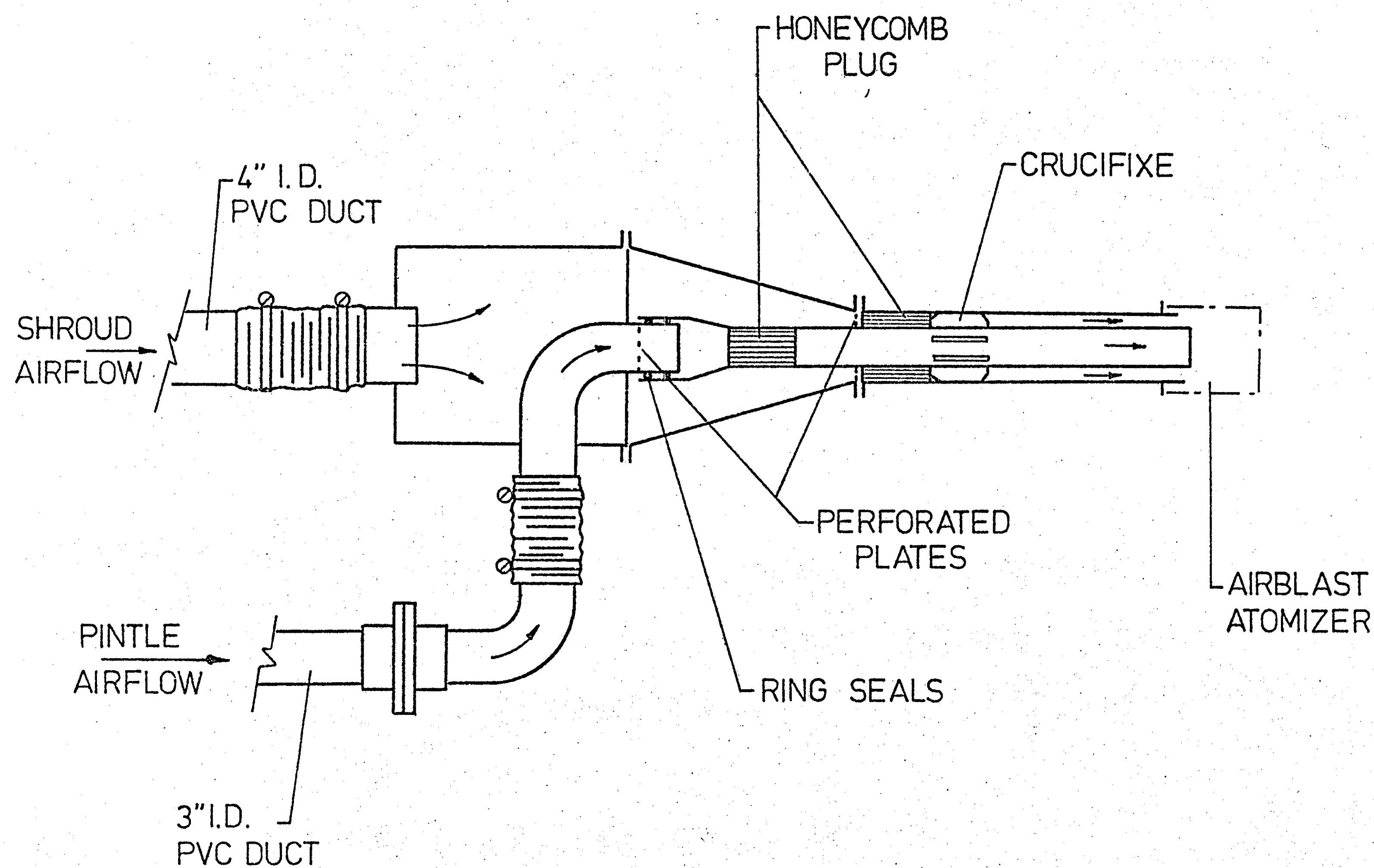


FIG. 14 COAXIAL DUCT ARRANGEMENT

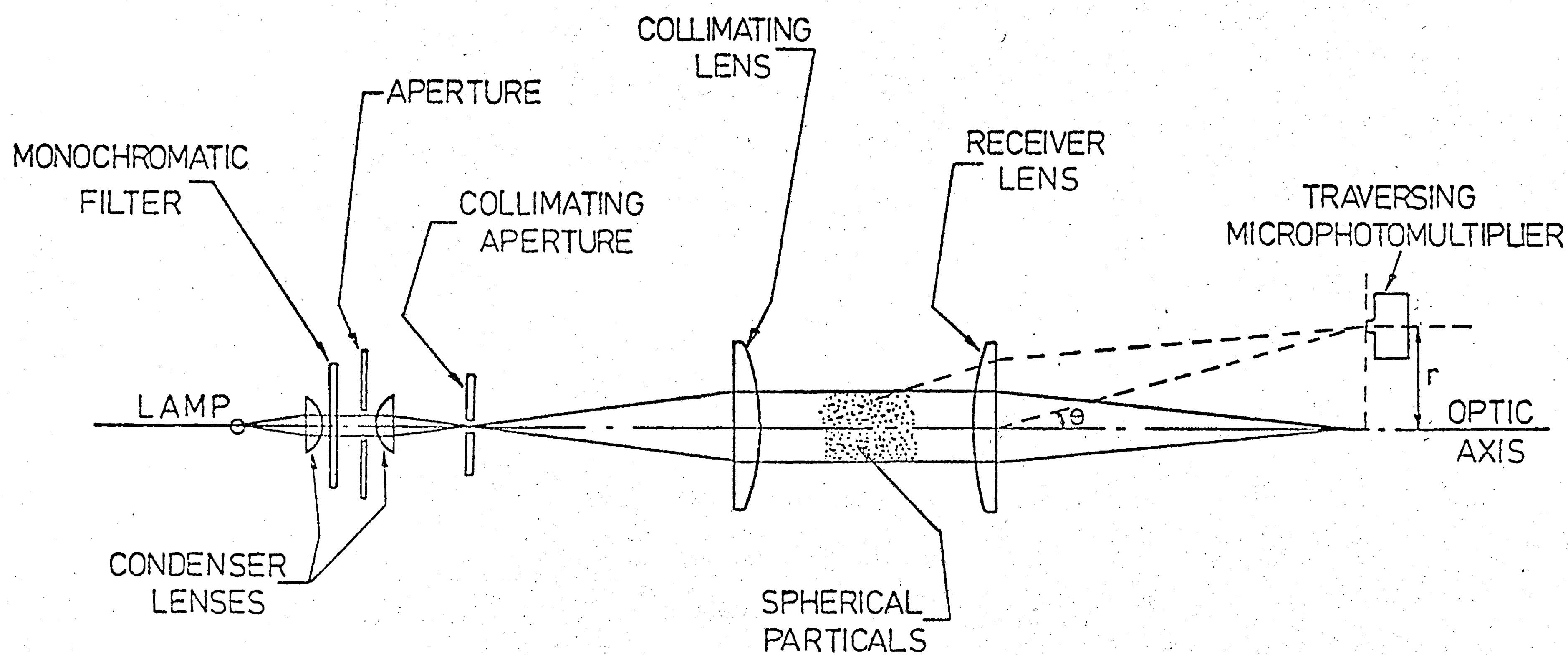


FIG 15 DOBBINS OPTICAL APPARATUS

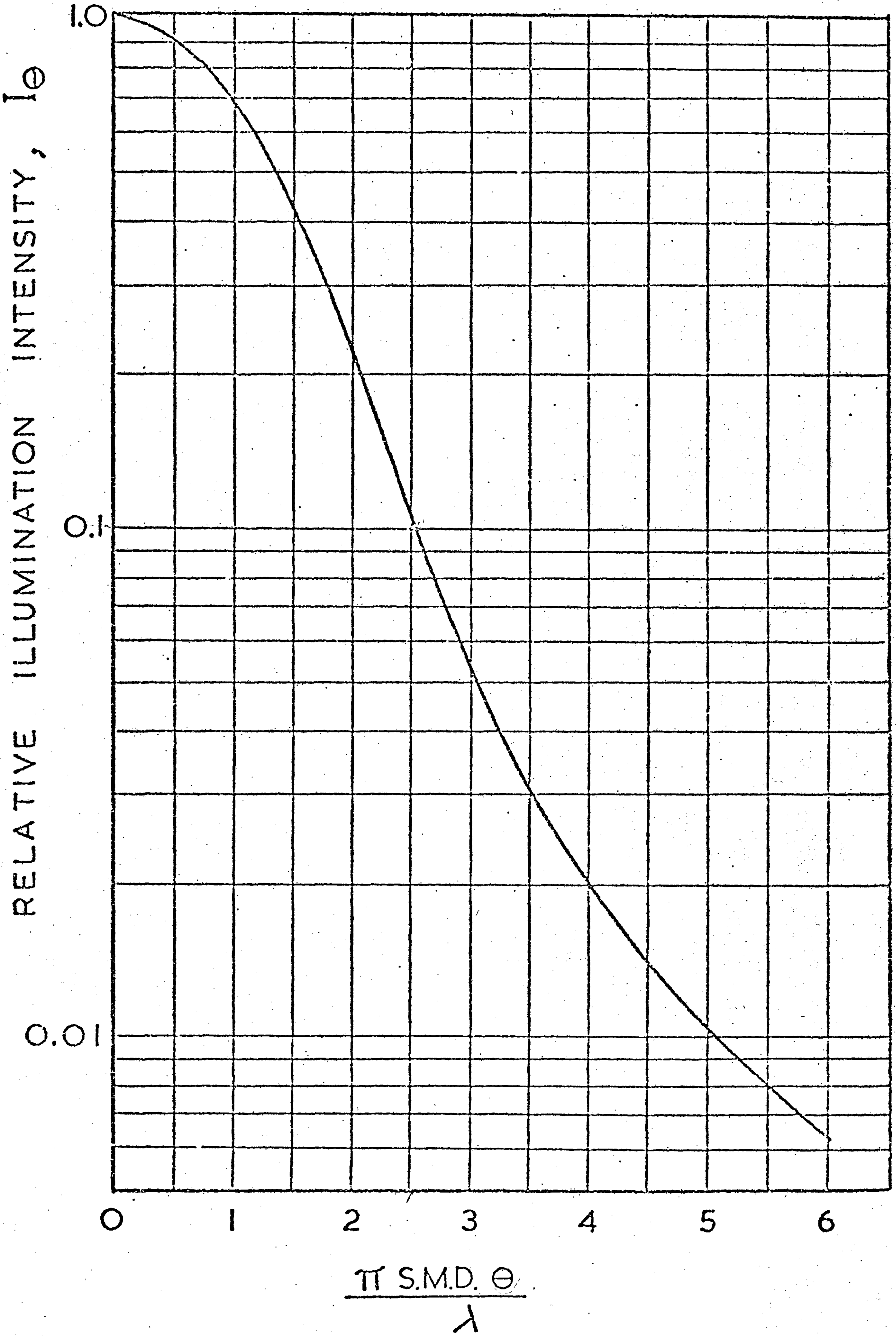


FIG. 16. MEAN THEORETICAL ILLUMINATION PROFILE, DOBBINS ET. AL.

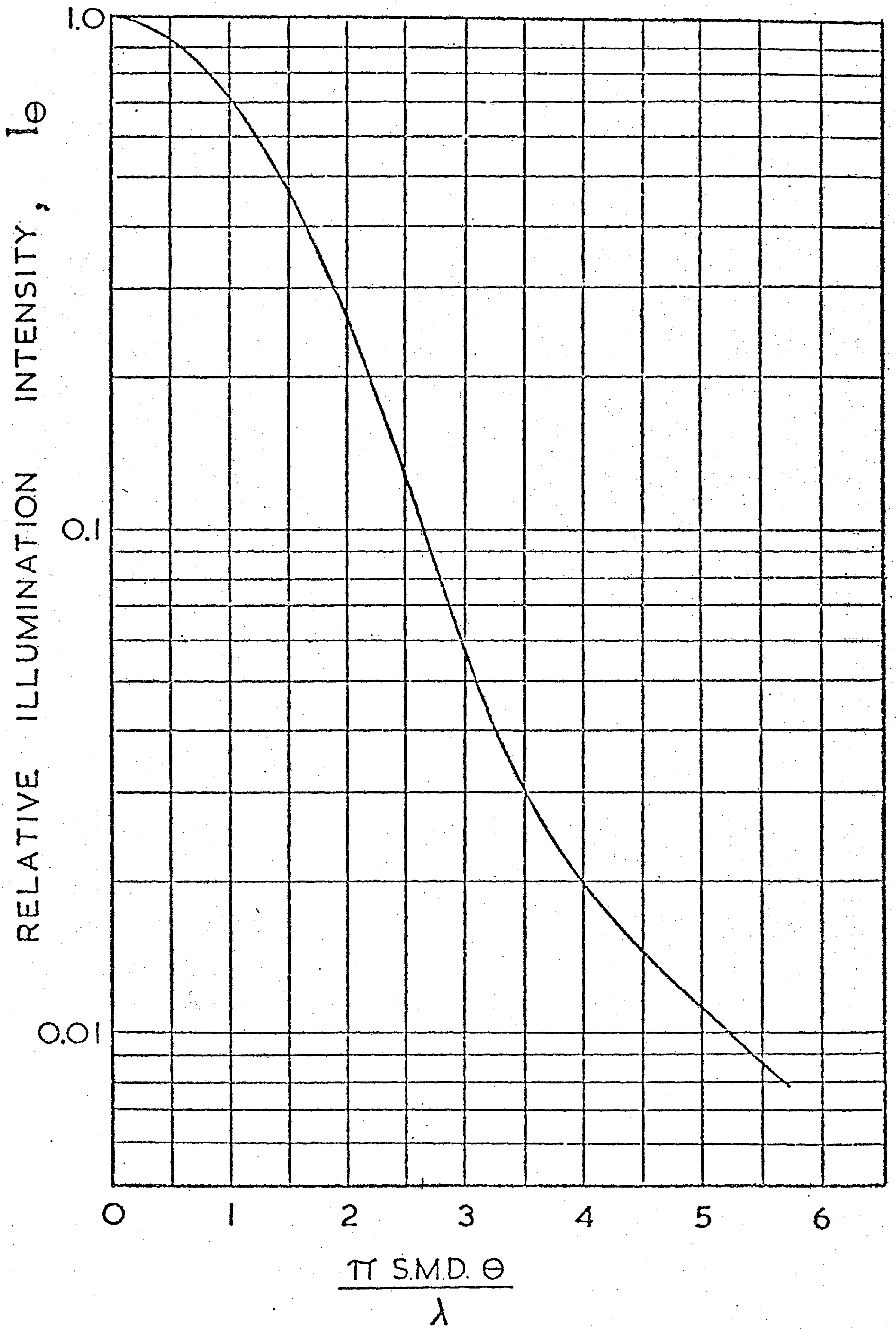
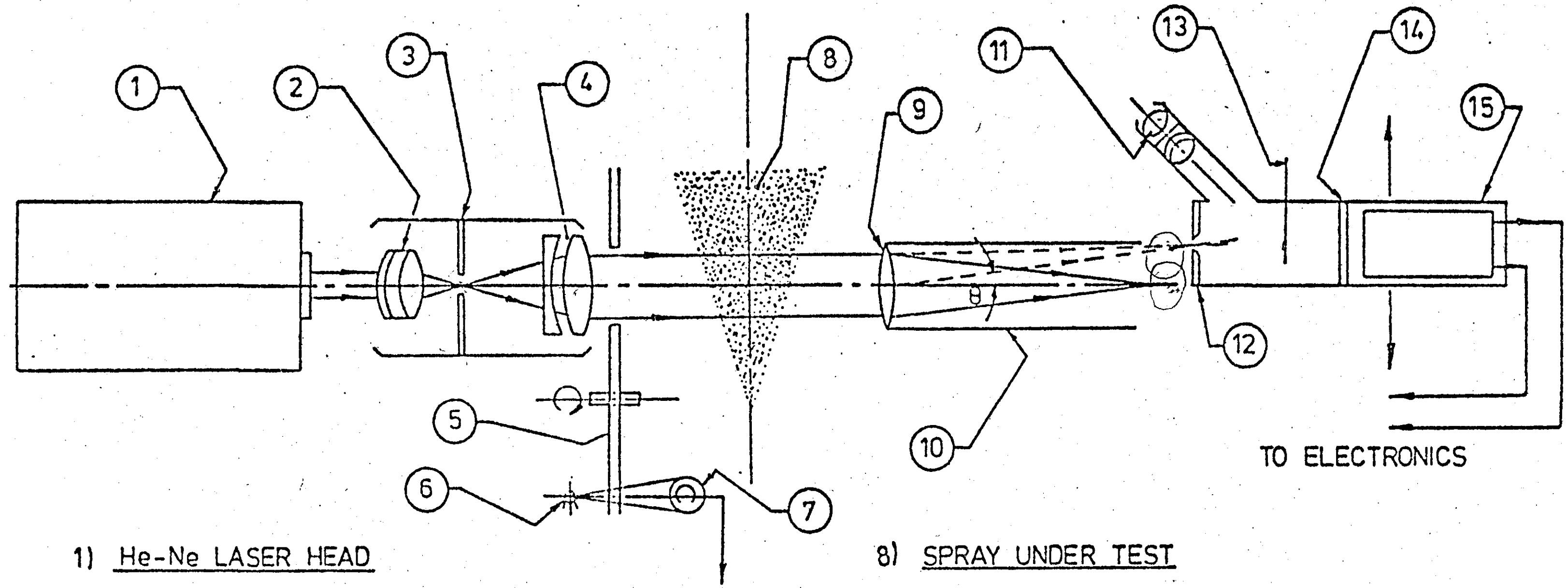


FIG. 17. REVISED MEAN THEORETICAL ILLUMINATION PROFILE, ROBERTS AND WEBB



1) He-Ne LASER HEAD
2) CONDENSING LENS
3) SPATIAL FILTER (APERTURE)
4) TELESCOPE-COLLIMATING LENS
5) ROTATING DISC (CHOPPER)
6) SMALL LAMP
7) PHOTO CELL
8) SPRAY UNDER TEST
9) RECIEVER LENS (60cm FOCAL LENGTH)
10) STRAY LIGHT SHIELD
11) EYEPIECE
12) PIN-HOLE APERTURE
13) SHUTTER
14) NEUTRAL DENSITY FILTER
15) TRAVERSING PHOTOMULTIPLIER

FIG. 18. DIAGRAMMATIC FORM OF OPTICAL SYSTEM

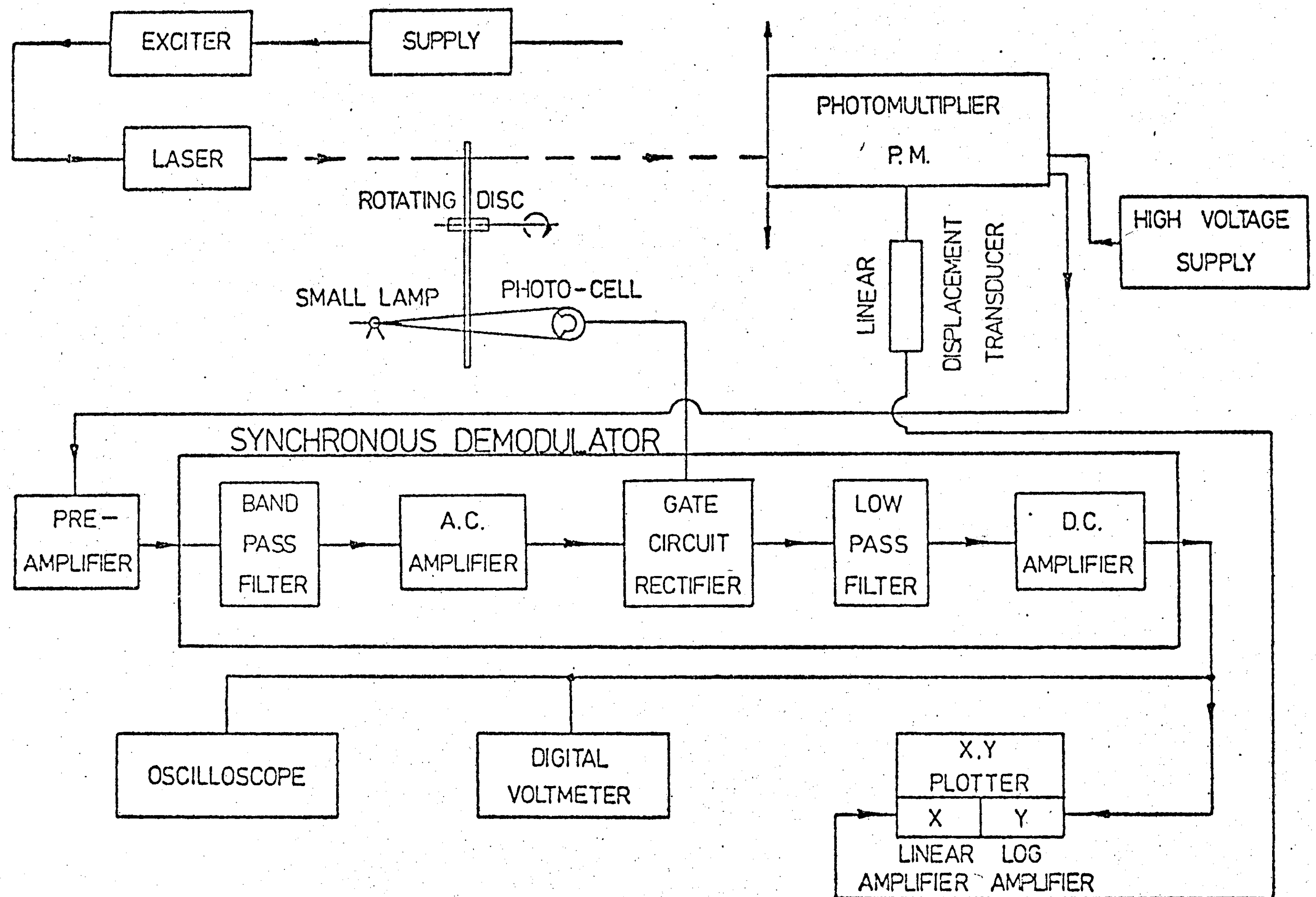
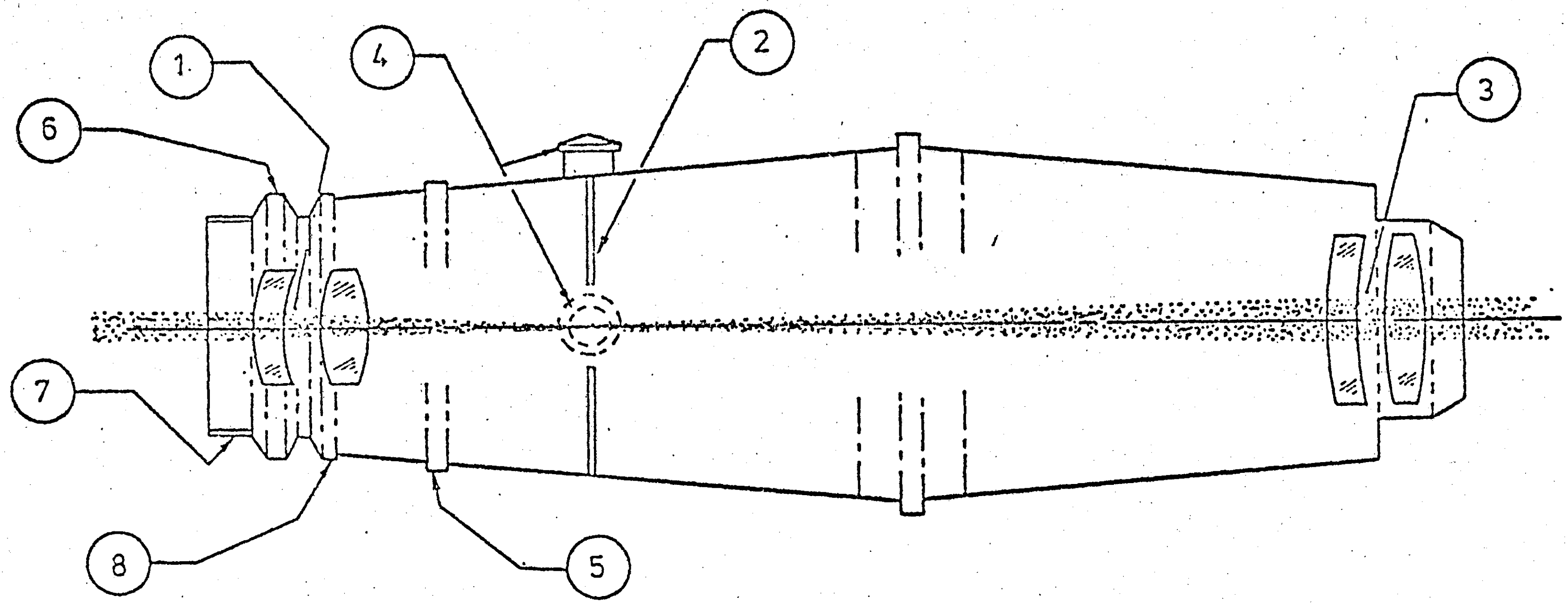


FIG. 19. LIGHT SCATTERING INSTRUMENTATION



1) EXPANDING LENS:- EQUIVALENT FOCAL LENGTH: 12.8mm

2) SPATIAL FILTER:- PRECISION PIN HOLE: 22μ

3) TELESCOPE COLLIMATING LENS:- EQUIVALENT FOCAL LENGTH 85mm

4) APERTURE X&Y MOTION ADJUSTING KNOBS:-

5) APERTURE Z MOTION ADJUST RING:-

6) ROTATIONAL LOCK RING:-

7) 1"-32 MOUNTING THREAD:-

8) AXIAL ALIGNMENT LOCK RING:-

FIG. 20 BEAM EXPANDING ASSEMBLY

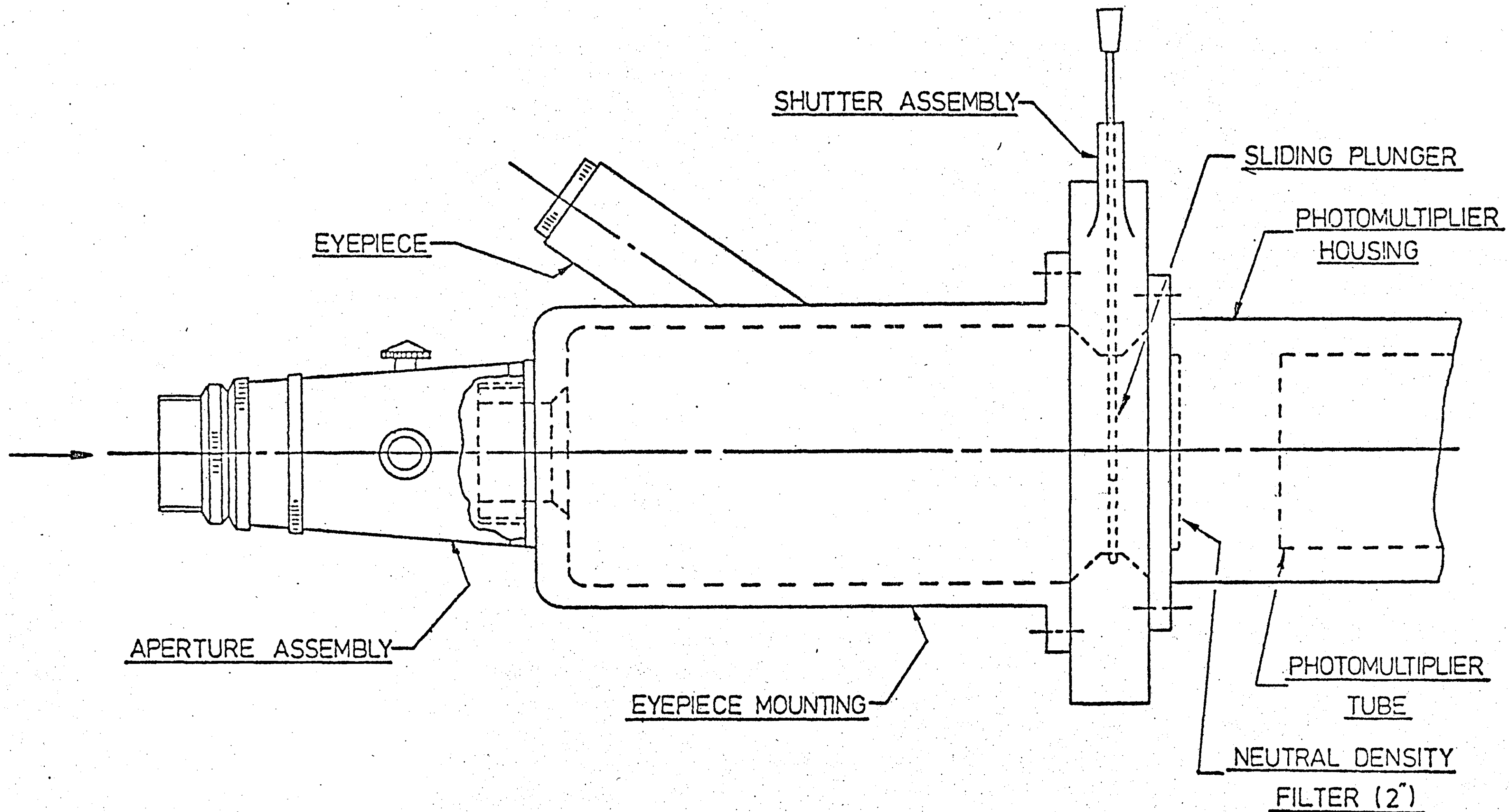


FIG. 21 LIGHT RECEIVING SYSTEM

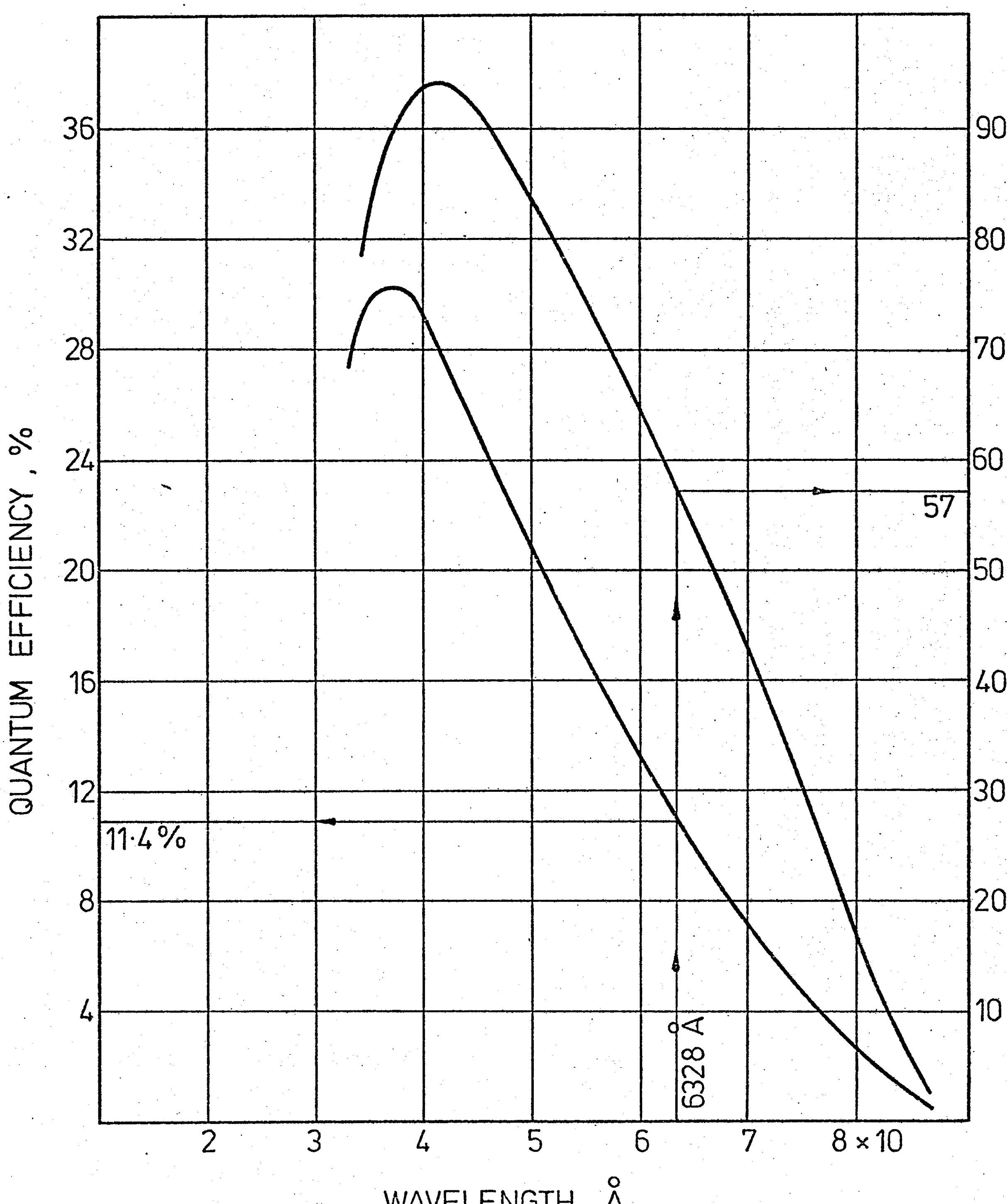


FIG. 22. E.M.I. - 9658 MR PHOTOMULTIPLIER SPECTRAL RESPONSE

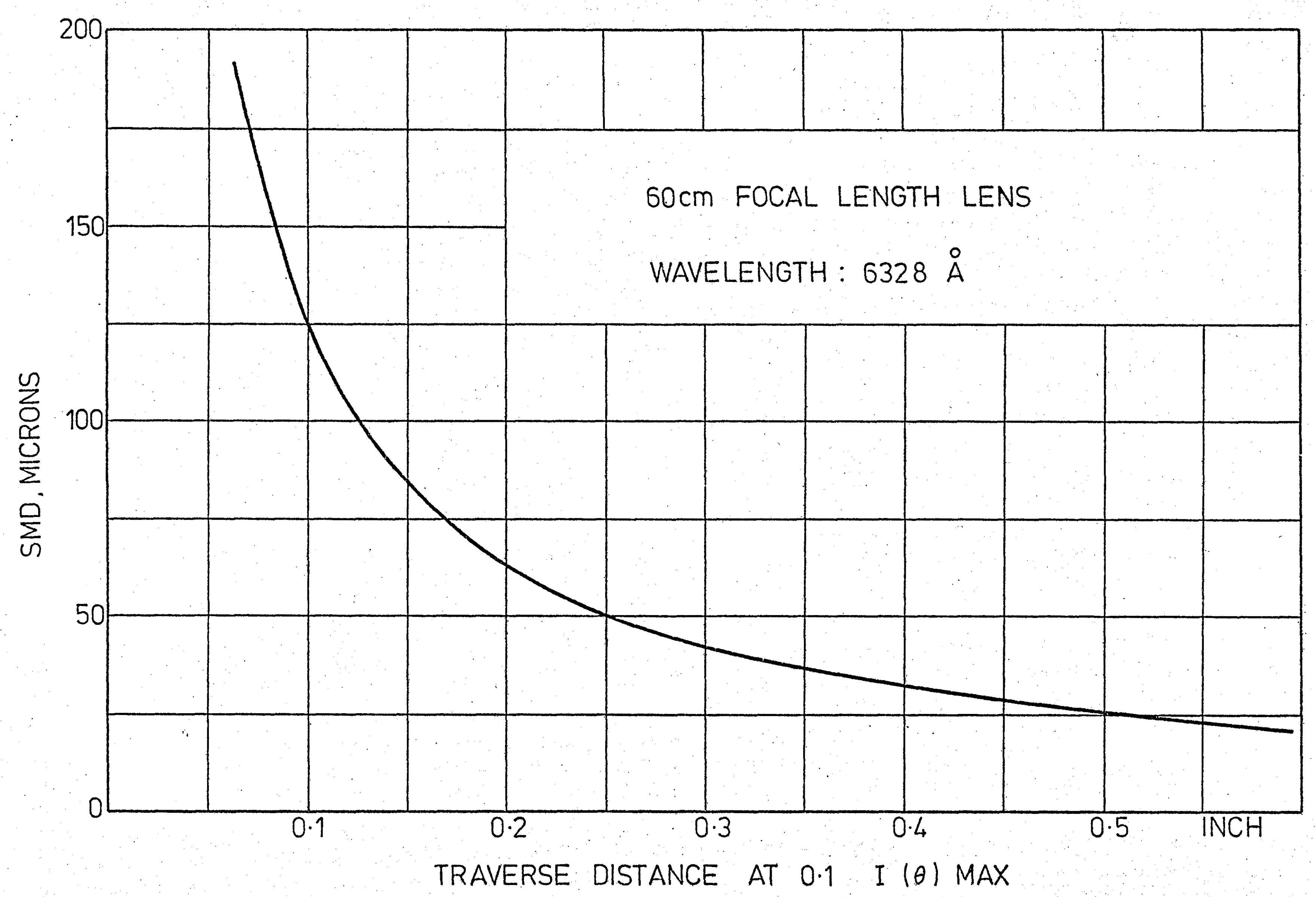


FIG. 23. SMD vs TRAVERSE DISTANCE

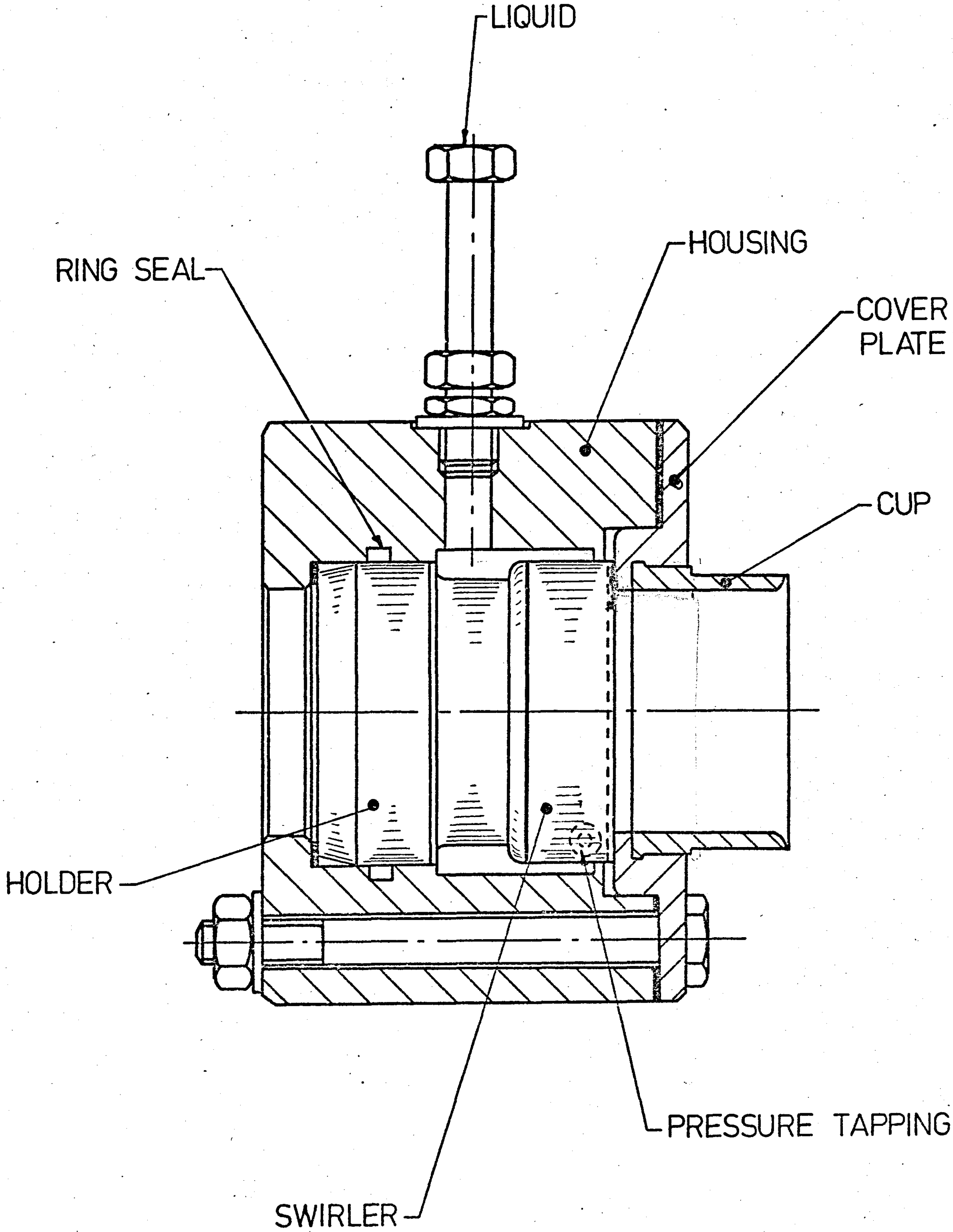
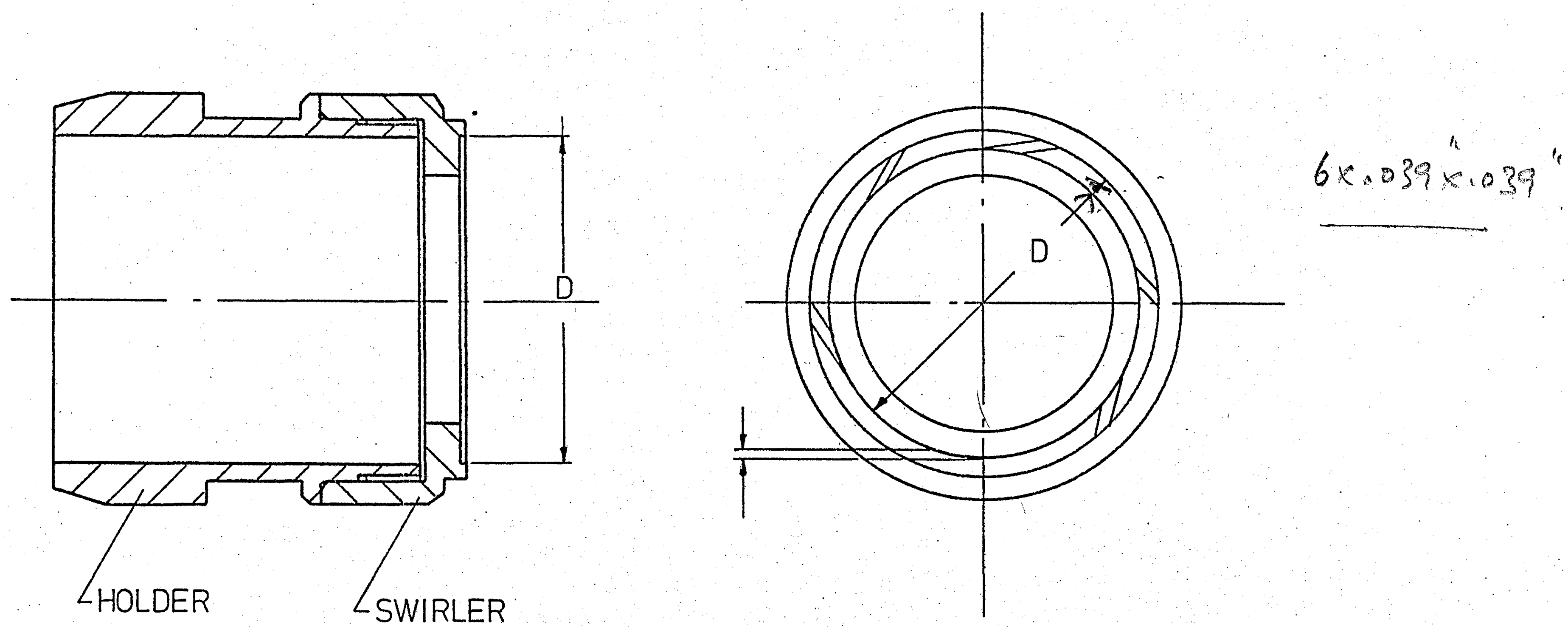


FIG. 24. SWIRLERS' TEST SECTION

X



D = OFFSET DIAMETER OF SLOTS { 12·7mm, 25·4 mm, 50·8 mm

W - WIDTH OF SLOT ± ·002"
SLOTS EQUISPACED AND TANGENTIAL TO INSIDE DIAMETER

FIG. 25 LIQUID SWIRLER AND HOLDER

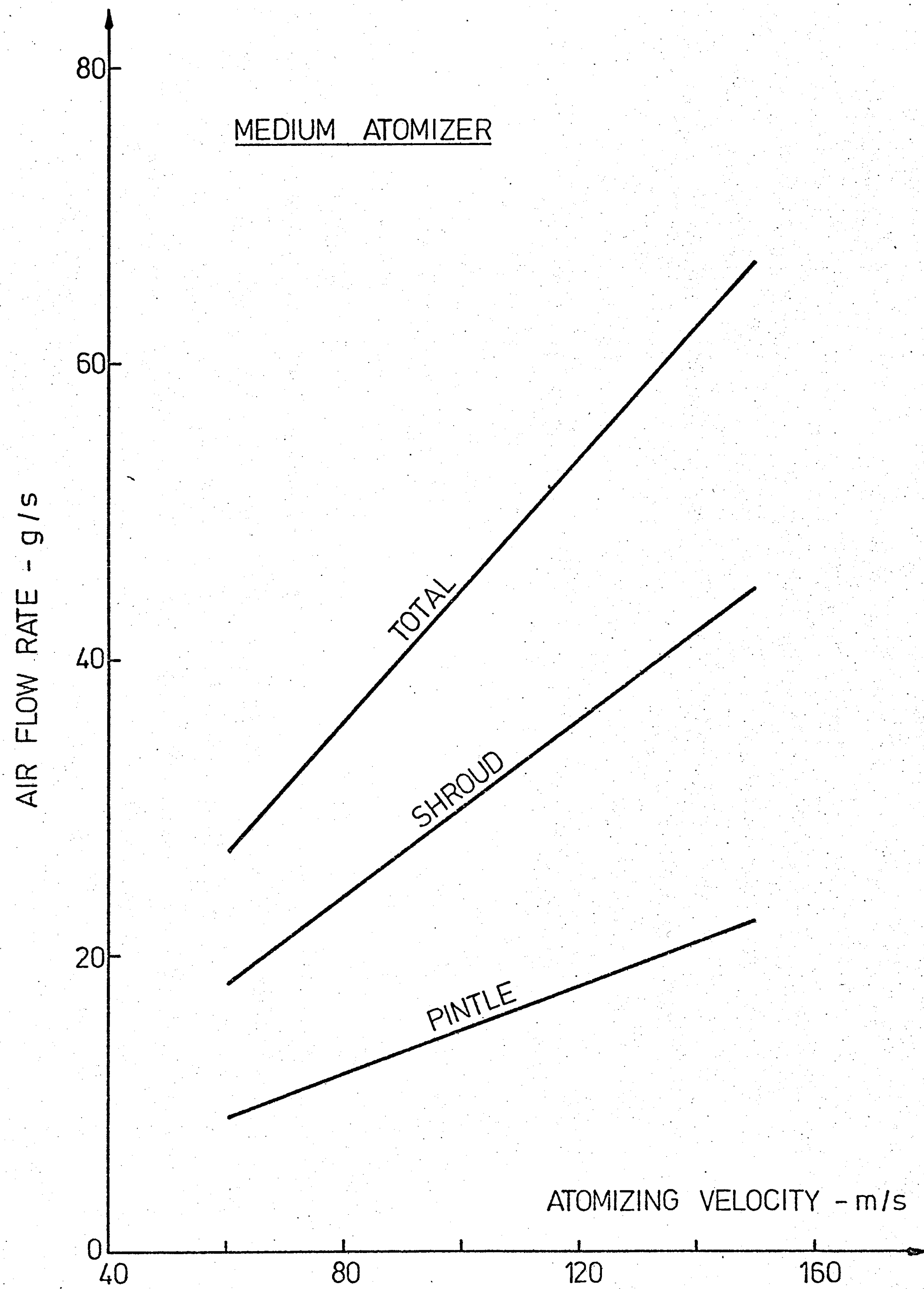


FIG. 26. FLOW CHARACTERISTICS OF THE ATOMIZING AIR

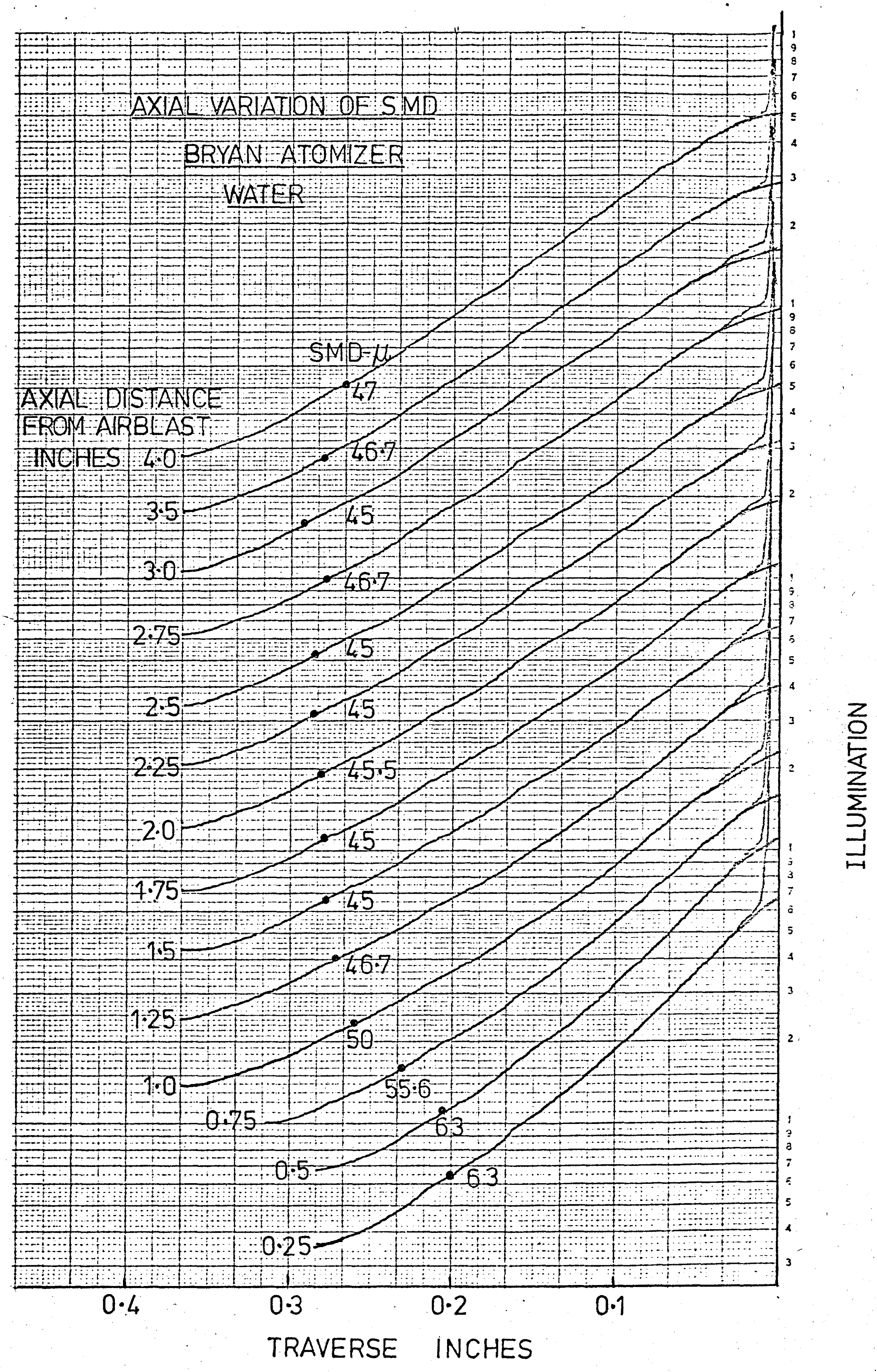


FIG. 27. TYPICAL LIGHT SCATTER PROFILES

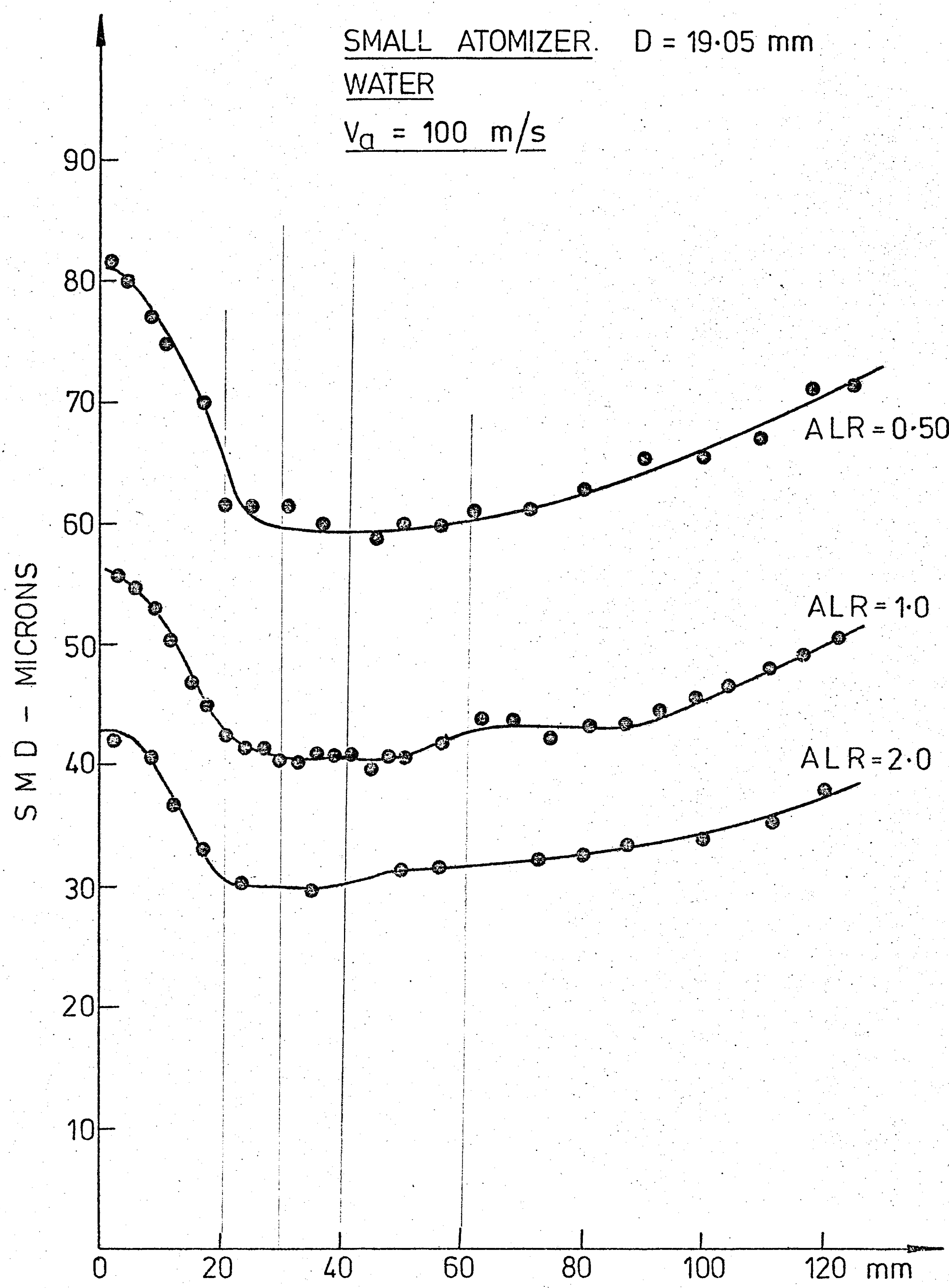


FIG. 28. VARIATION OF SMD WITH DISTANCE, FROM AIRBLAST ATOMIZER EXIT PLANE, ALONG SPRAY AXIS

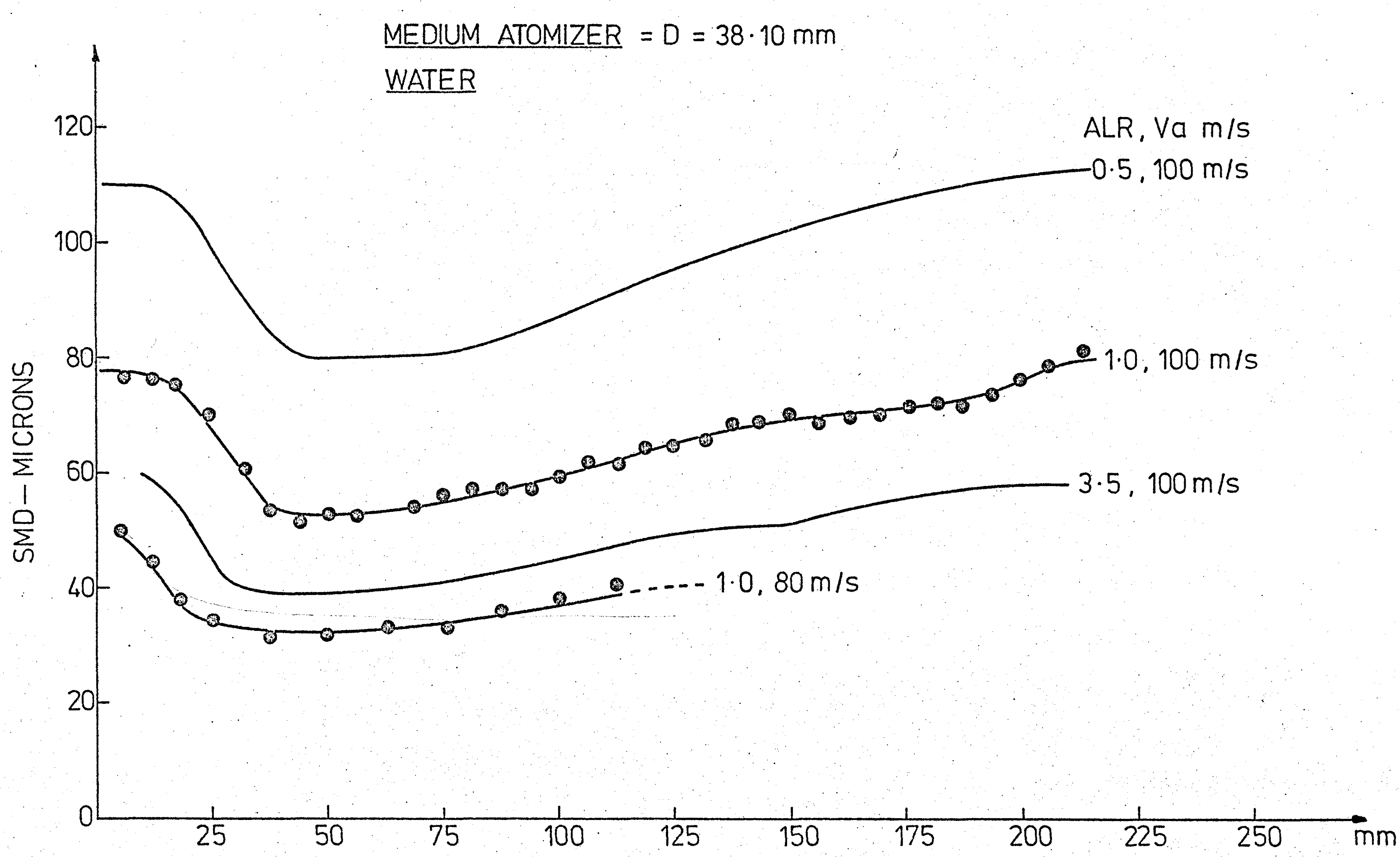


FIG. 29. VARIATION OF SMD WITH DISTANCE, FROM AIRBLAST ATOMIZER EXIT PLANE, ALONG SPRAY AXIS

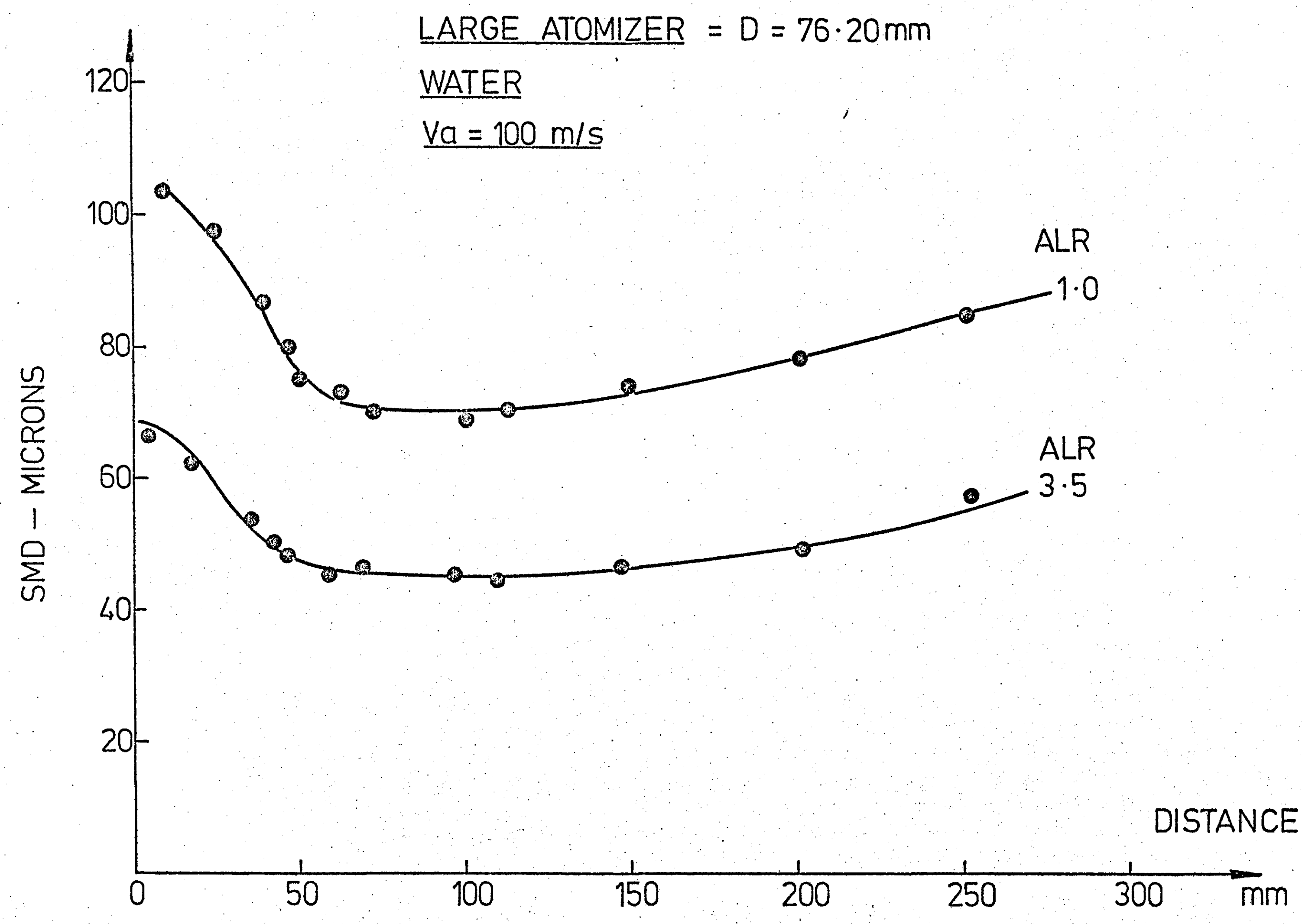


FIG. 30. VARIATION OF SMD WITH DISTANCE, FROM AIRBLAST ATOMIZER EXIT PLANE, ALONG SPRAY AXIS

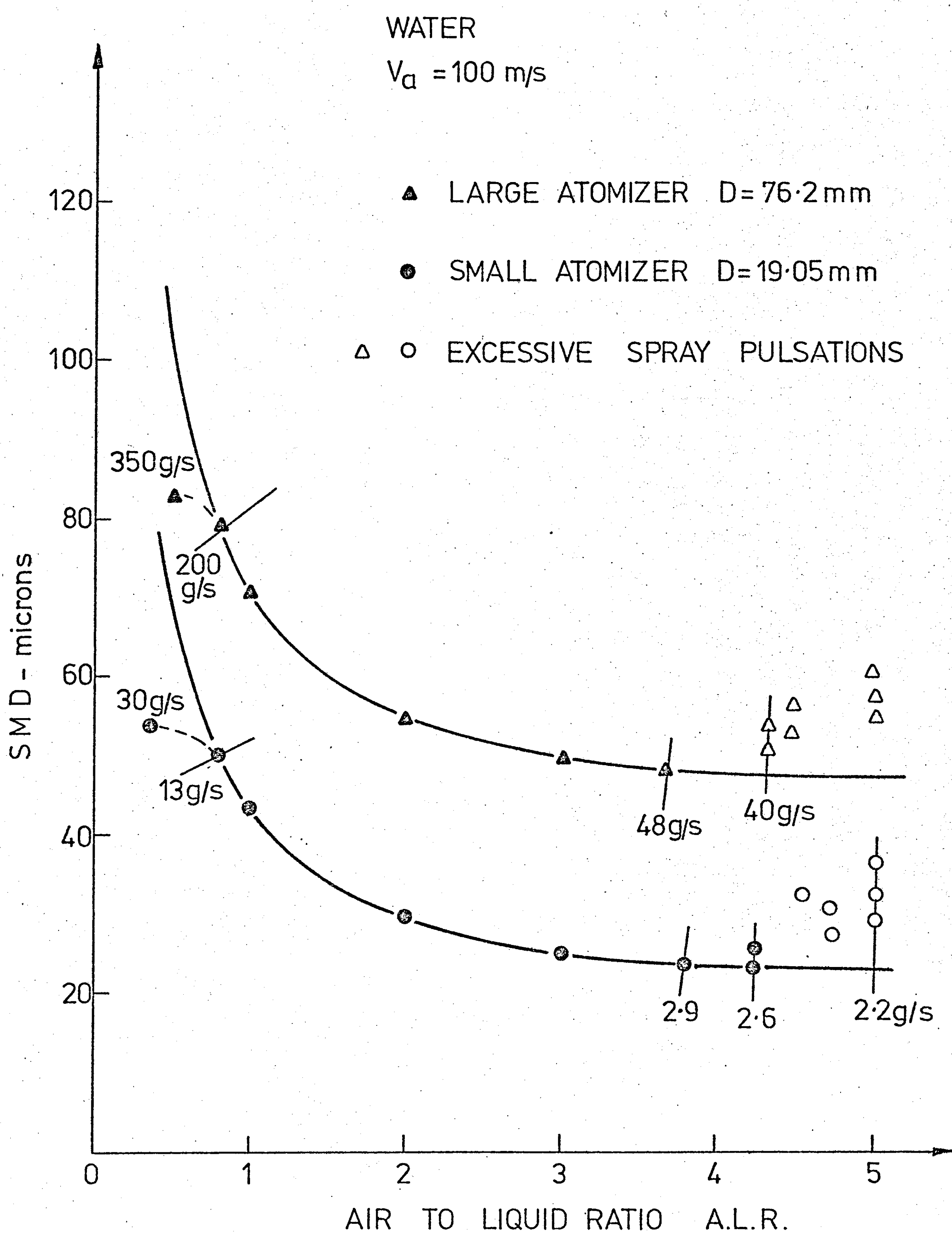


FIG. 31 EFFECT OF LIQUID-RATE ON SPRAY MEAN DIAMETER

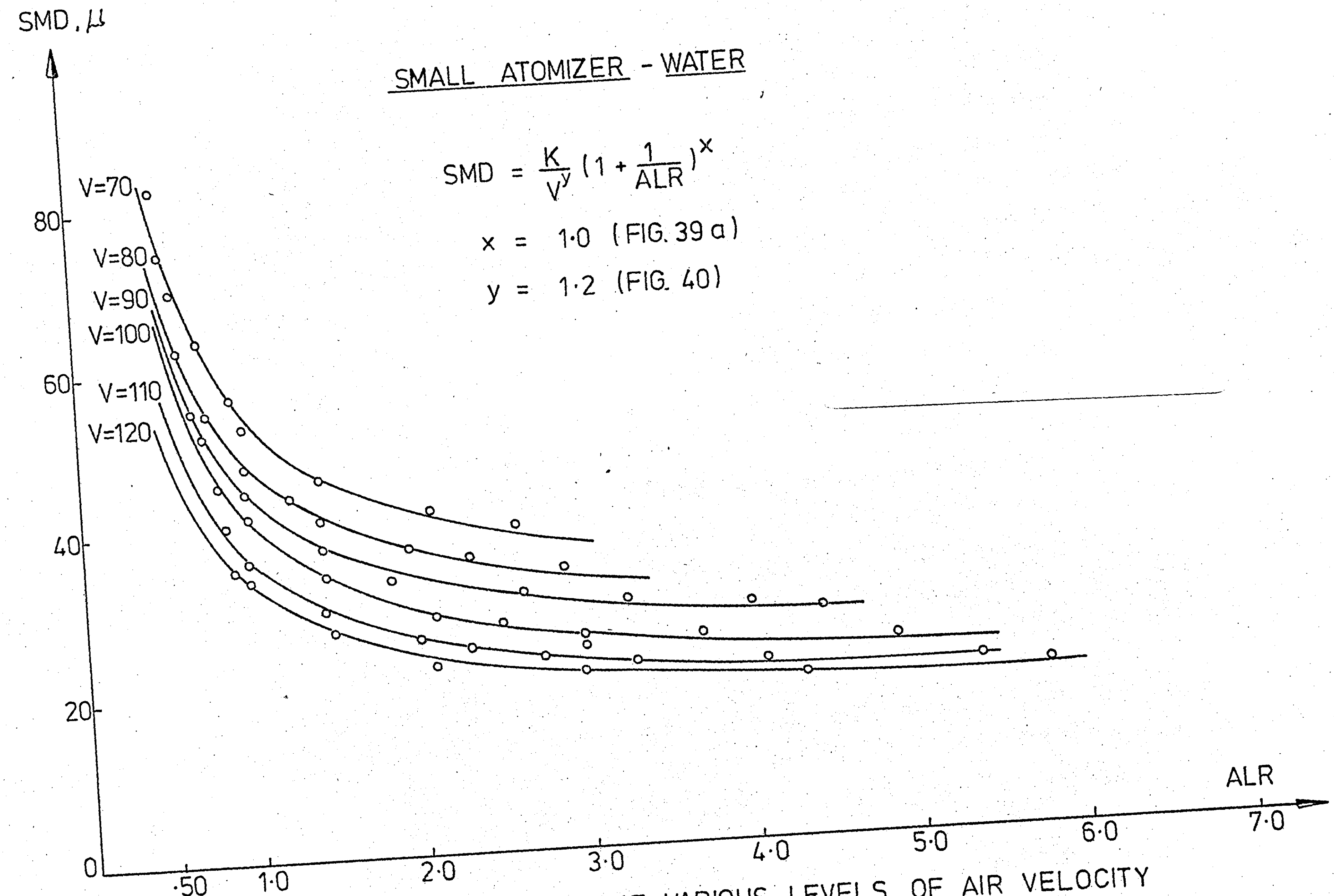


FIG. 32. VARIATION OF SMD WITH ALR, AT VARIOUS LEVELS OF AIR VELOCITY

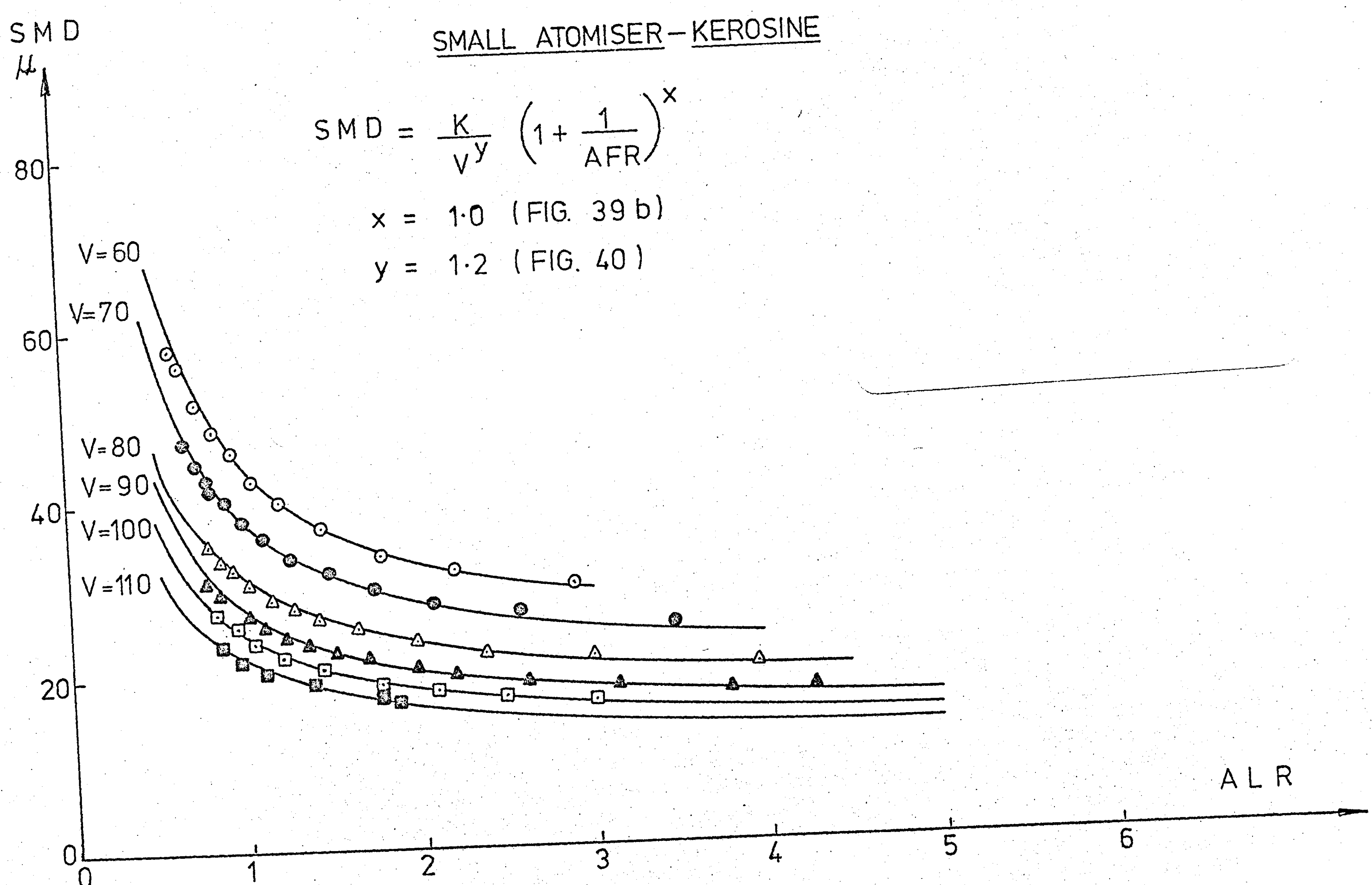


FIG. 33. VARIATION OF SMD WITH ALR, AT VARIOUS LEVELS OF AIR-VELOCITY

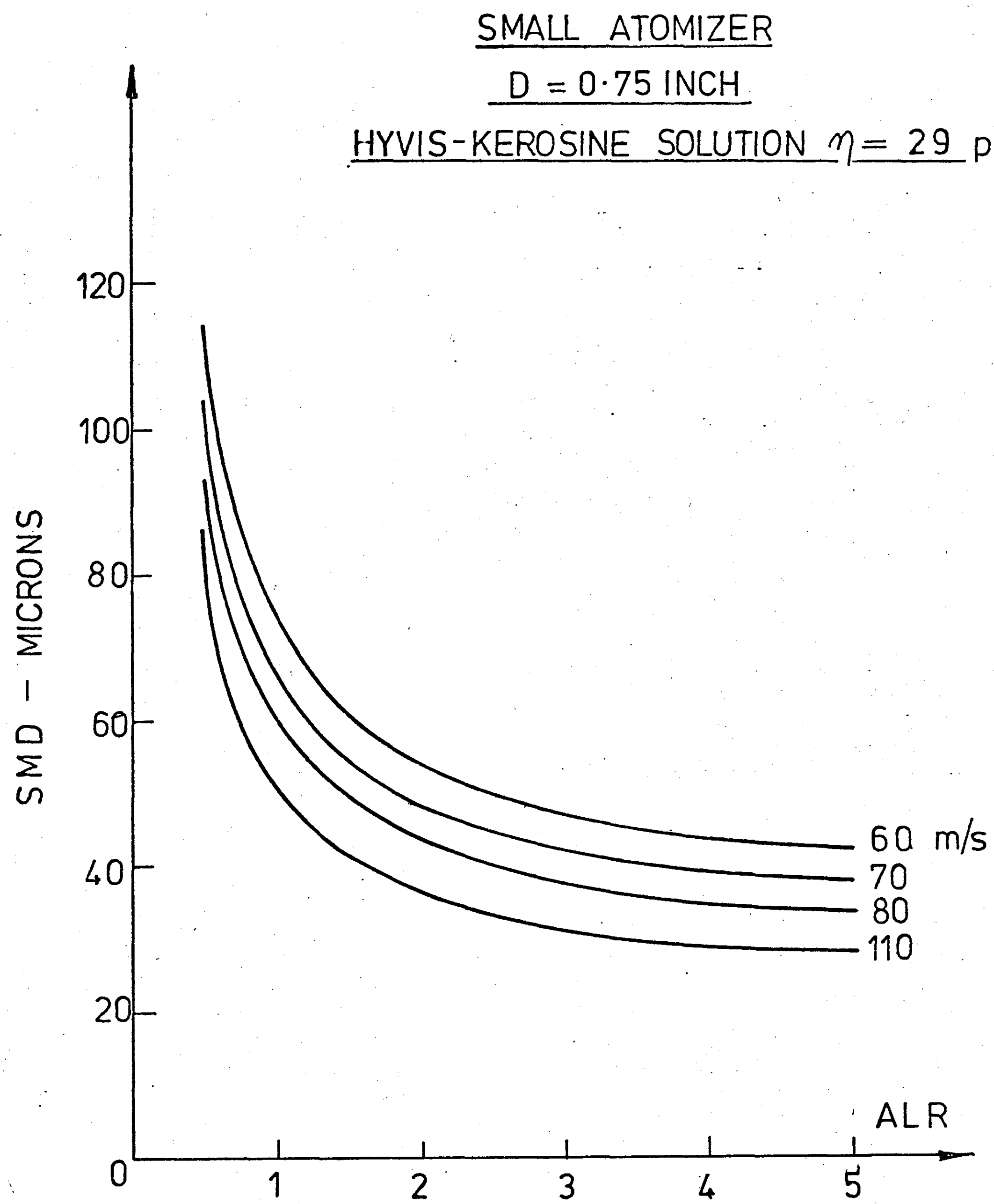


FIG. 34. HIGH VISCOSITY LIQUID SPRAYS – VARIATION OF SMD WITH ALR AT VARIOUS LEVELS OF AIR-VELOCITY

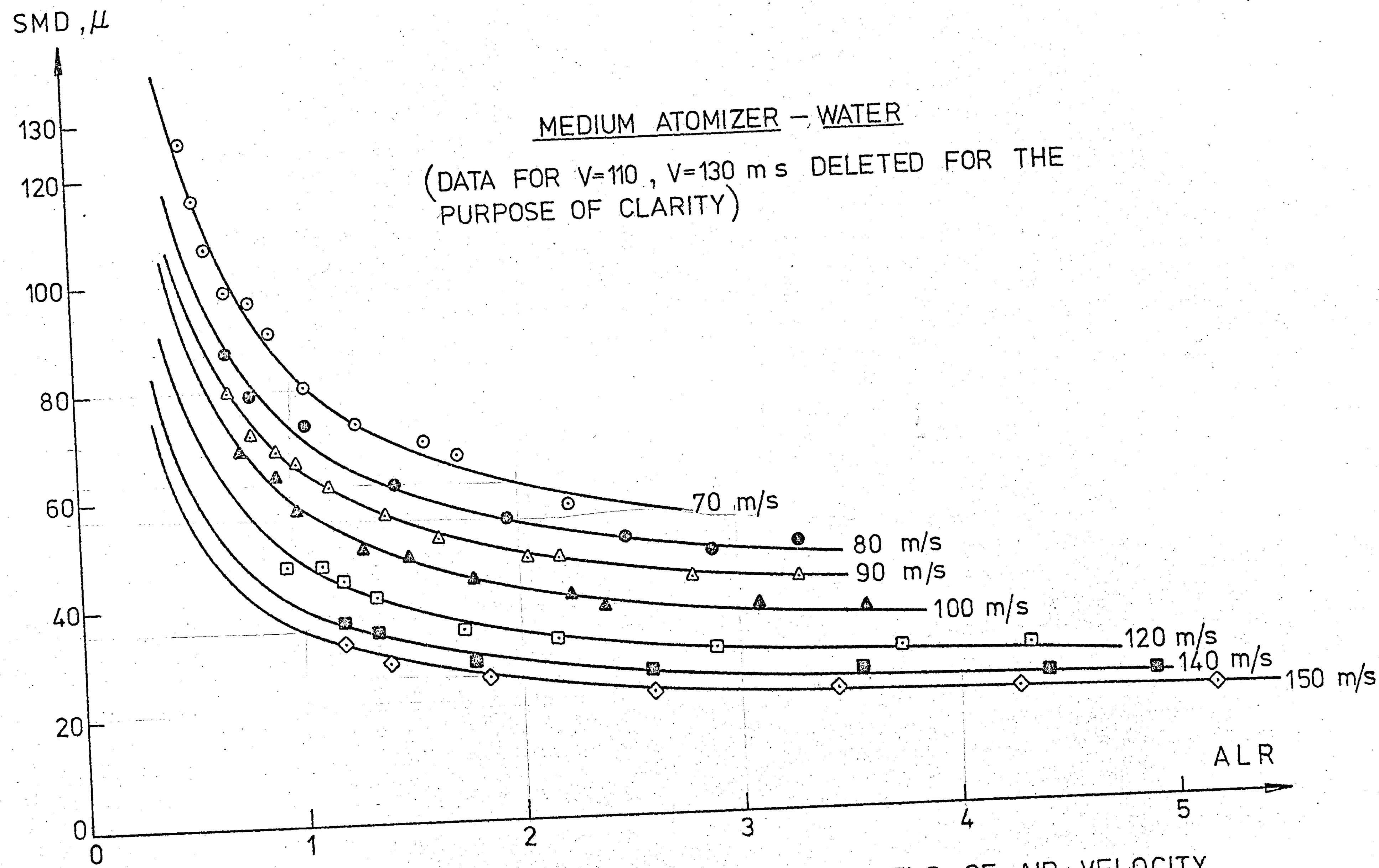


FIG. 35. VARIATION OF SMD WITH ALR, AT VARIOUS LEVELS OF AIR-VELOCITY

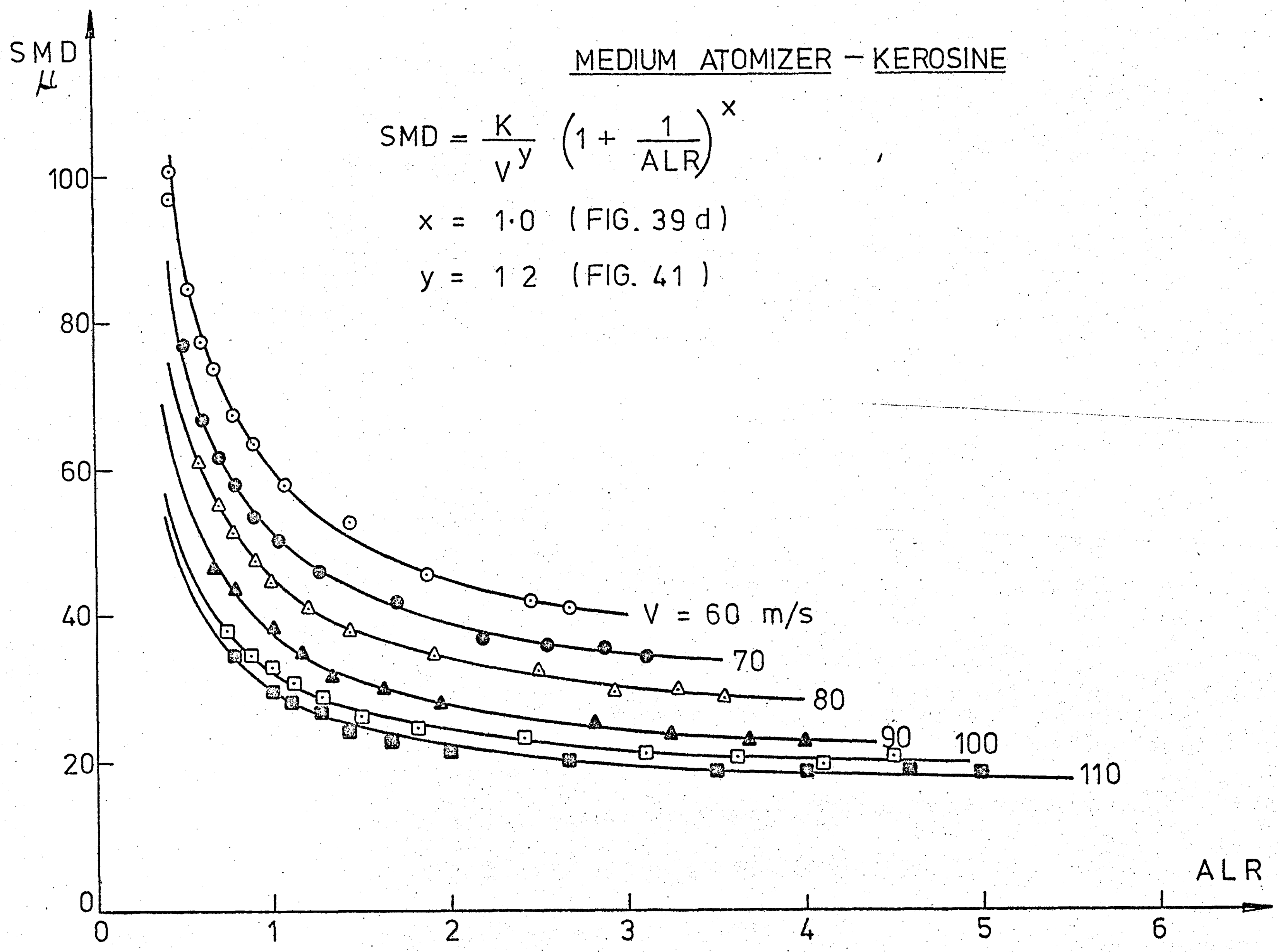


FIG. 36. VARIATION OF SMD WITH ALR, AT VARIOUS LEVELS OF AIR-VELOCITY

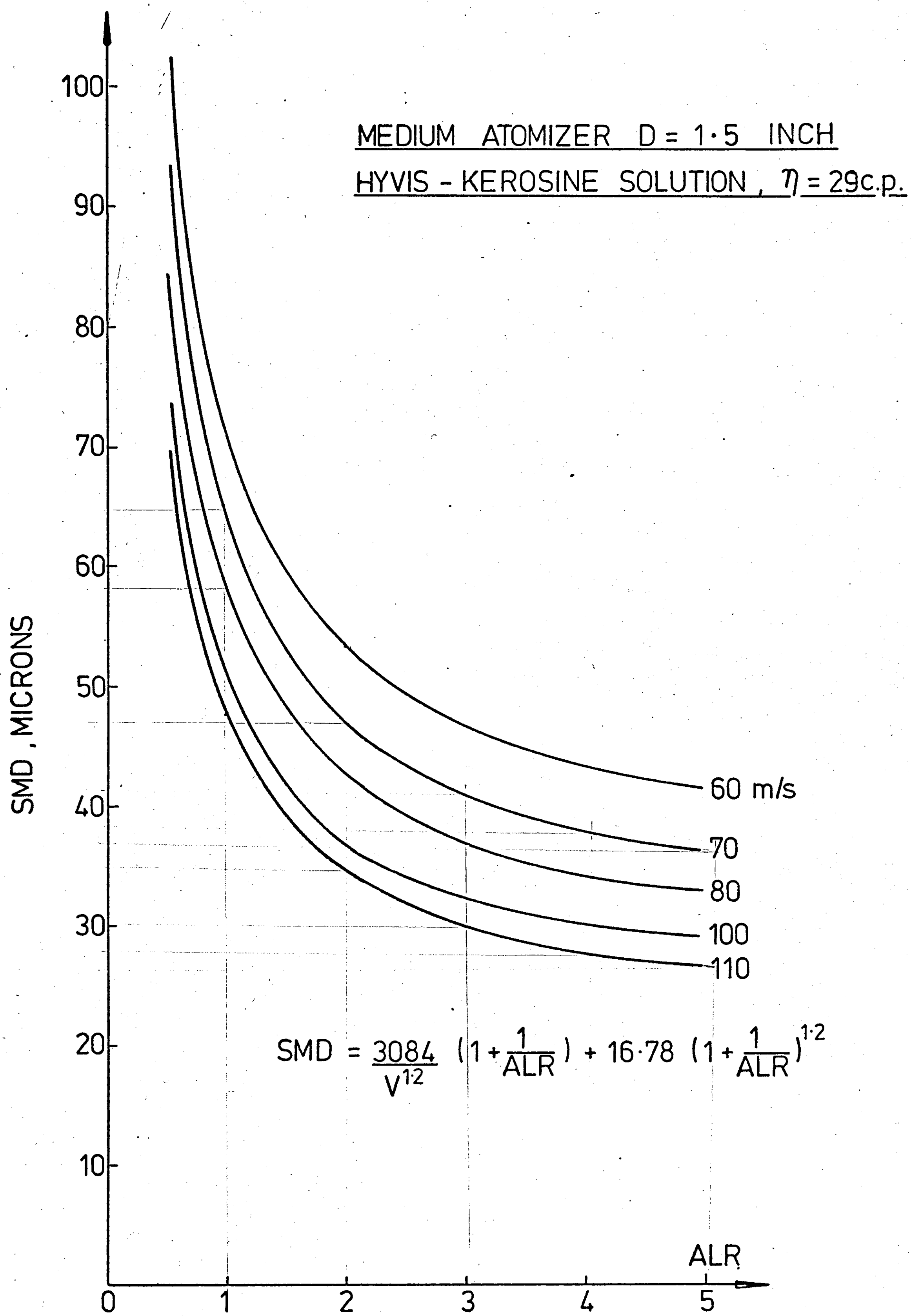


FIG. 37. VARIATION OF SMD WITH ALR, AT VARIOUS LEVELS OF AIR-VELOCITY

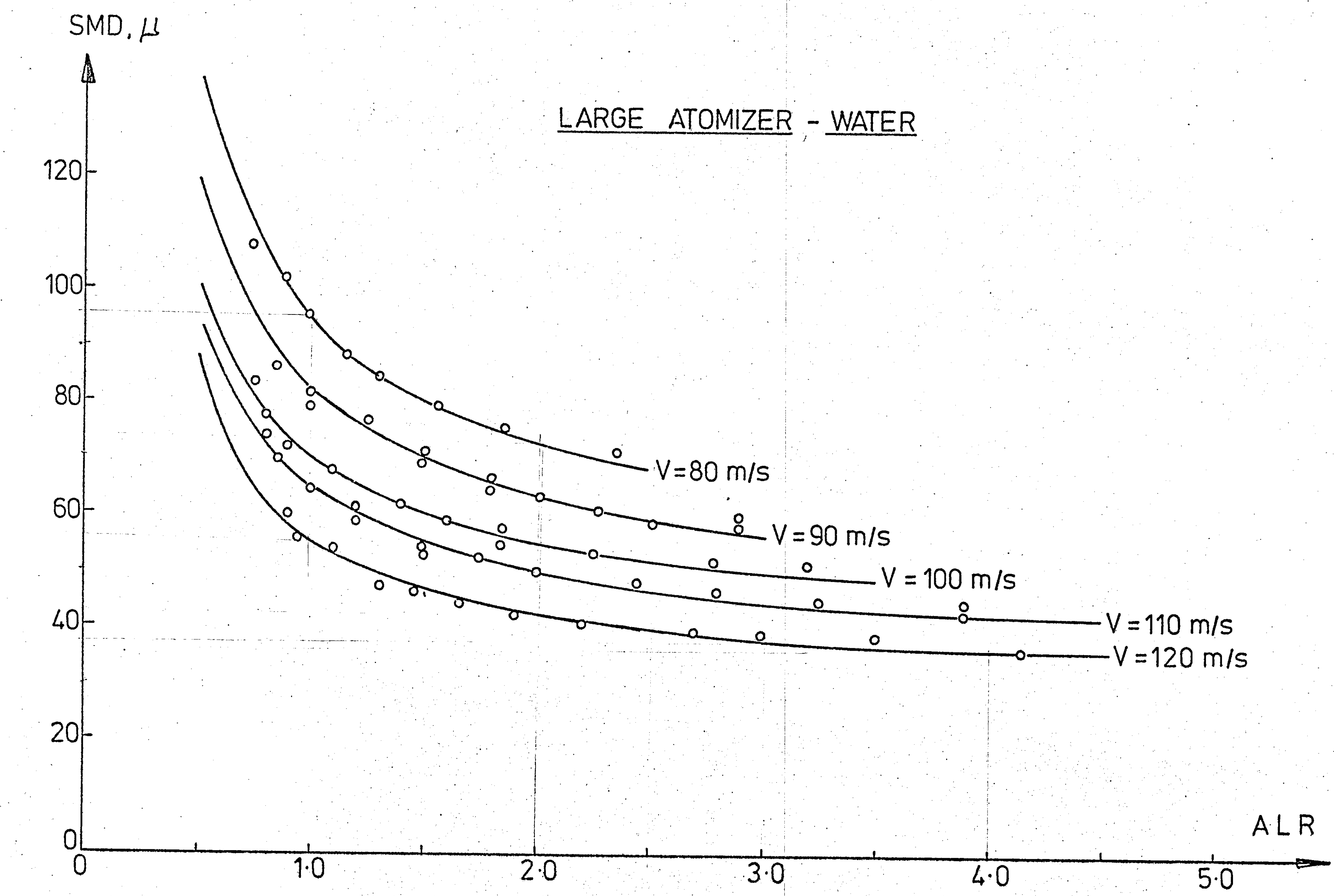


FIG. 38. VARIATION OF SMD WITH ALR, AT VARIOUS LEVELS OF AIR-VELOCITY

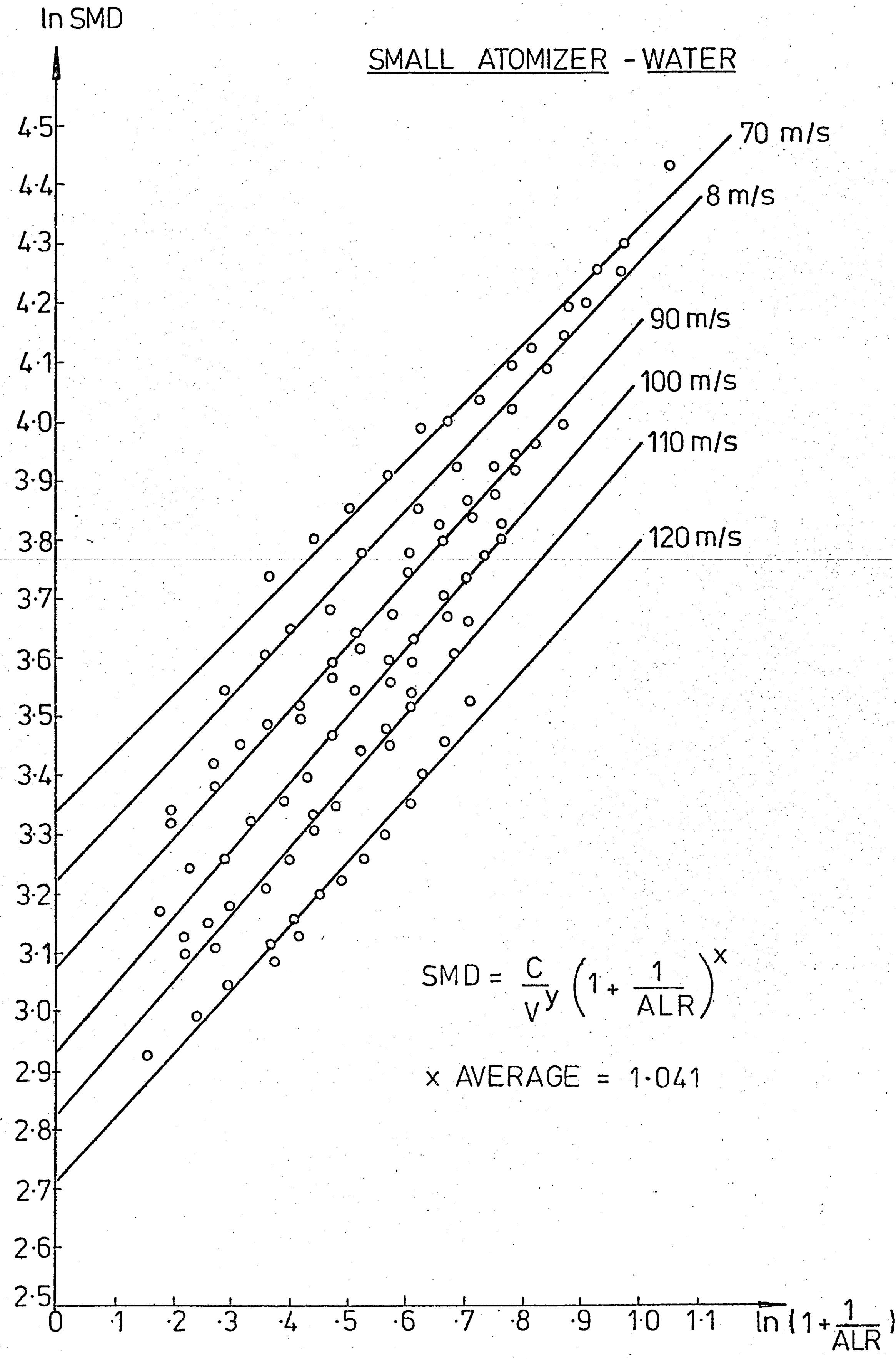


FIG 39 a CORRELATIONS FOR VARIATION OF SMD WITH ALR AT CONSTANT LEVELS OF AIR-VELOCITY

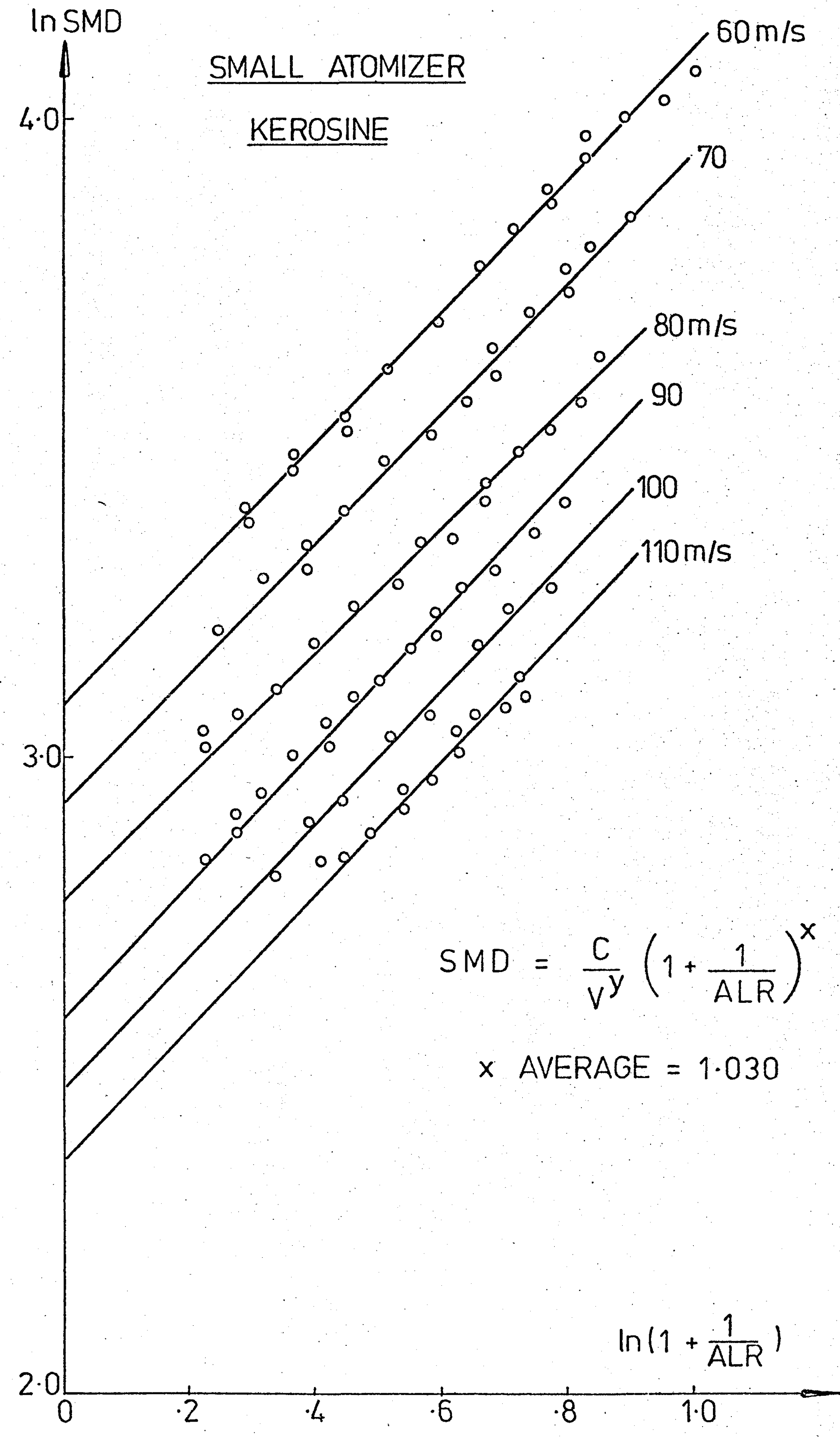


FIG. 39 b. CORRELATION OF DATA-POINTS, FOR VARIATION OF SMD WITH ALR AT CONSTANT LEVELS OF AIR-VELOCITY

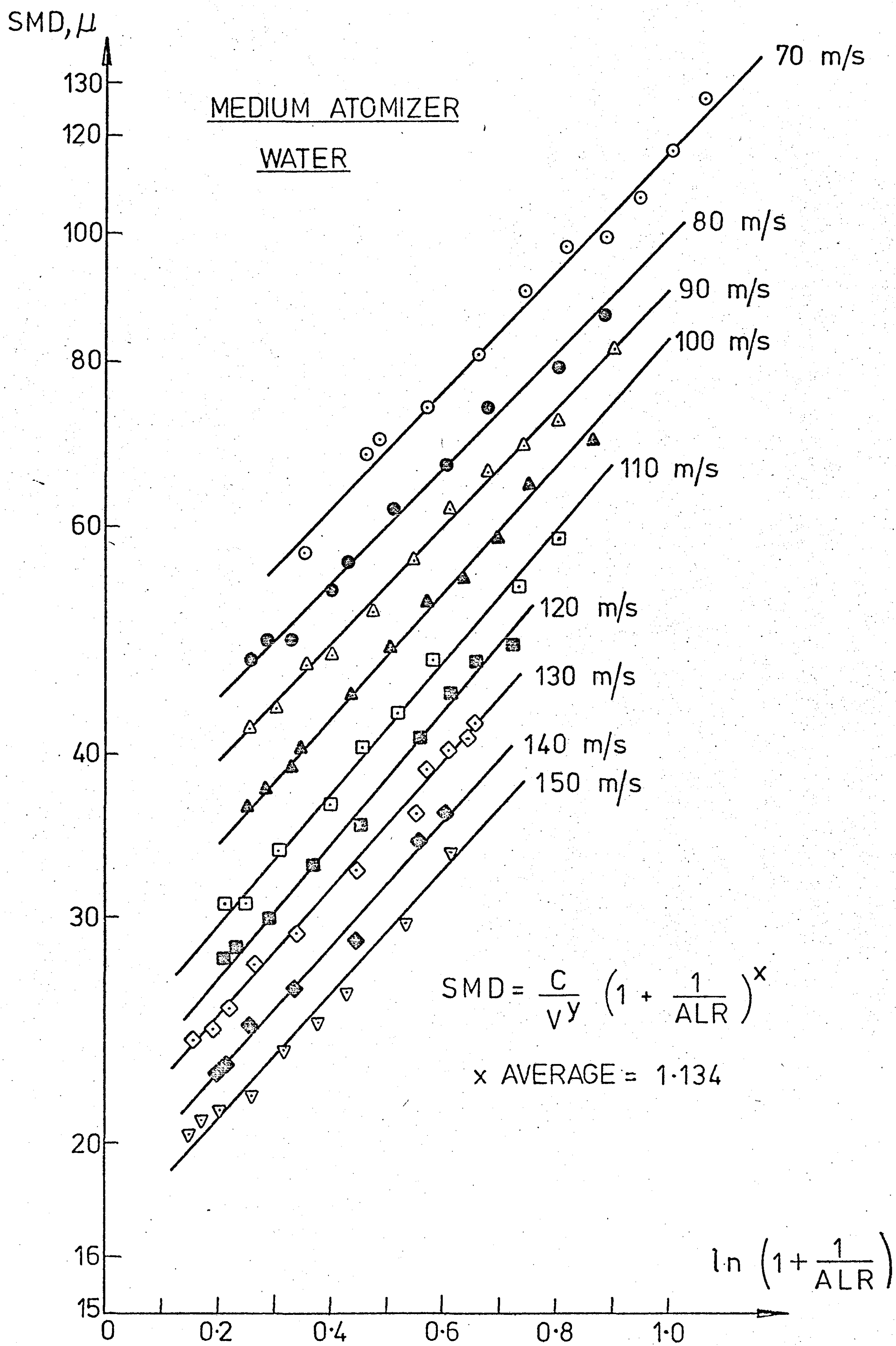


FIG. 39c. CORRELATION FOR VARIATION OF SMD WITH ALR AT CONSTANT LEVELS OF AIR-VELOCITY

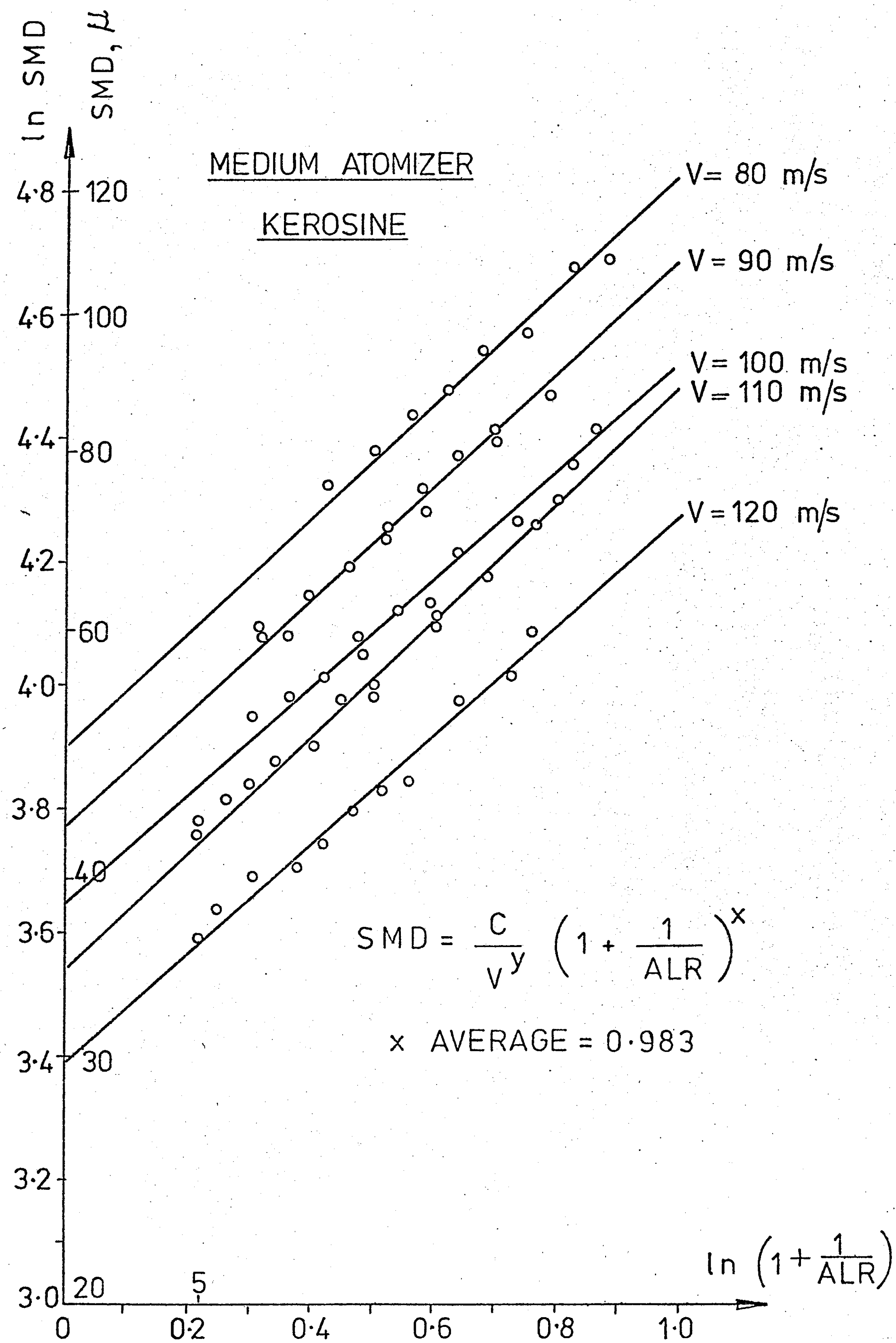


FIG. 39 d. CORRELATION FOR VARIATION OF SMD WITH ALR AT CONSTANT LEVELS OF AIR-VELOCITY

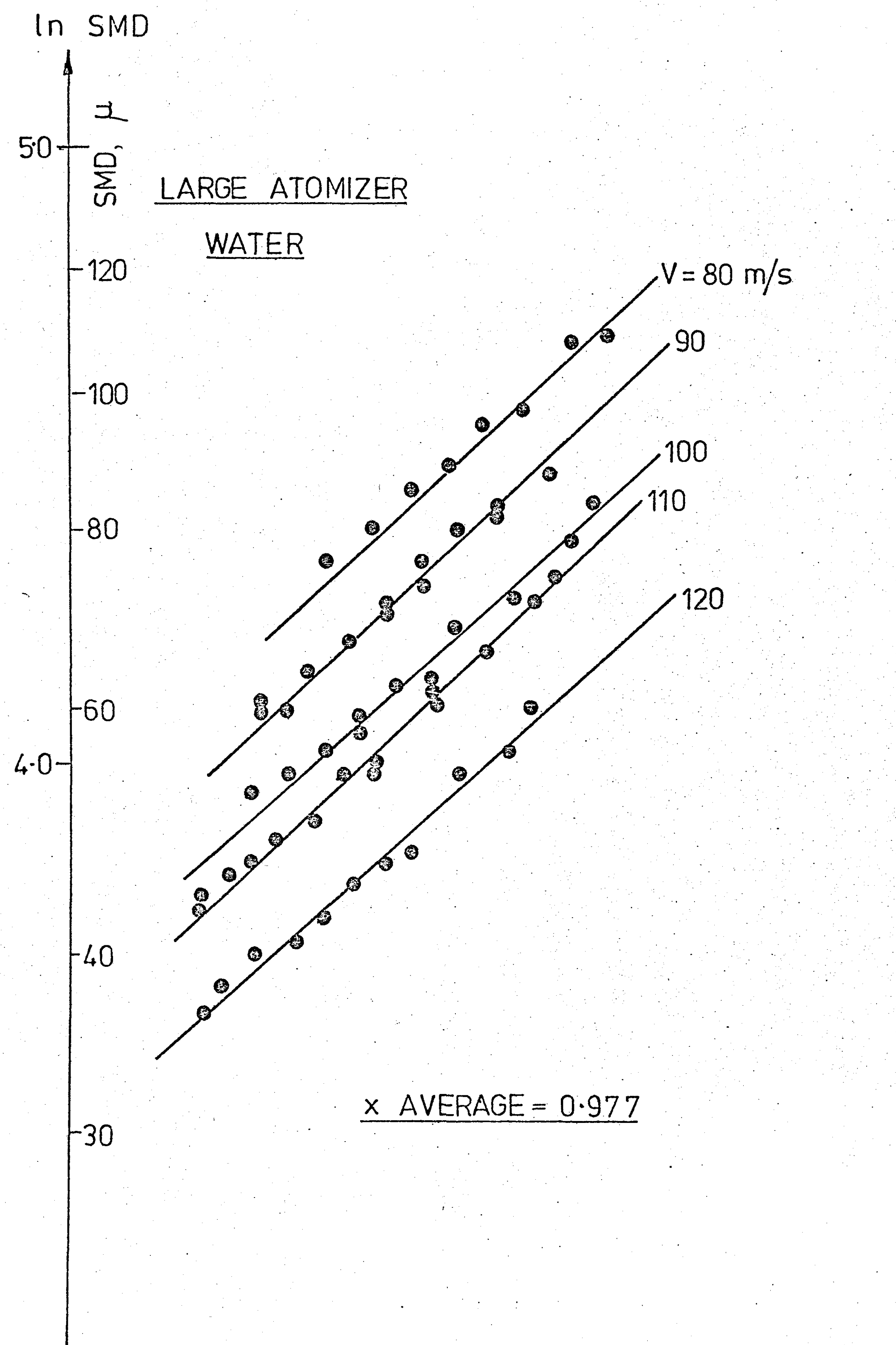


FIG 39e VARIATION OF SMD WITH ALR AT VARIOUS LEVELS OF ATOMIZING AIR-VELOCITY

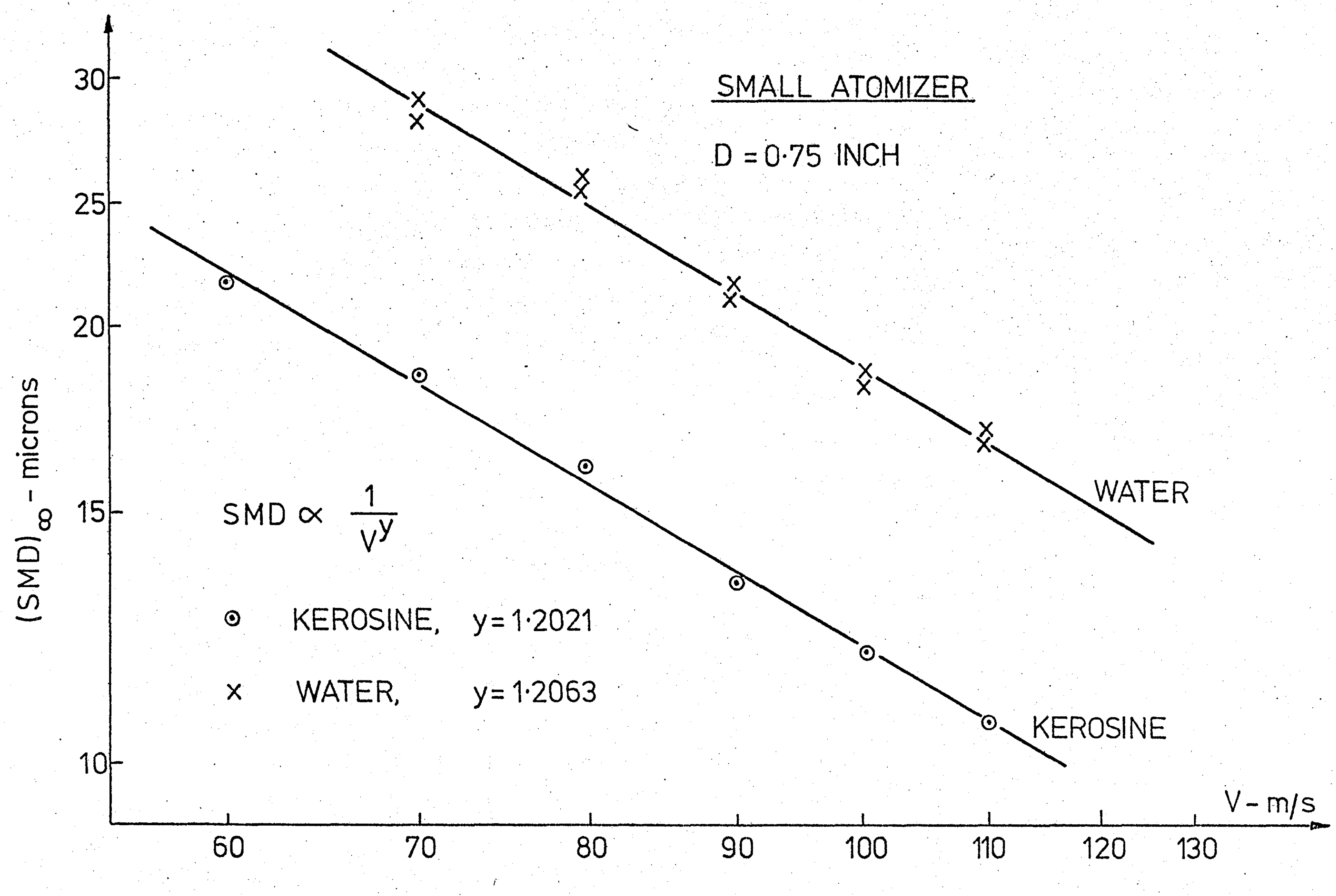


FIG. 40 RELATIONSHIP BETWEEN THE ATOMIZING - AIR VELOCITY AND THE SMD OF LOW VISCOSITY LIQUID SPRAYS

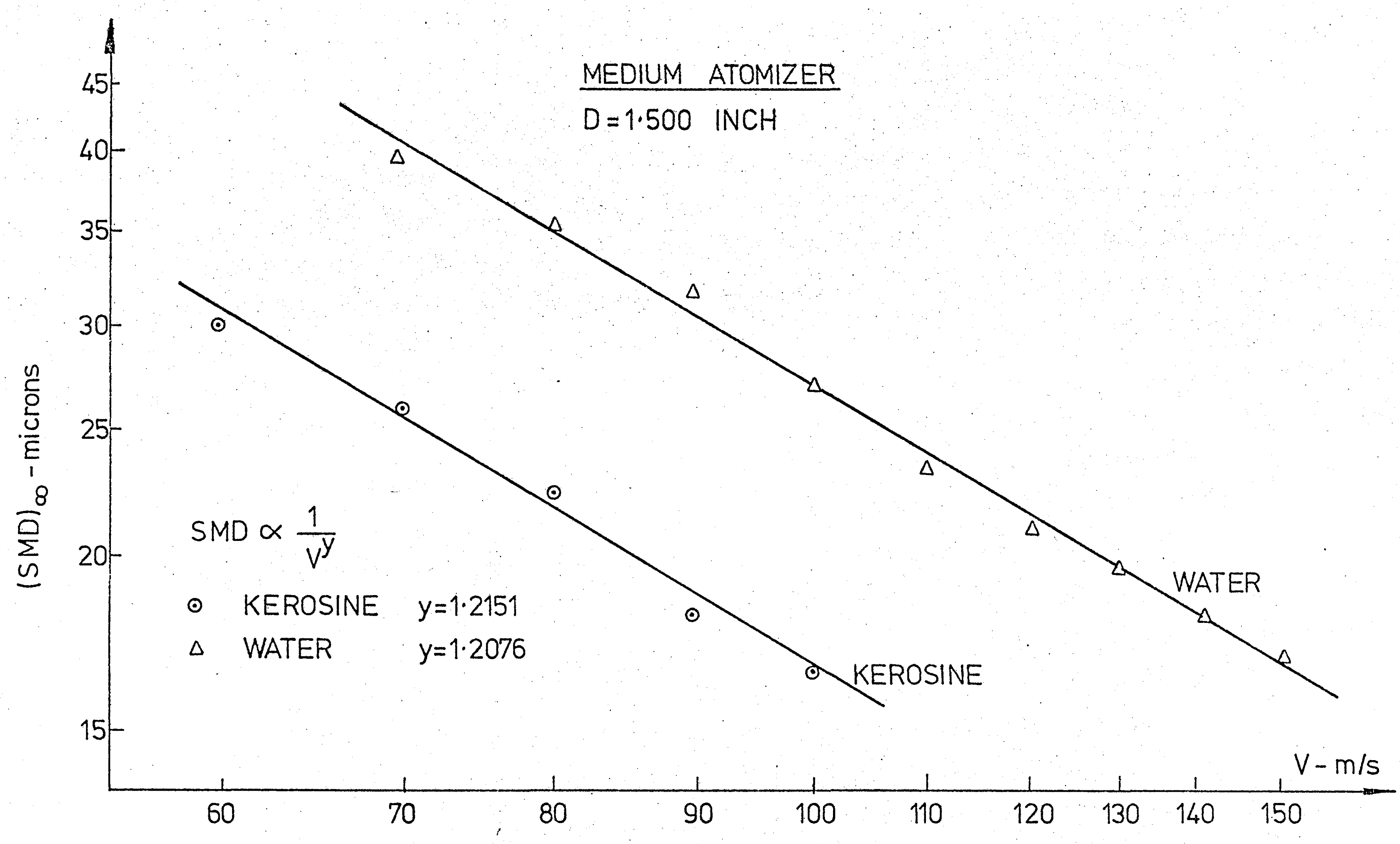


FIG 41 RELATIONSHIP BETWEEN THE ATOMIZING - AIR VELOCITY AND THE SMD OF LOW VISCOSITY LIQUID SPRAY

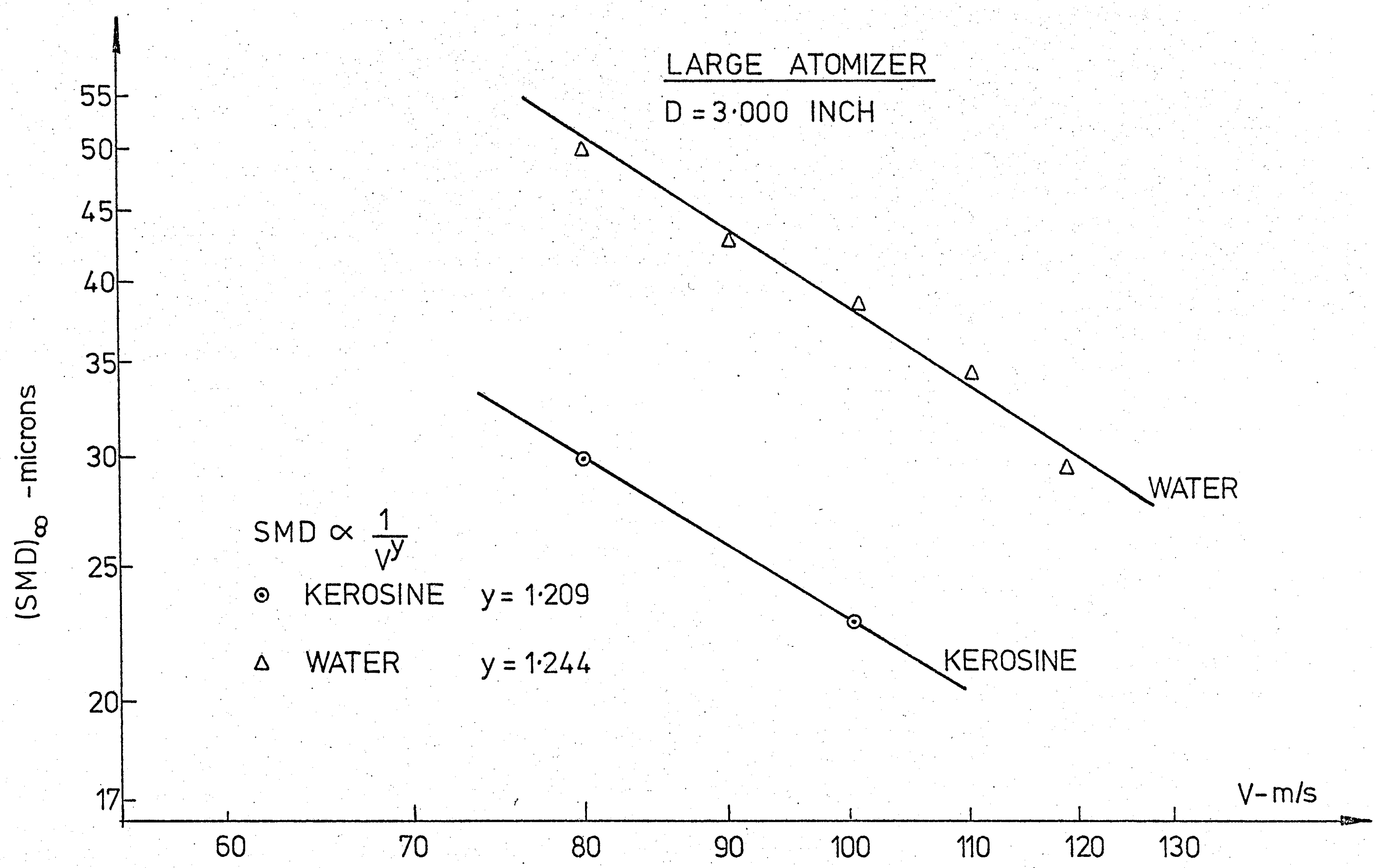


FIG 42 RELATIONSHIP BETWEEN THE ATOMIZING-AIR VELOCITY AND THE SMD OF LOW VISCOSITY LIQUID SPRAY

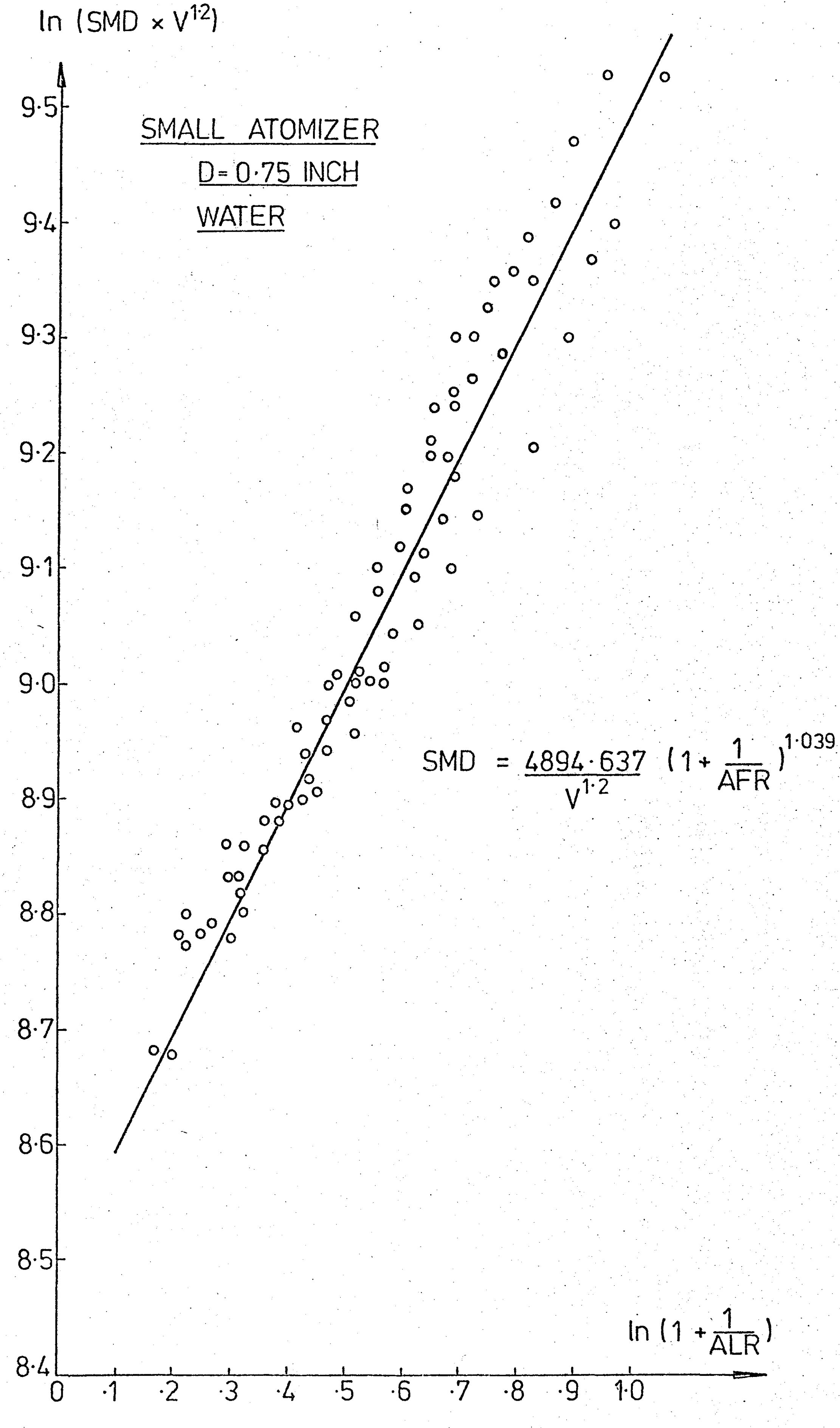


FIG. 43 a: CORRELATION FOR VARIATION OF SMD WITH AIR-VELOCITY AND ALR

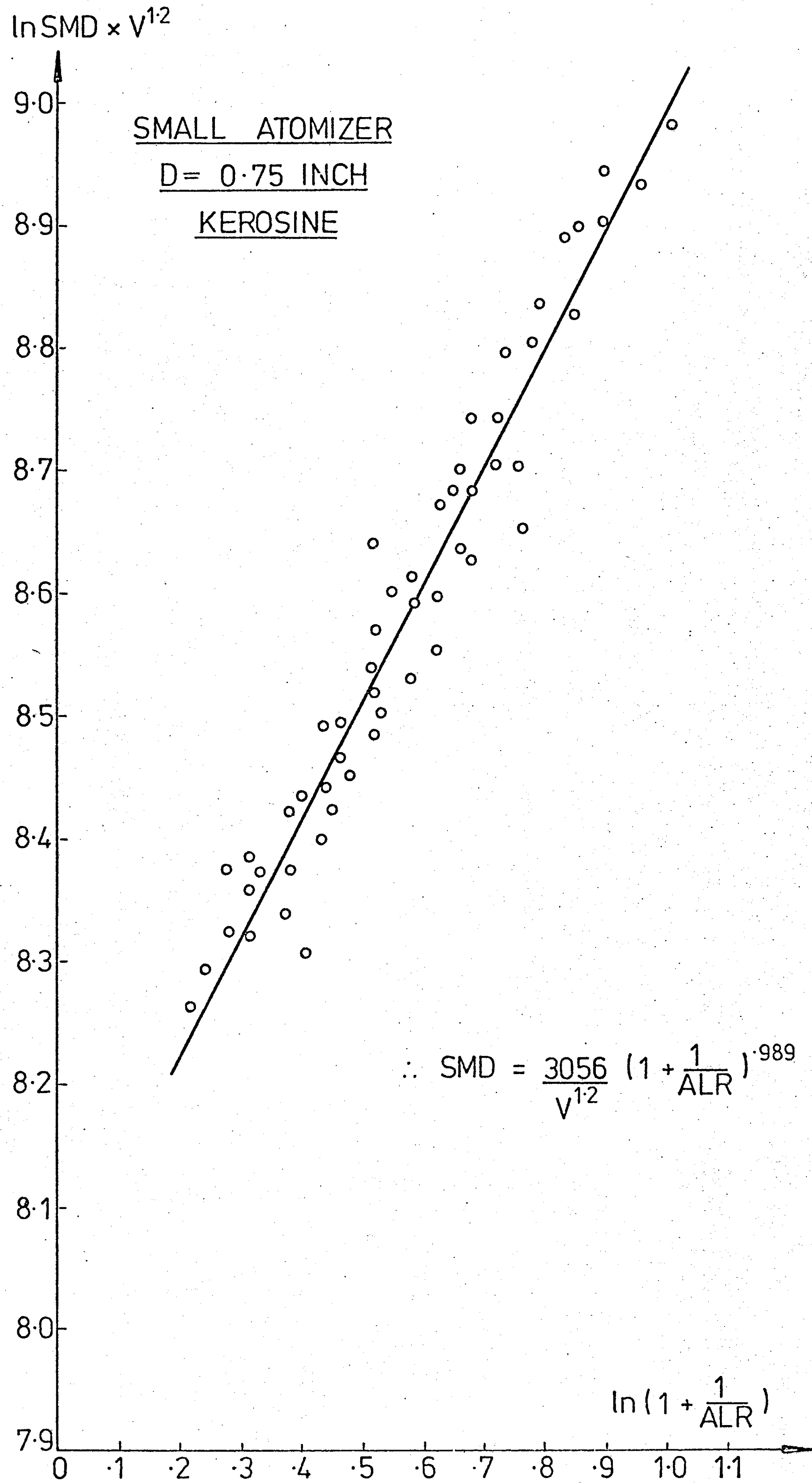


FIG. 43 b. CORRELATION OF DATA-POINTS FOR VARIATION OF SMD WITH AIR-VELOCITY AND ALR

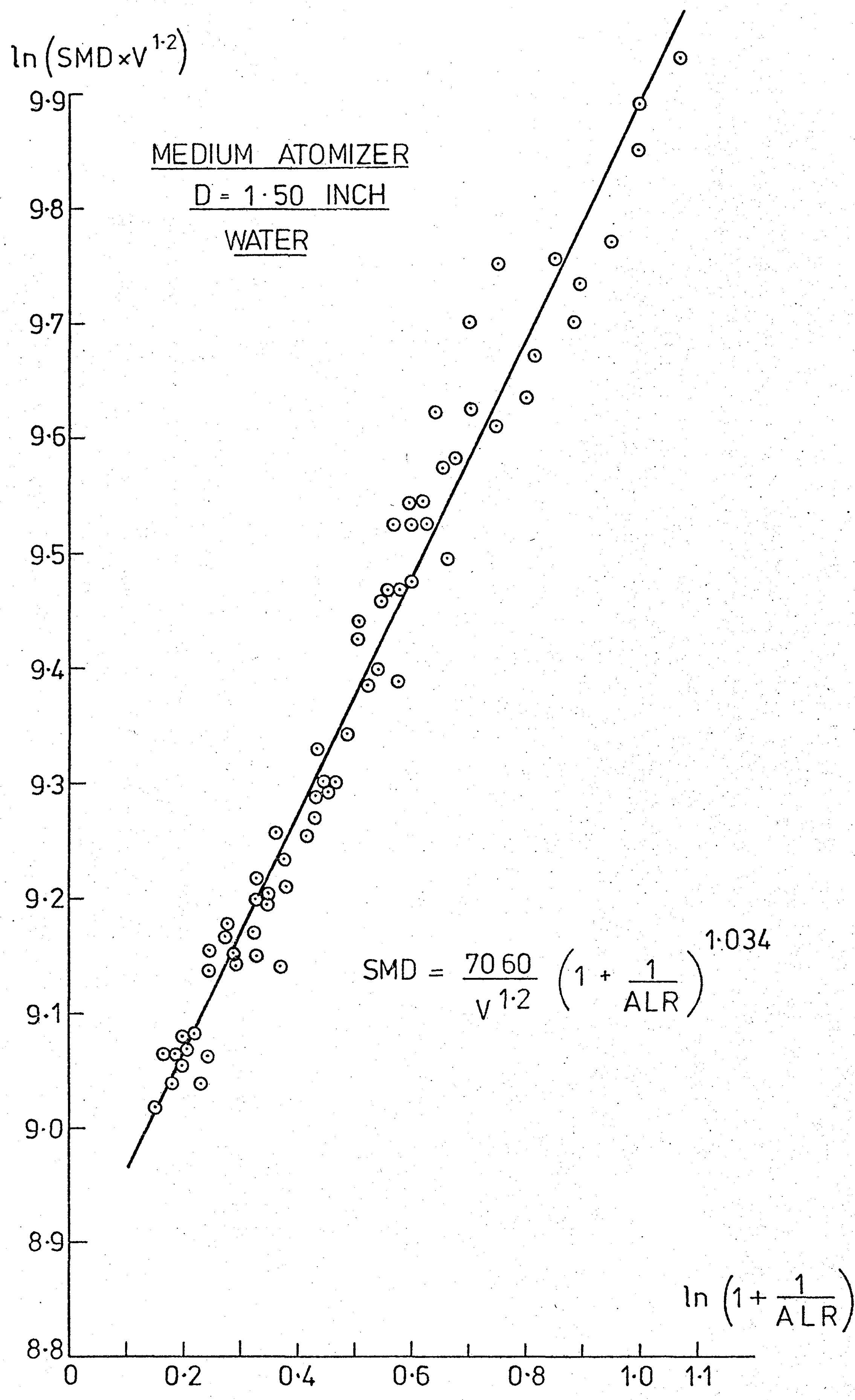


FIG. 44a. CORRELATION FOR VARIATION OF SMD WITH AIR-VELOCITY AND ALR

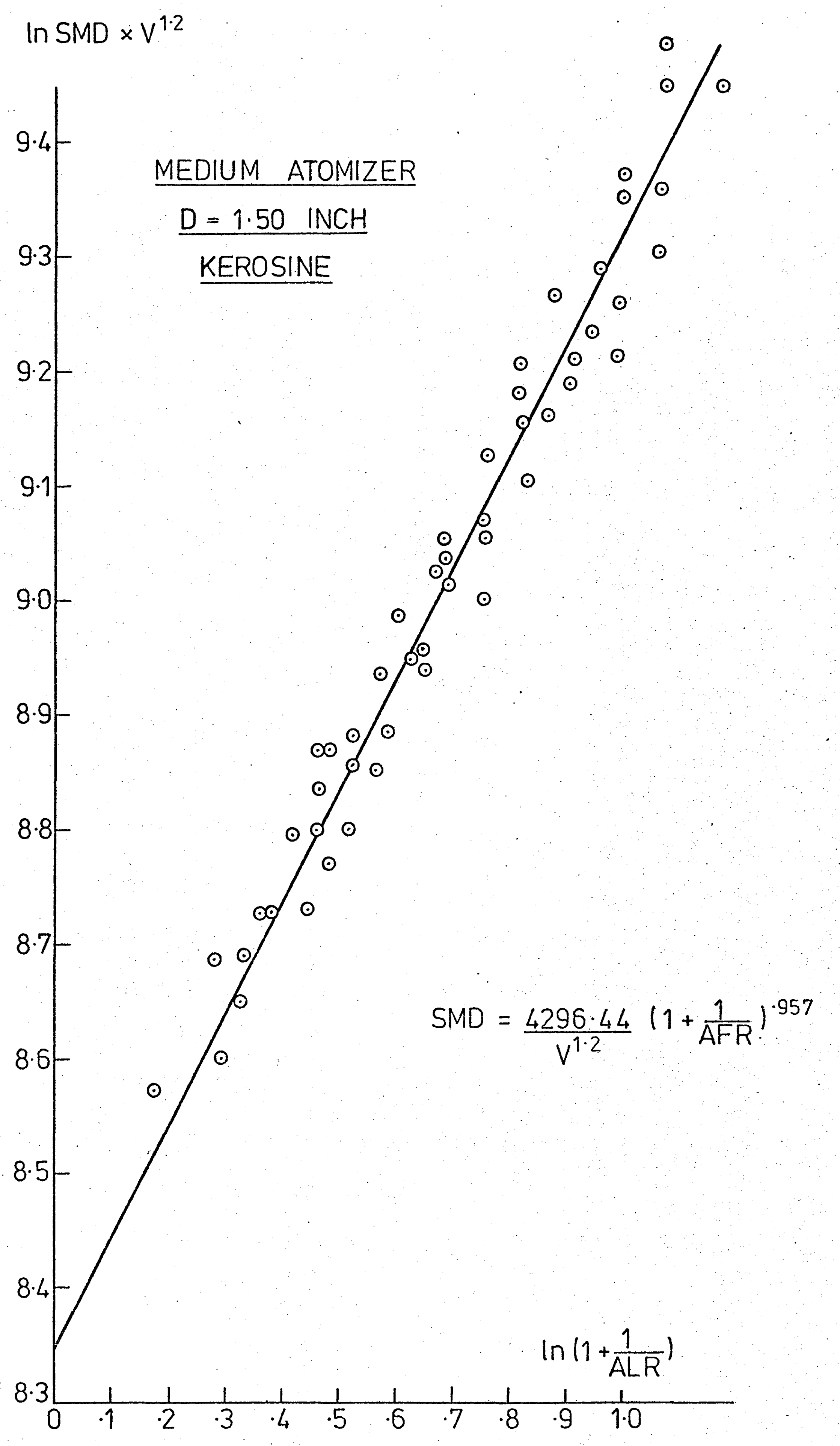


FIG. 44 b. CORRELATION OF DATA-POINTS FOR VARIATION OF SMD WITH AIR-VELOCITY AND ALR

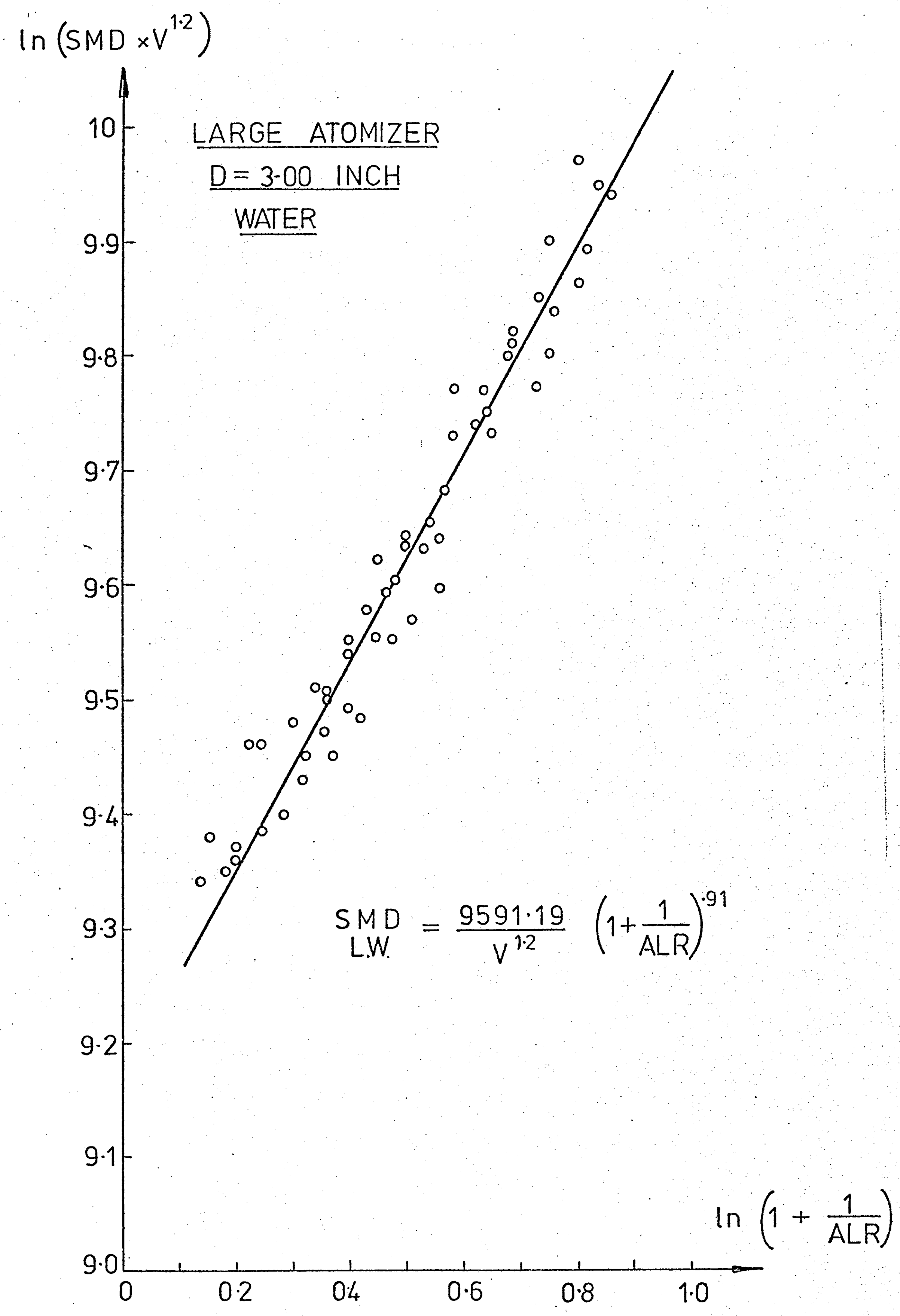


FIG. 45. CORRELATION FOR VARIATION OF SMD WITH AIR-VELOCITY AND ALR

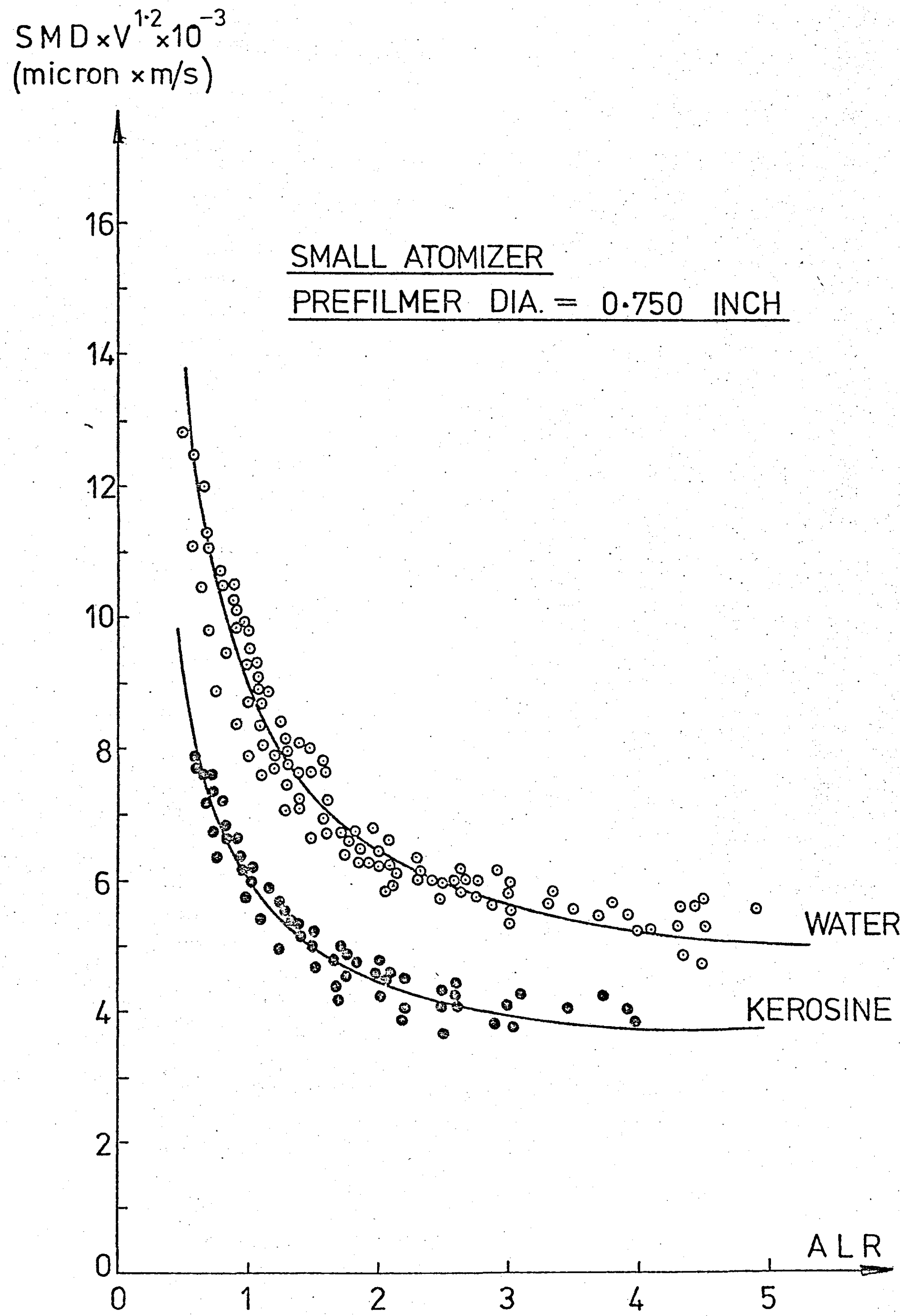


FIG. 46 COMPARISON BETWEEN WATER AND KEROSINE SPRAYS FOR VARIATION OF SMD WITH ALR

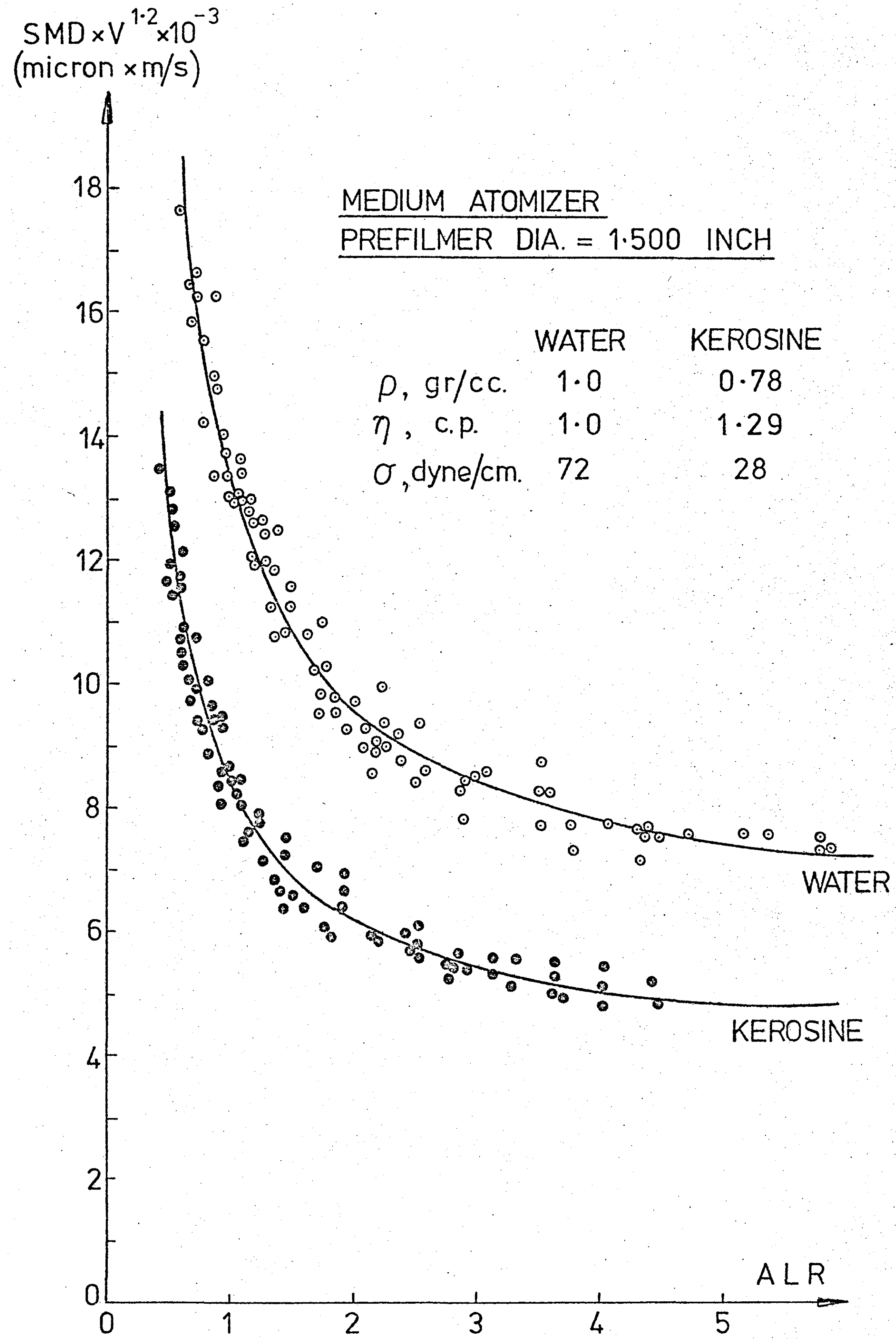


FIG. 47. COMPARISON BETWEEN WATER AND KEROSINE SPRAYS FOR VARIATION OF SMD WITH ALR

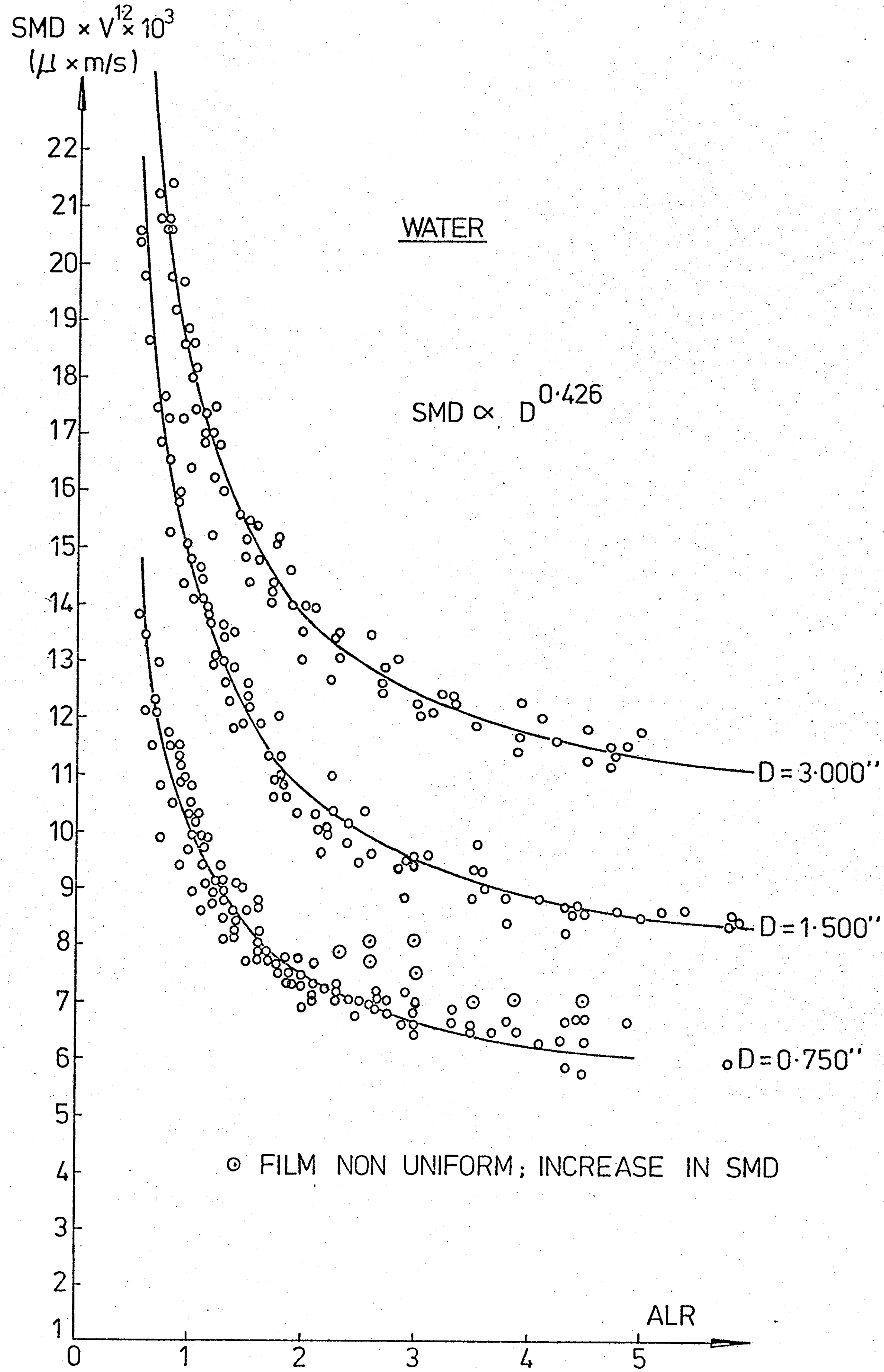


FIG. 48 EFFECT OF ATOMIZER LINEAR SCALE ON THE MEAN DROP SIZE

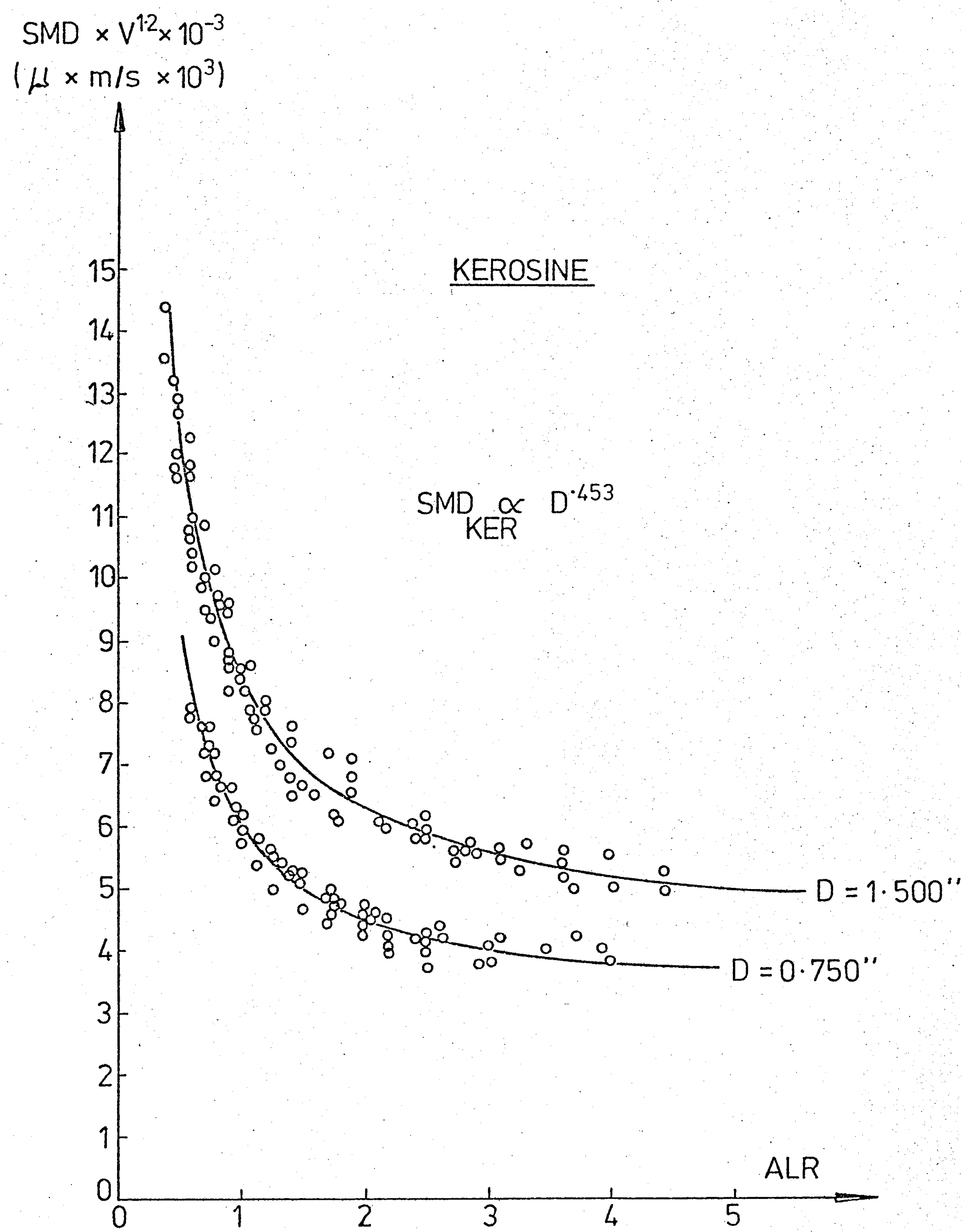


FIG. 49 EFFECT OF ATOMIZER LINEAR SCALE ON THE MEAN DROP SIZE

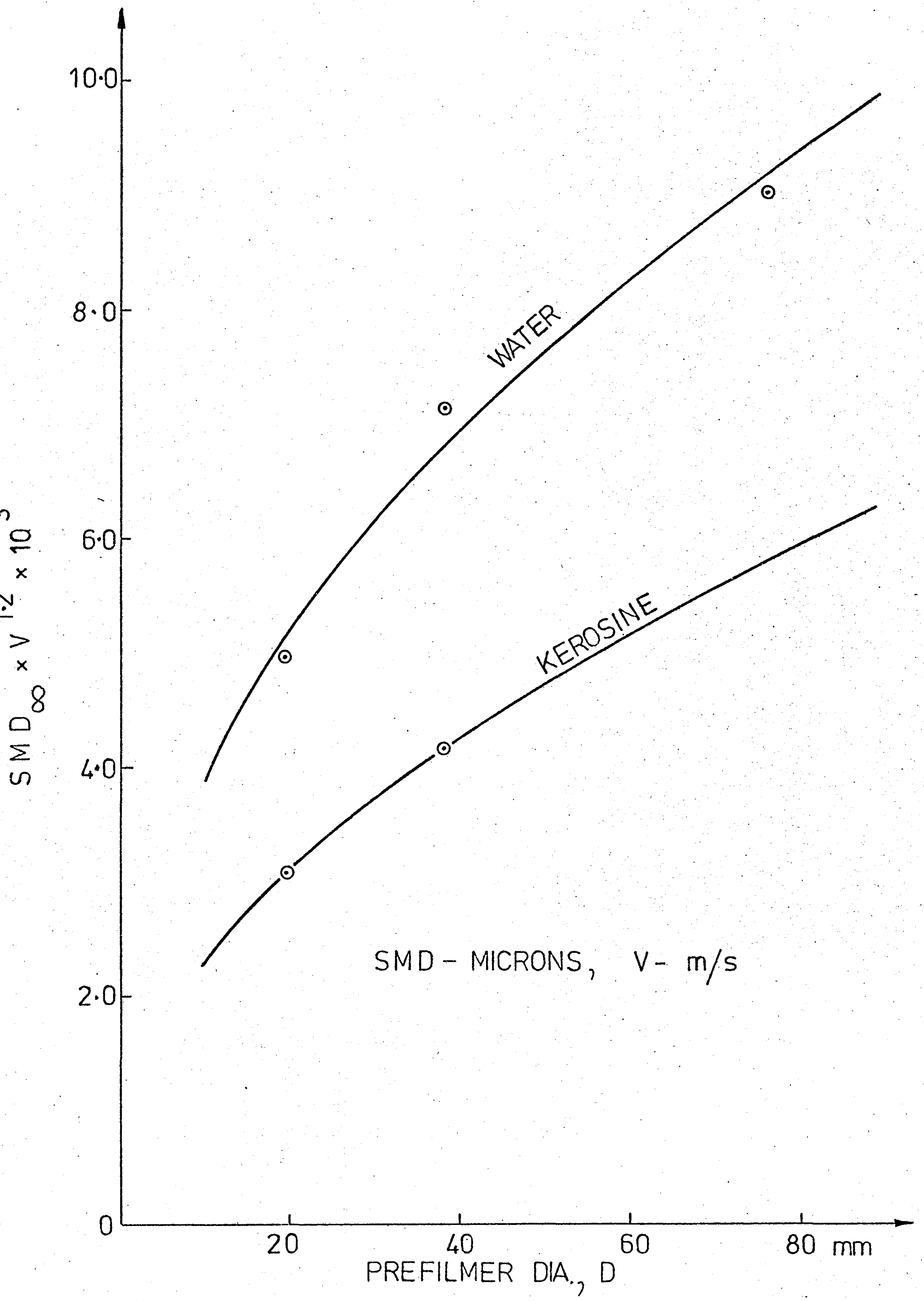


FIG. 50a. VARIATION OF THE SMD OF LOW VISCOSITY SPRAYS WITH ATOMIZER LINEAR SIZE

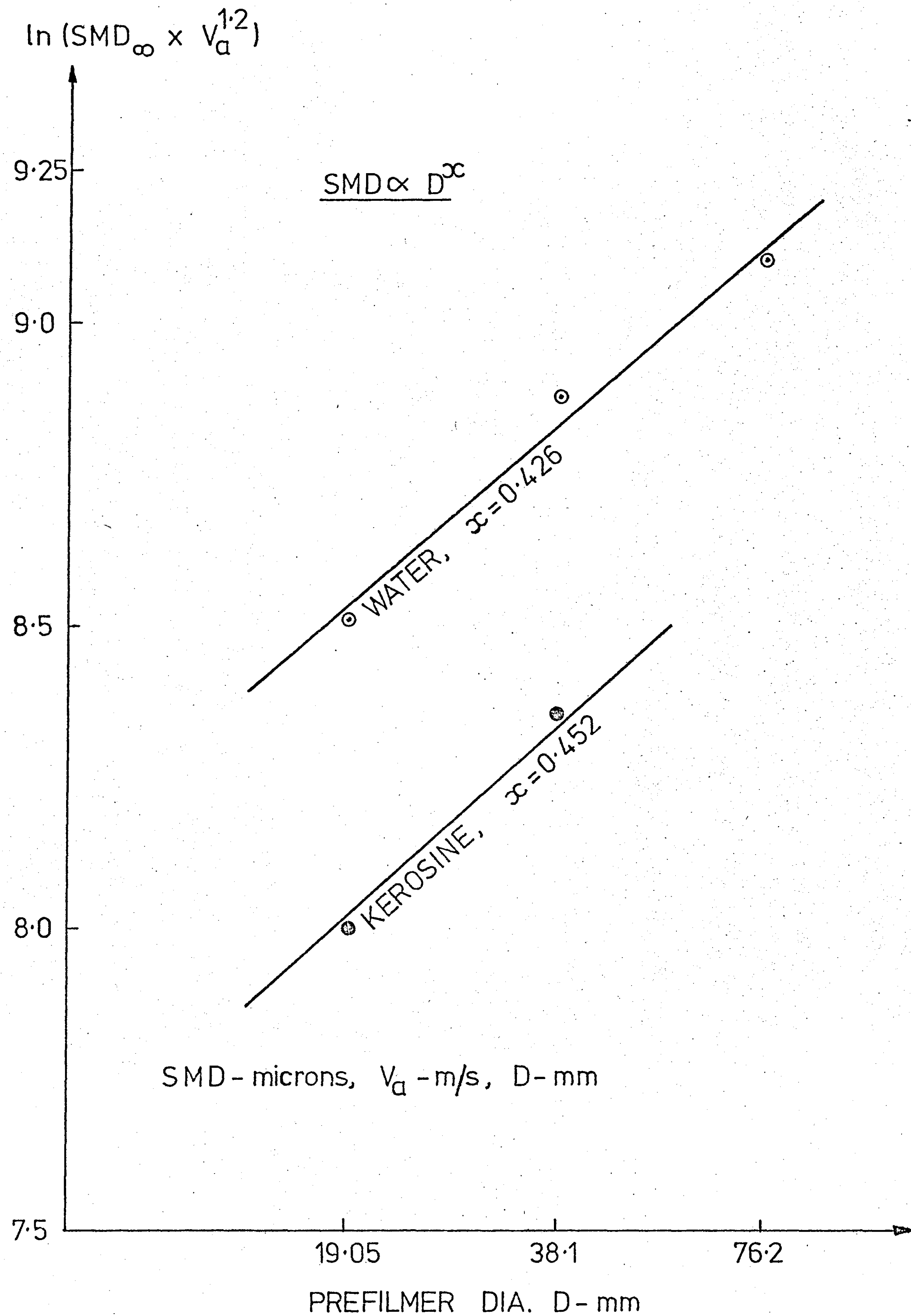


FIG. 50b. CORRELATION FOR THE VARIATION OF SMD WITH ATOMIZER LINEAR SIZE (AT VERY HIGH LEVEL OF ALR)

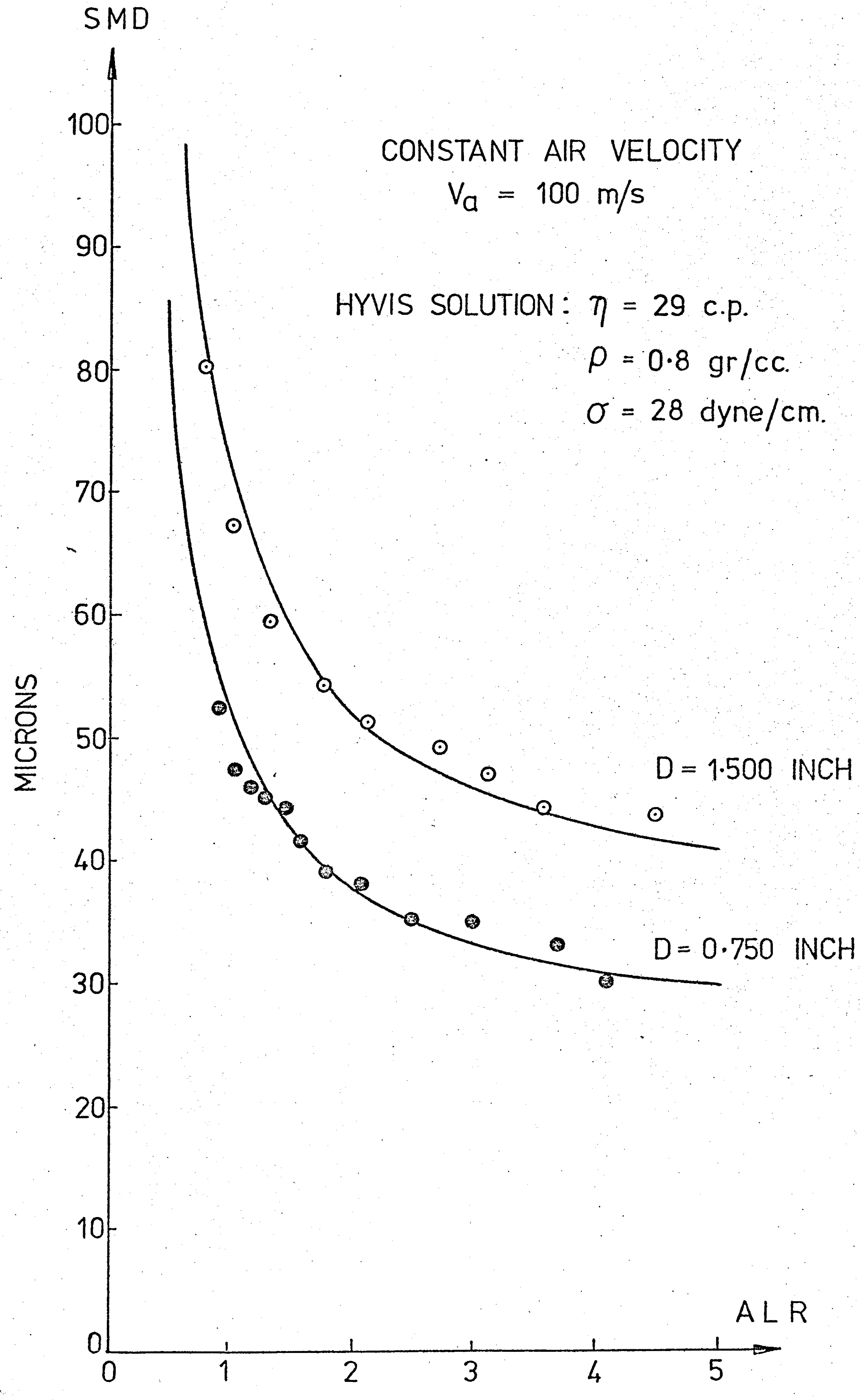


FIG. 51. EFFECT OF ATOMIZER SCALE ON VARIATION OF SMD WITH ALR AT CONSTANT ATOMIZING AIR VELOCITY FOR HIGH VISCOSITY LIQUID SPRAYS

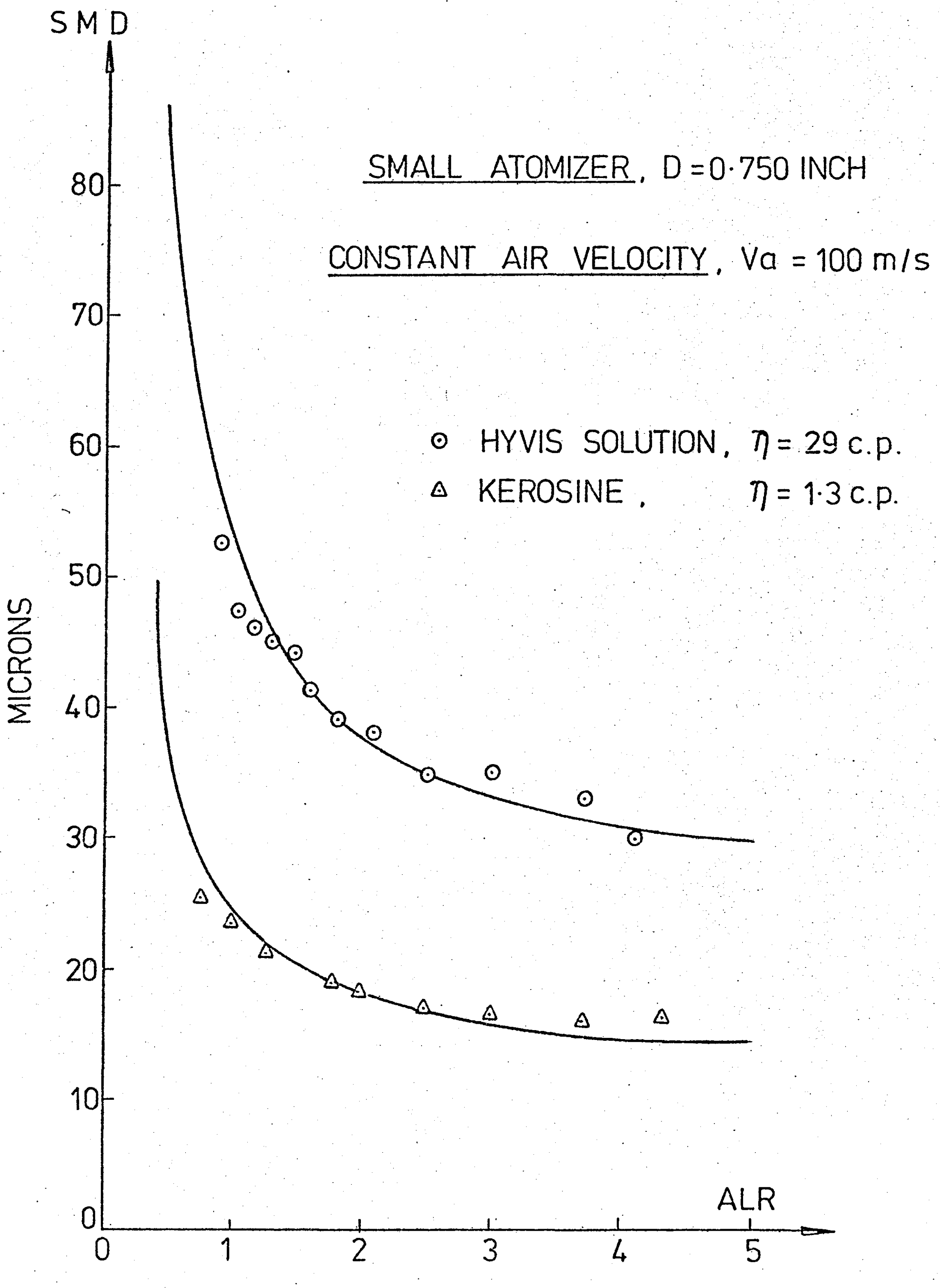


FIG. 52. COMPARISON BETWEEN VARIATION OF SMD OF LOW AND OF HIGH VISCOSITY SPRAYS, WITH A.L.R.

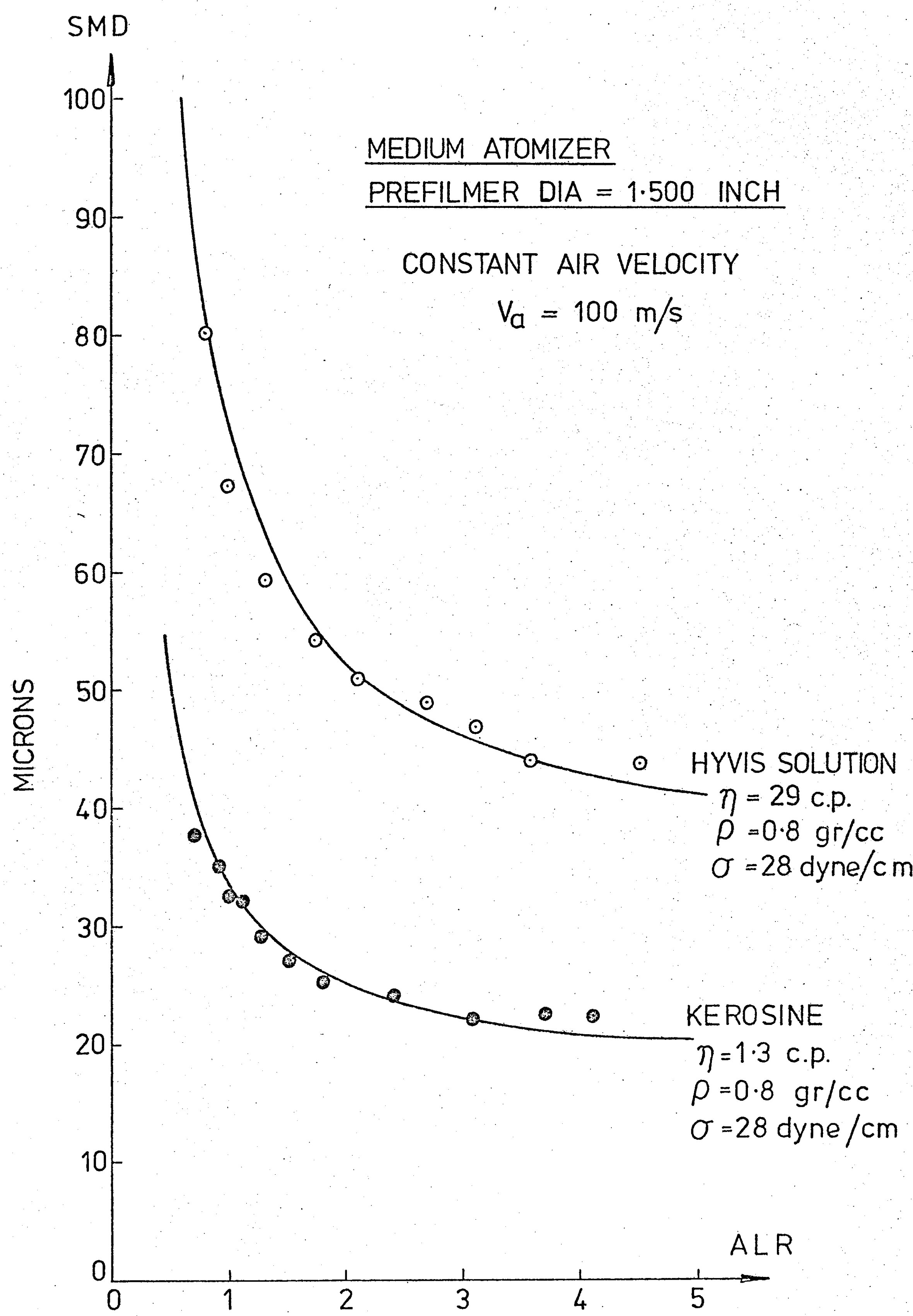


FIG. 53. COMPARISON BETWEEN VARIATION OF SMD OF LOW AND OF HIGH VISCOSITY SPRAYS WITH A.L.R.

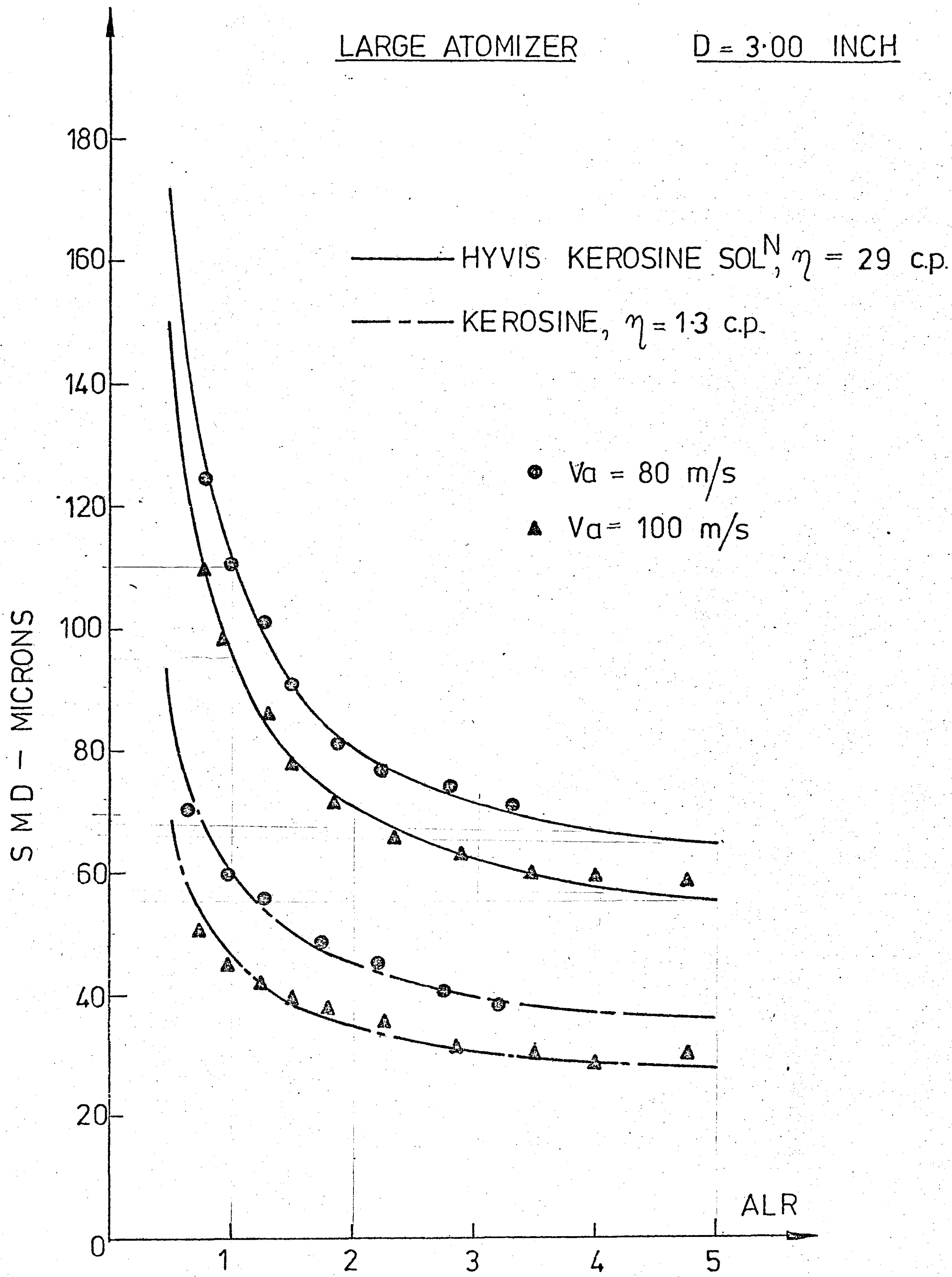


FIG. 54. HIGH VISCOSITY LIQUID AND KEROSINE SPRAYS — VARIATION OF THE SMD WITH VARIATIONS IN THE ALR, AT DIFFERENT LEVELS OF ATOMIZING AIR-VELOCITY

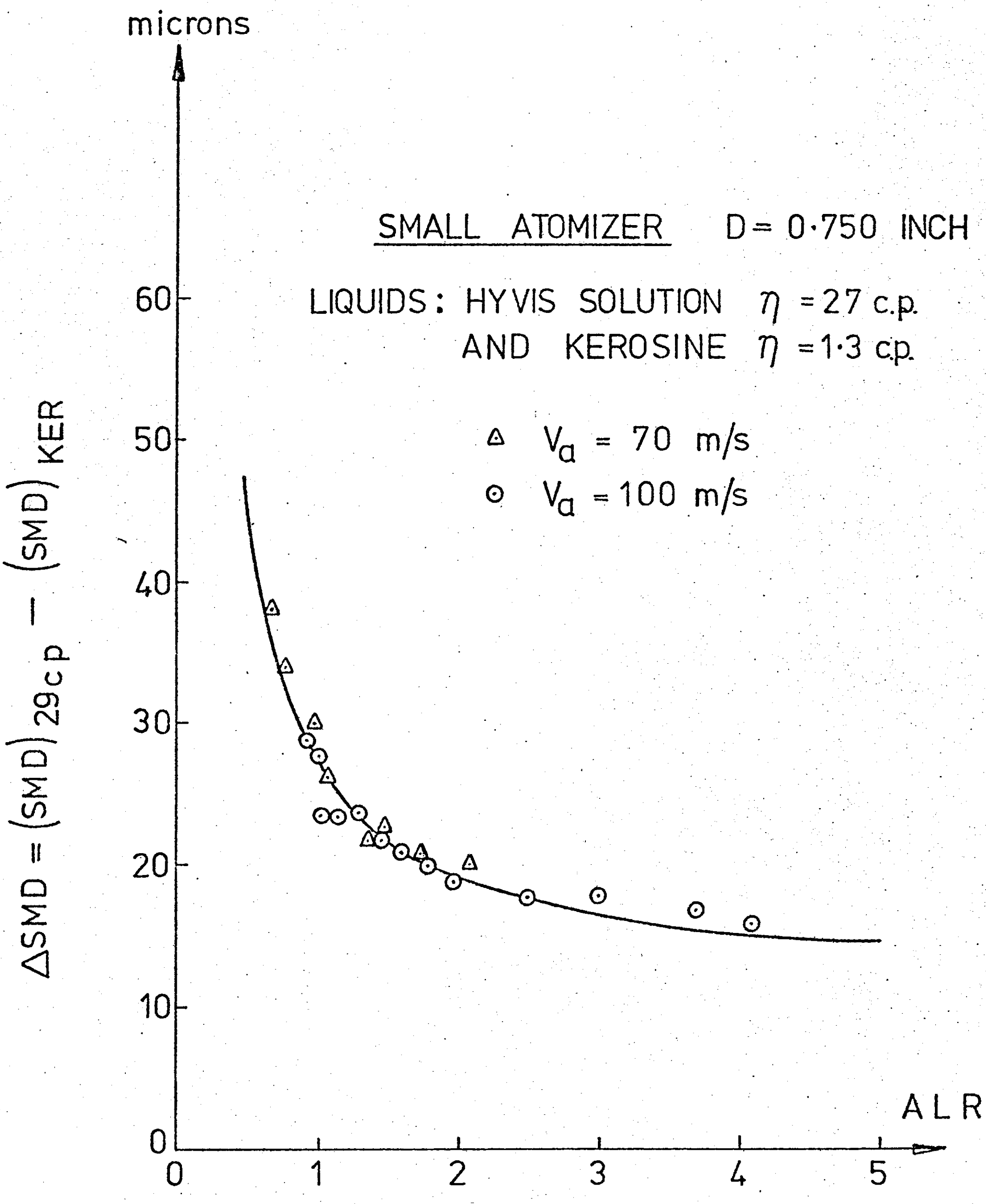


FIG. 55a. VARIATION OF THE INCREMENT IN THE SPRAY SMD, DUE TO INCREASE IN VISCOSITY, WITH VARIATION IN THE A.L.R.

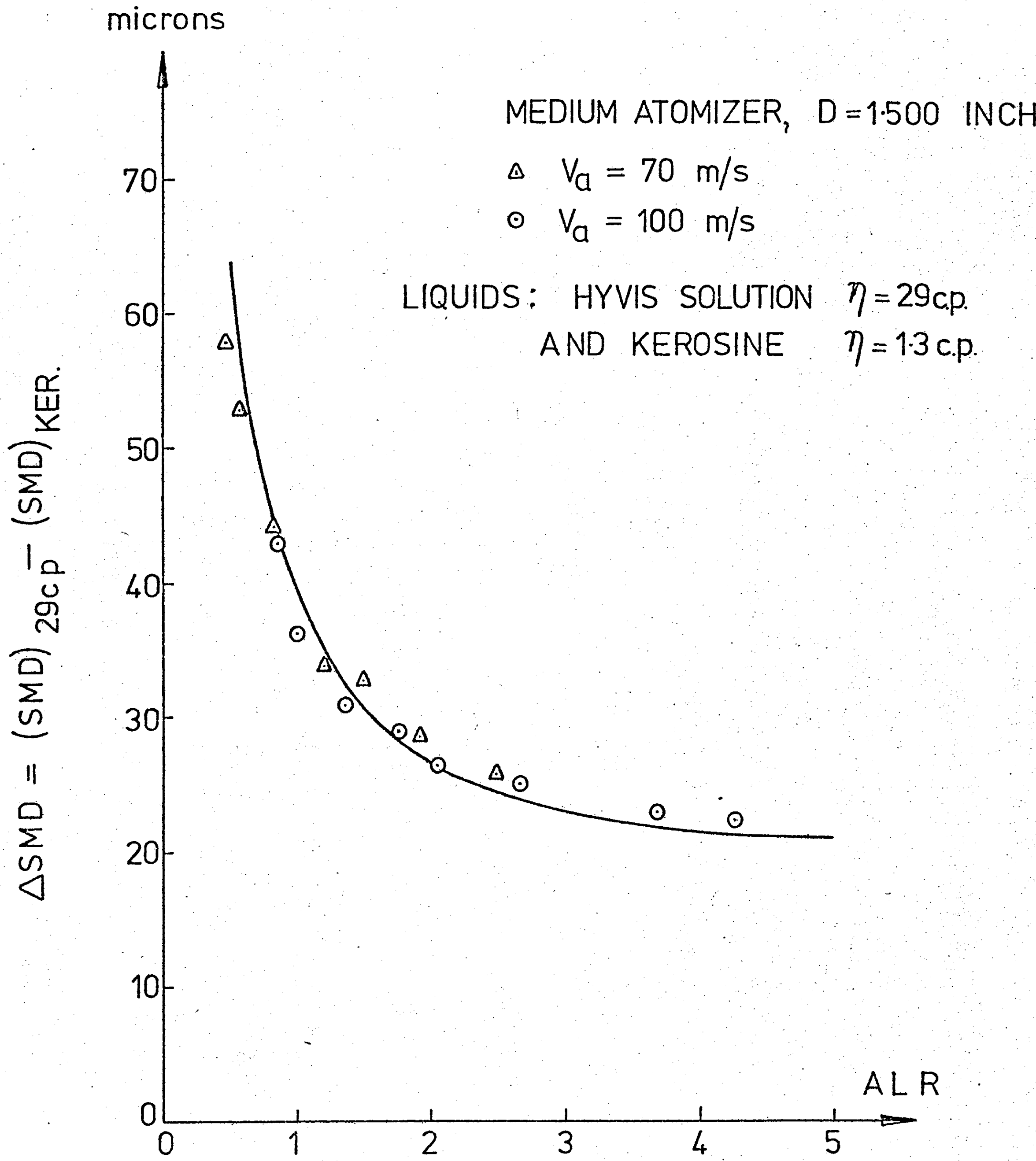


FIG. 55b. VARIATION OF THE INCREMENT IN THE SPRAY SMD, DUE TO INCREASE IN VISCOSITY, WITH VARIATION IN THE A.L.R.

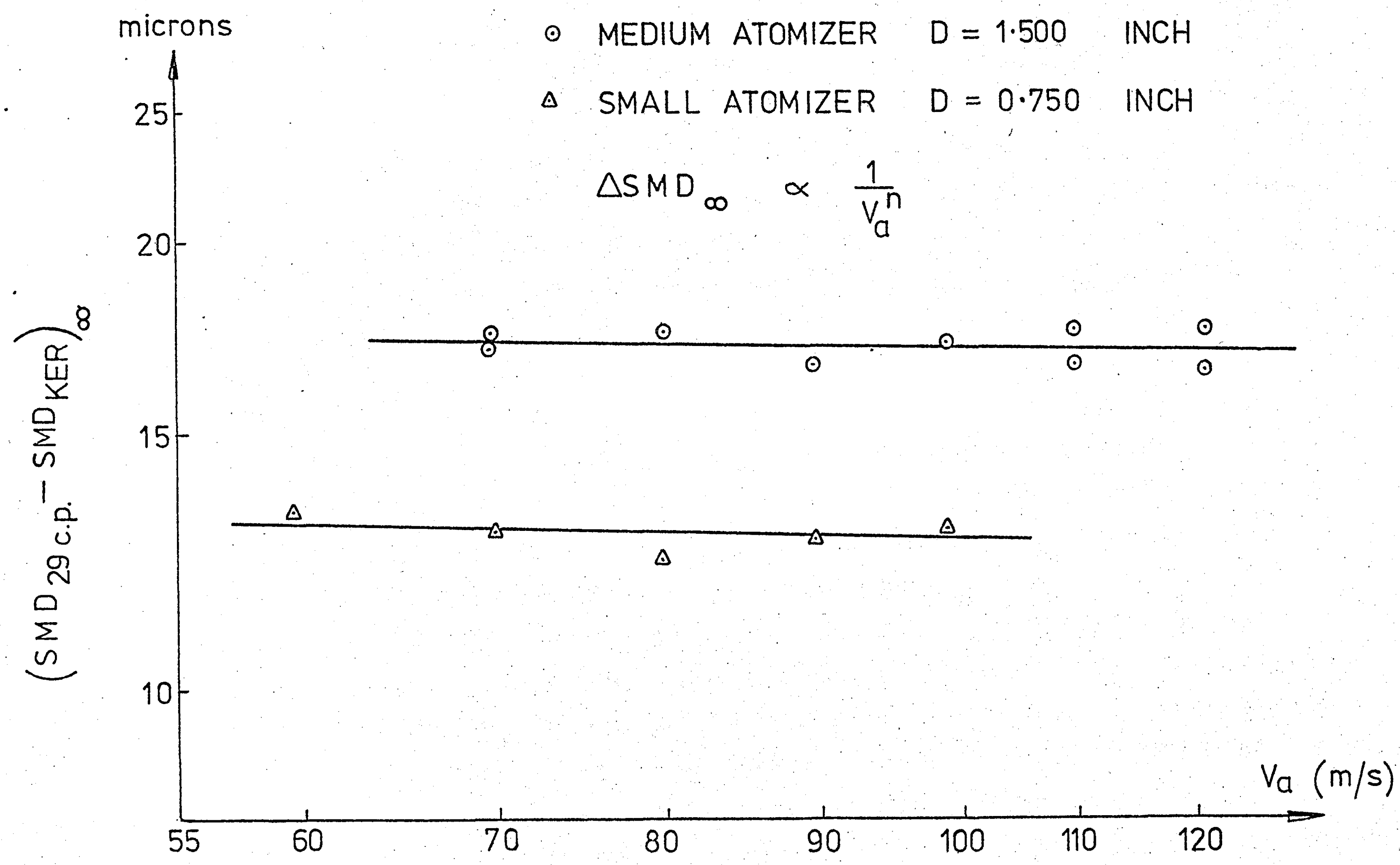


FIG :56. EFFECT OF ATOMIZING AIR VELOCITY ON THE INCREMENTAL SMD DUE TO INCREASED LIQUID VISCOSITY, AT VERY LARGE ALR

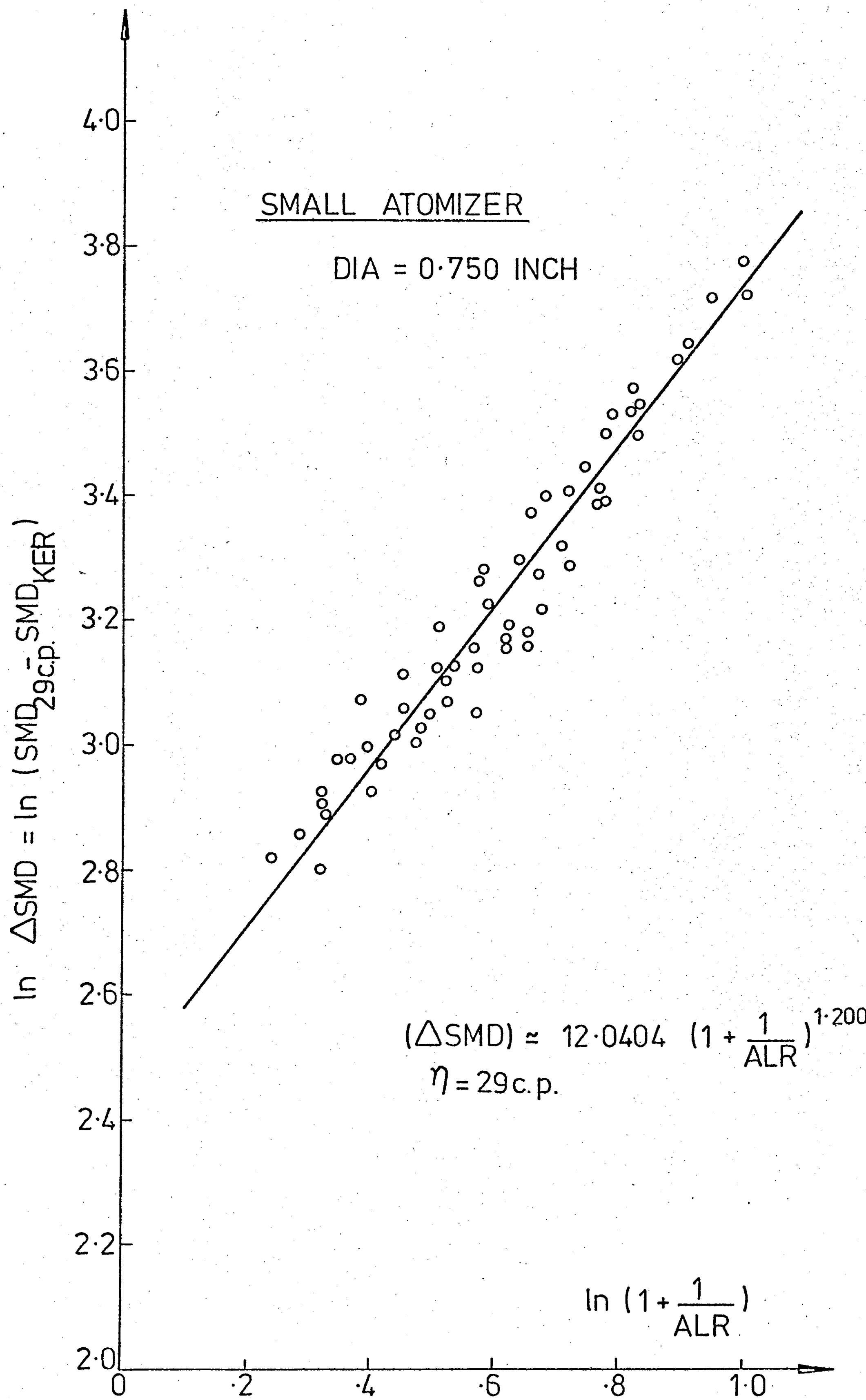


FIG 57a CORRELATION FOR THE VARIATION OF ΔSMD WITH ALR

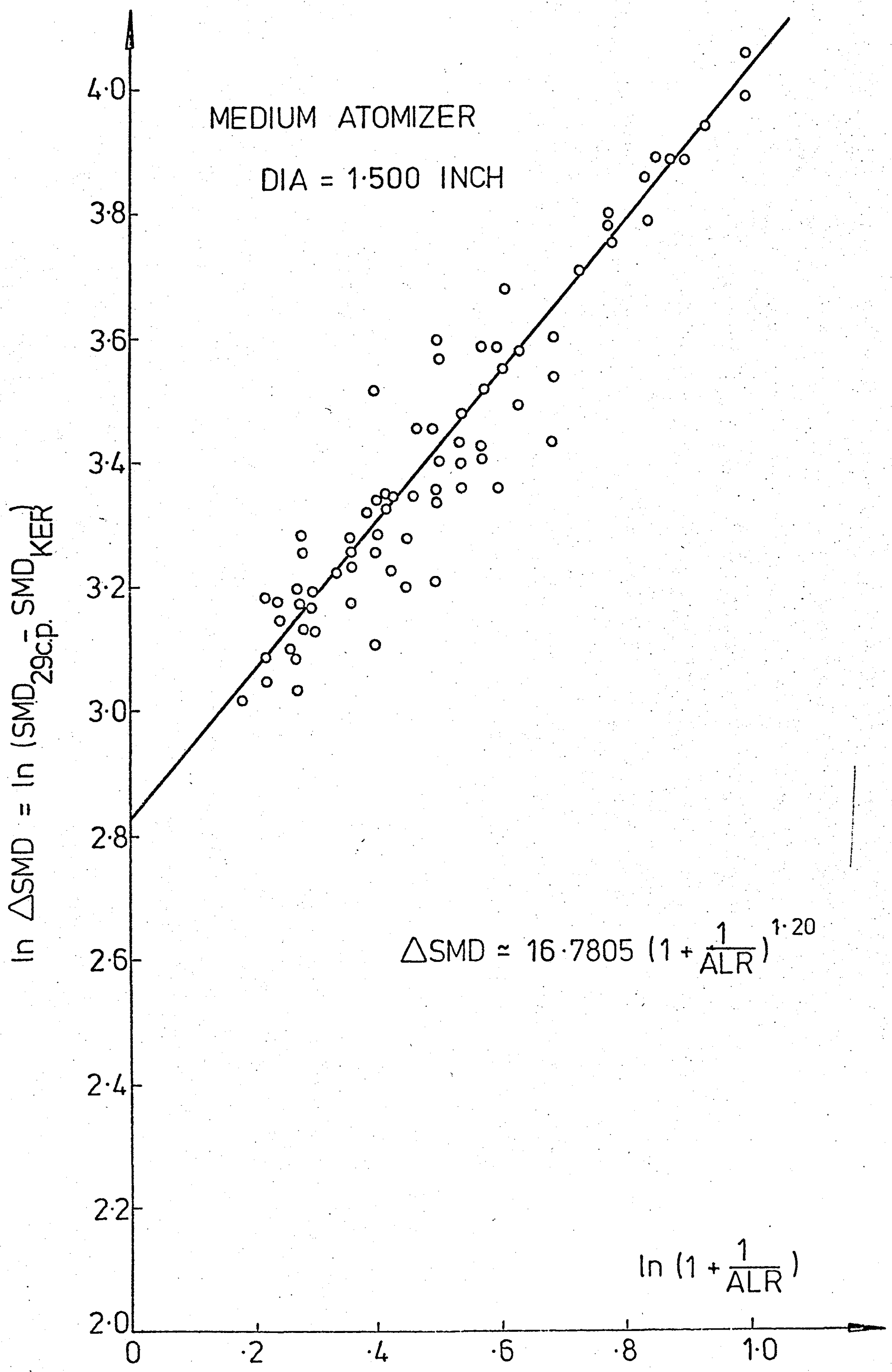


FIG. 57b. CORRELATION FOR THE VARIATION OF ΔSMD WITH ALR

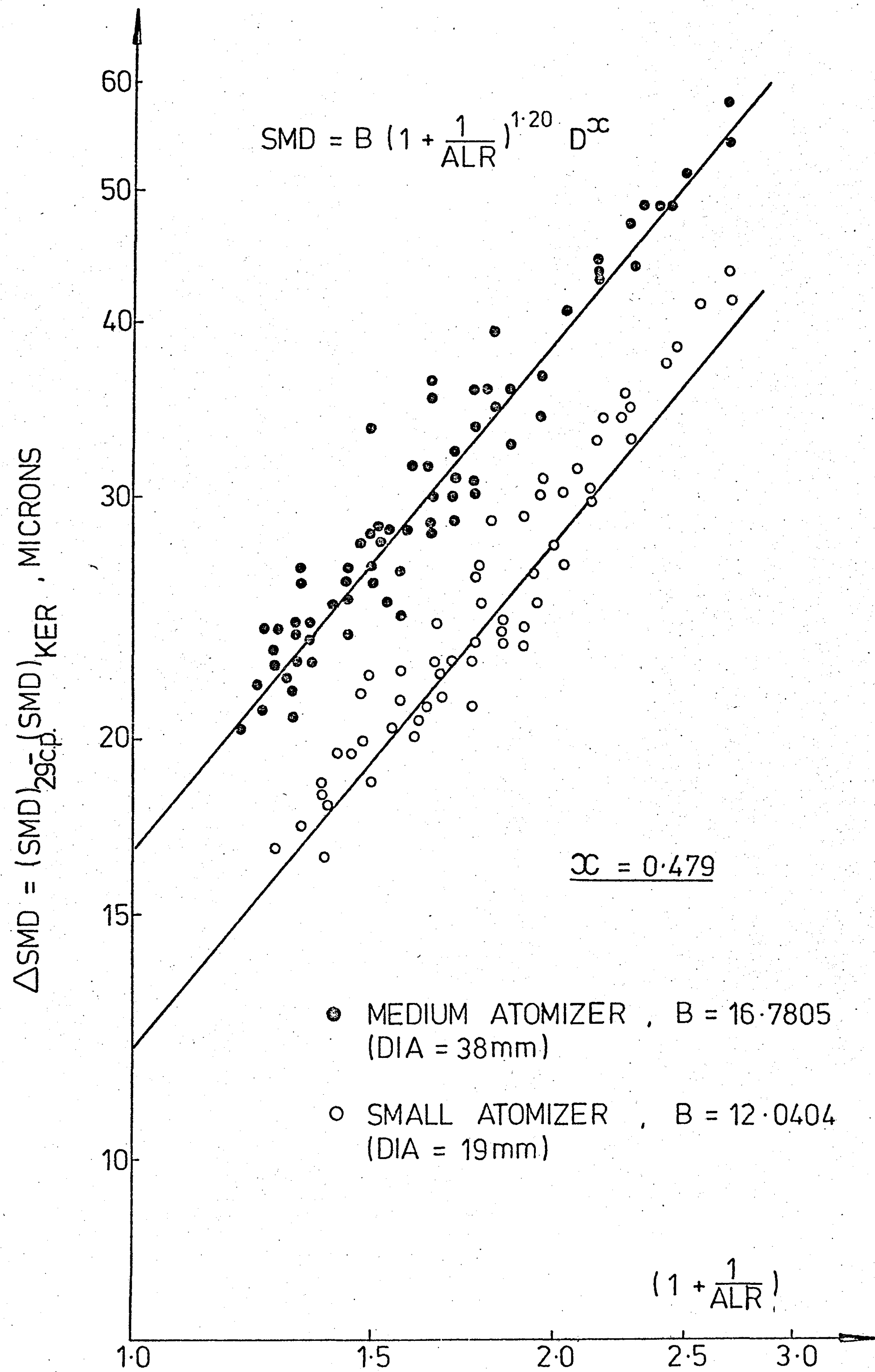


FIG 58a CORRELATION FOR THE VARIATION OF $(\Delta SMD)_{vi}$ WITH ATOMIZER LINEAR DIMENSION

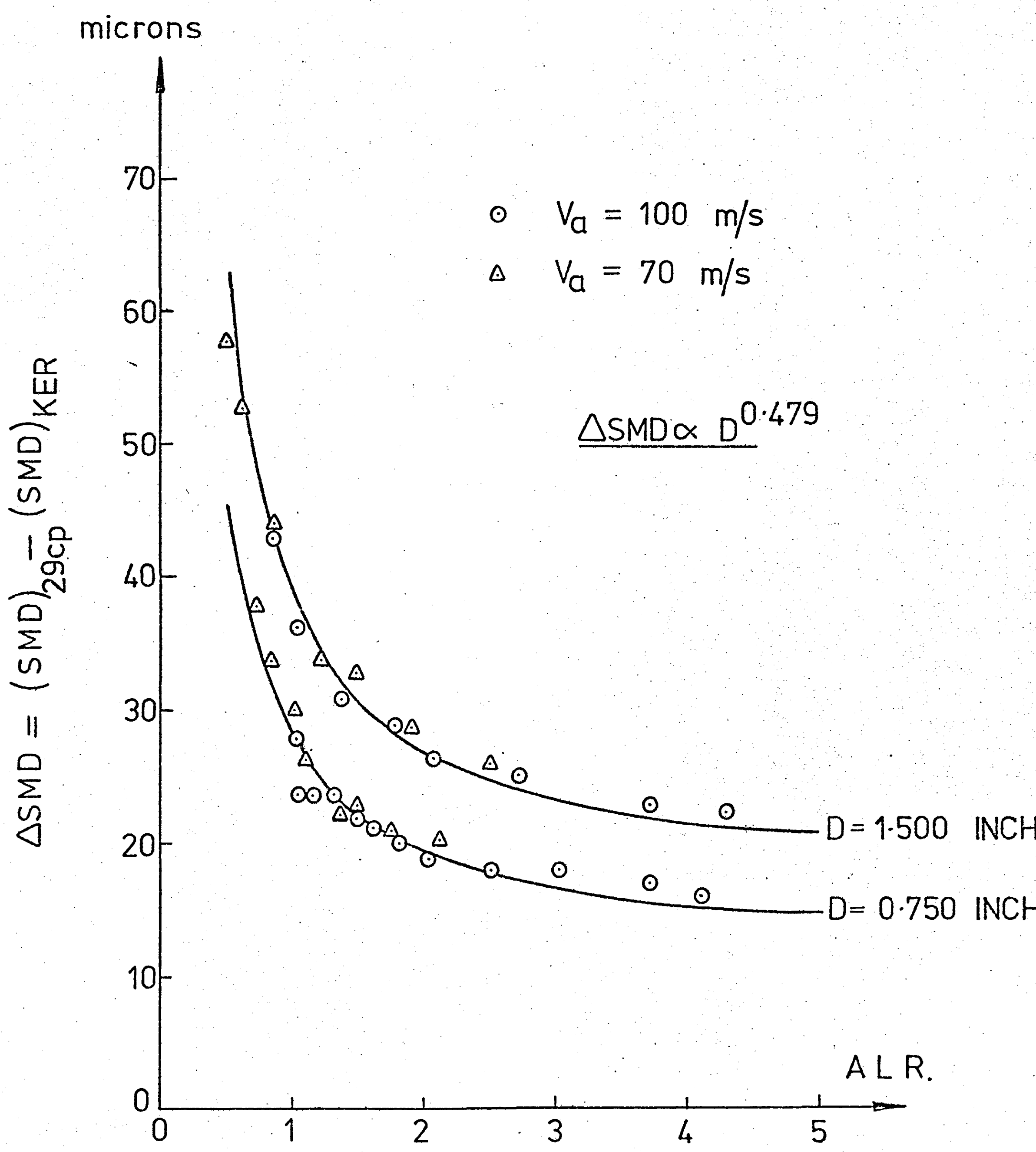


FIG. 58b. EFFECT OF ATOMIZER SCALE ON THE VARIATION OF THE INCREMENT IN THE SMD ATTRIBUTED TO LIQUID VISCOSITY WITH VARIATION IN THE A.L.R.

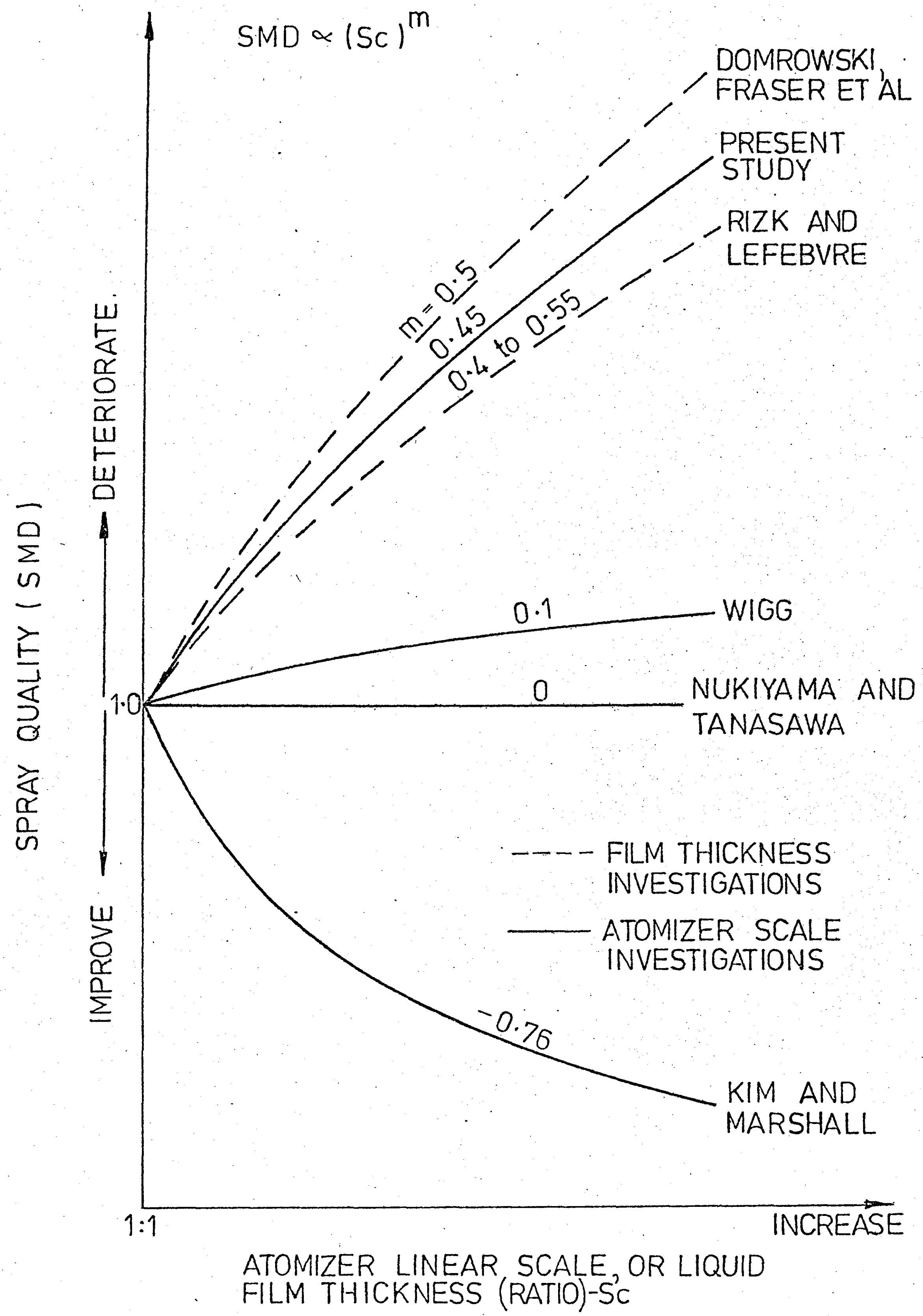


FIG. 59. COMPARISON BETWEEN THE RESULTS OF SEVERAL INVESTIGATIONS INTO THE EFFECT OF ATOMIZER SCALE, AND LIQUID STREAM THICKNESS ON THE QUALITY OF AIRBLAST SPRAYS

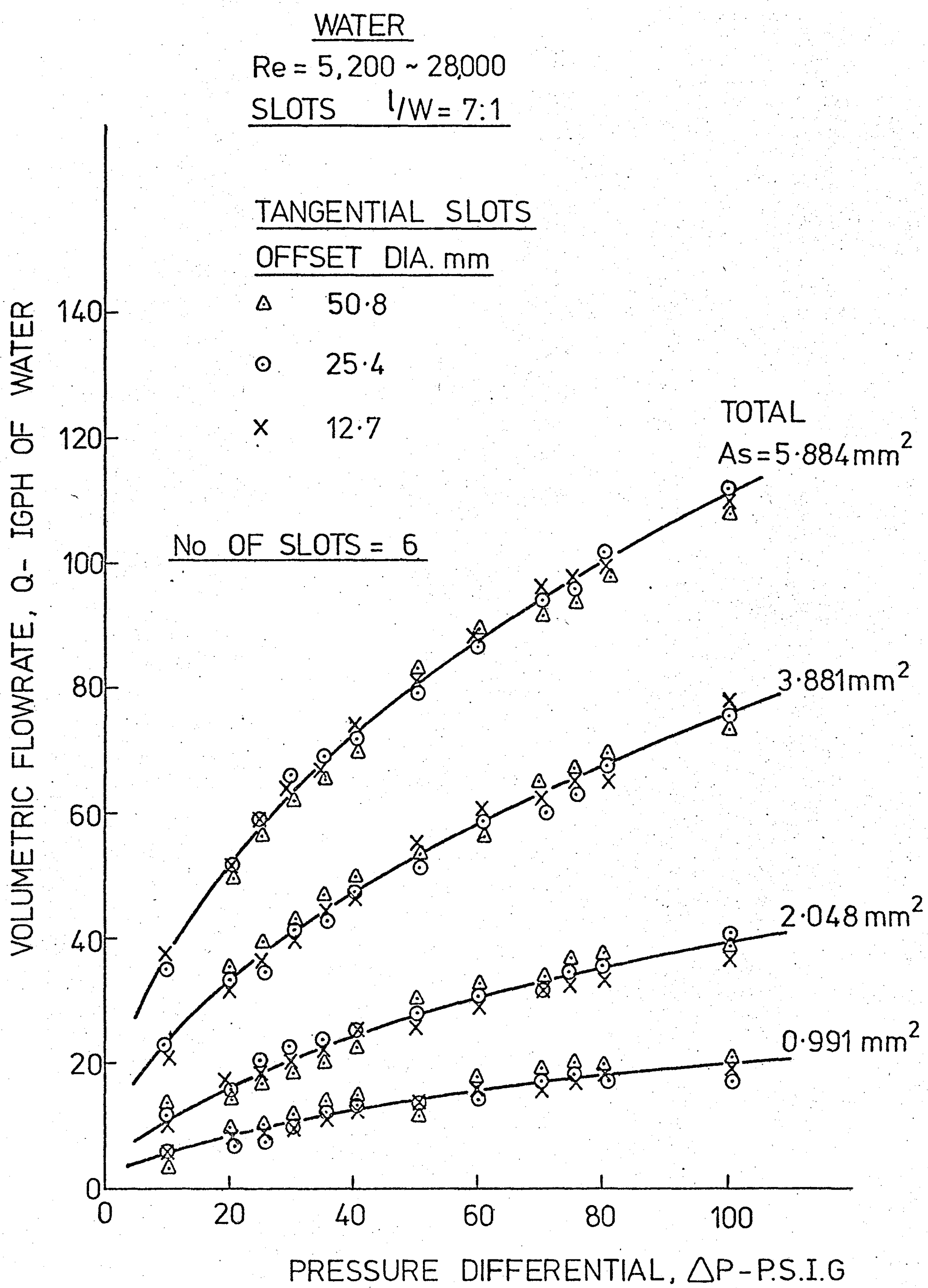


FIG. 60a INFLUENCE OF PRESSURE DIFFERENTIAL ON LIQUID FLOW RATE FOR VARIOUS DISCHARGE AREAS

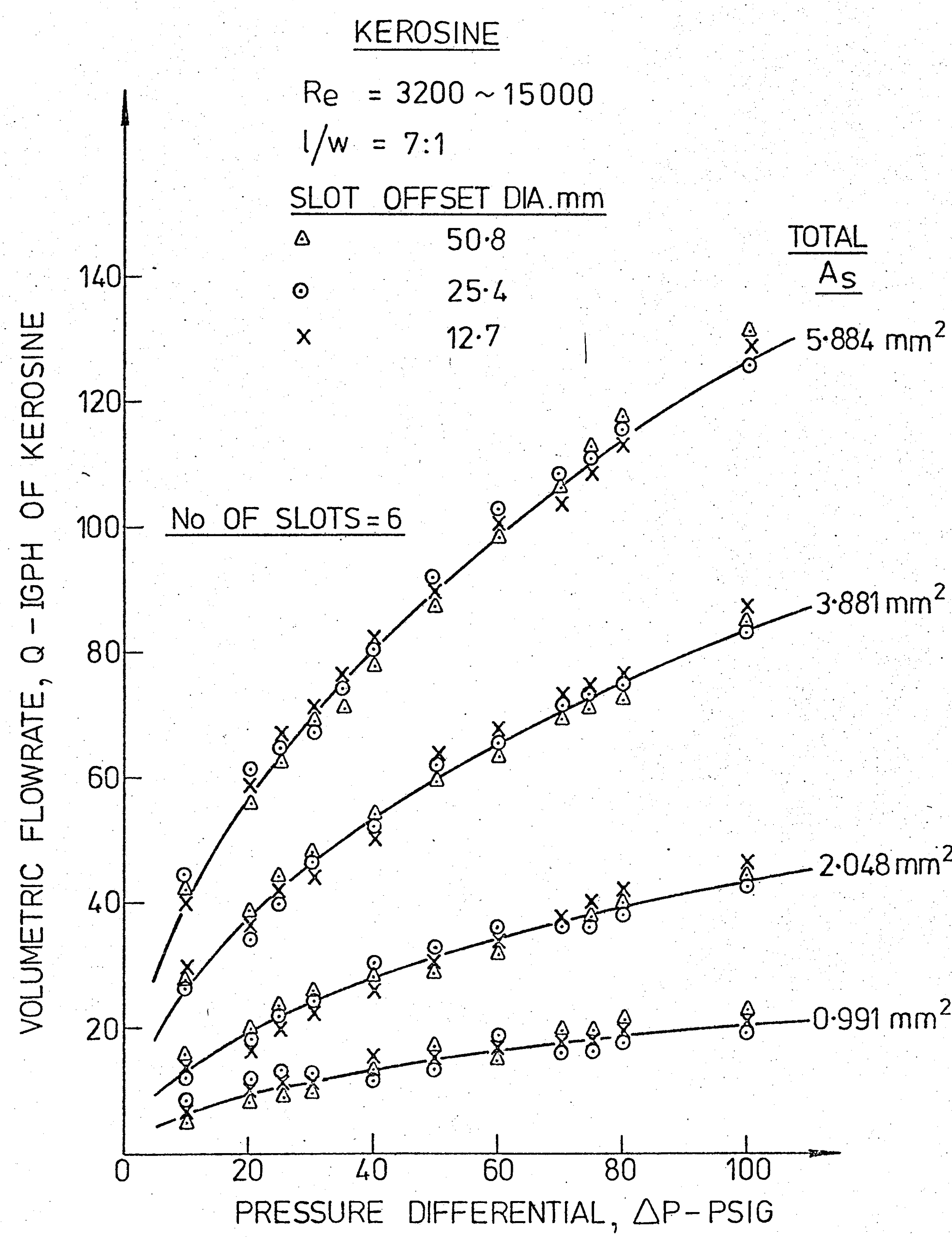


FIG. 60b. INFLUENCE OF PRESSURE DIFFERENTIAL ON LIQUID FLOW RATE FOR VARIOUS DISCHARGE AREAS

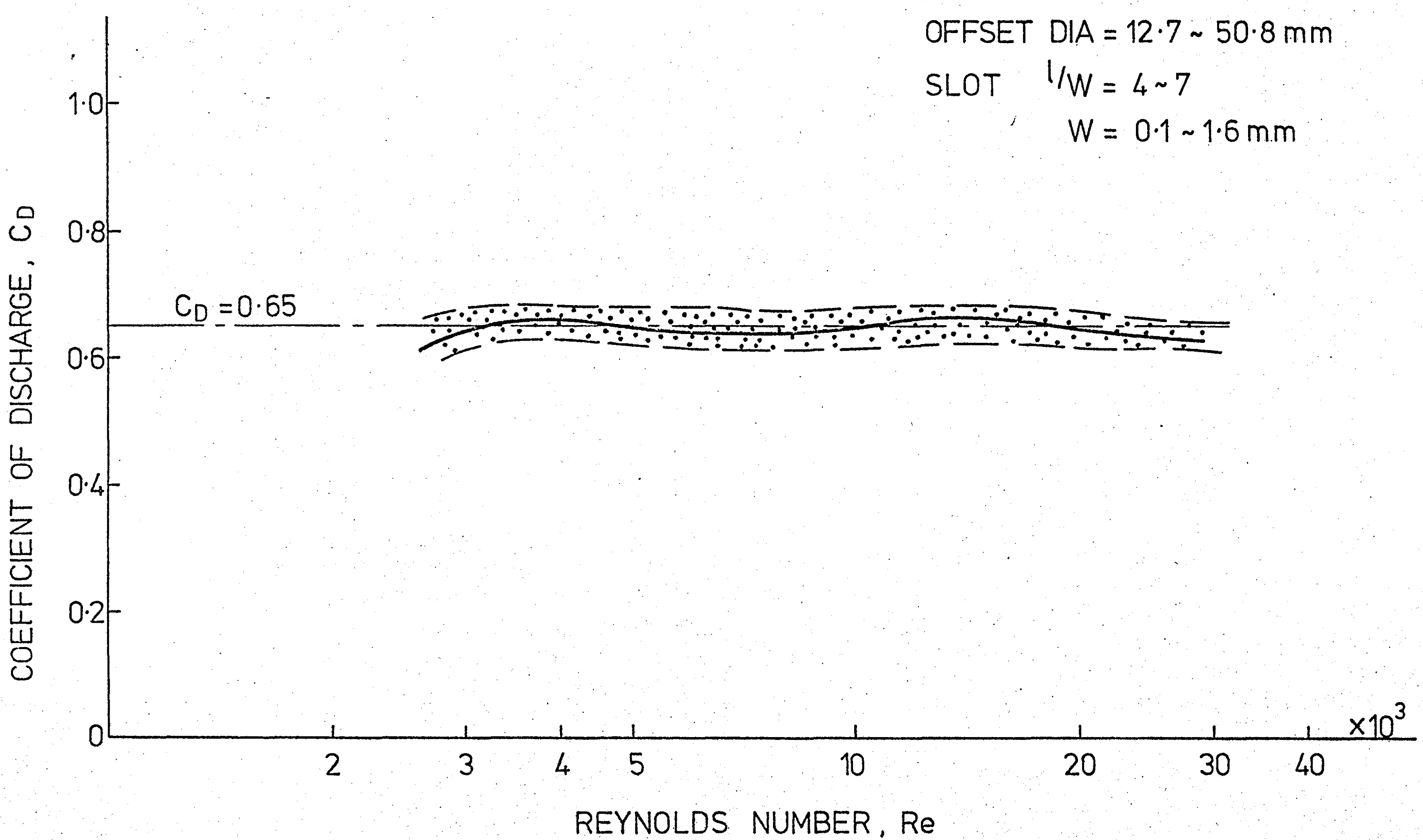


FIG. 61 COEFFICIENT OF DISCHARGE OF LIQUID SWIRLERS

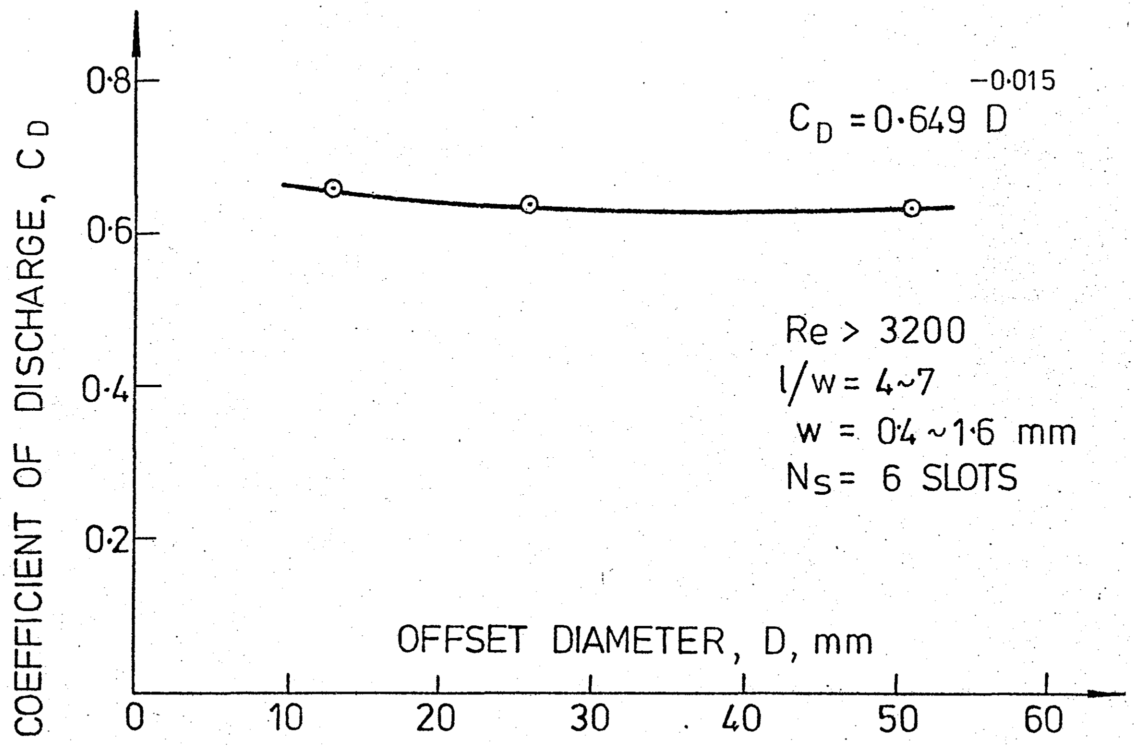


FIG. 62a EFFECT OF SLOT OFFSET DIA. ON C_D AT HIGH VALUES OF R_e

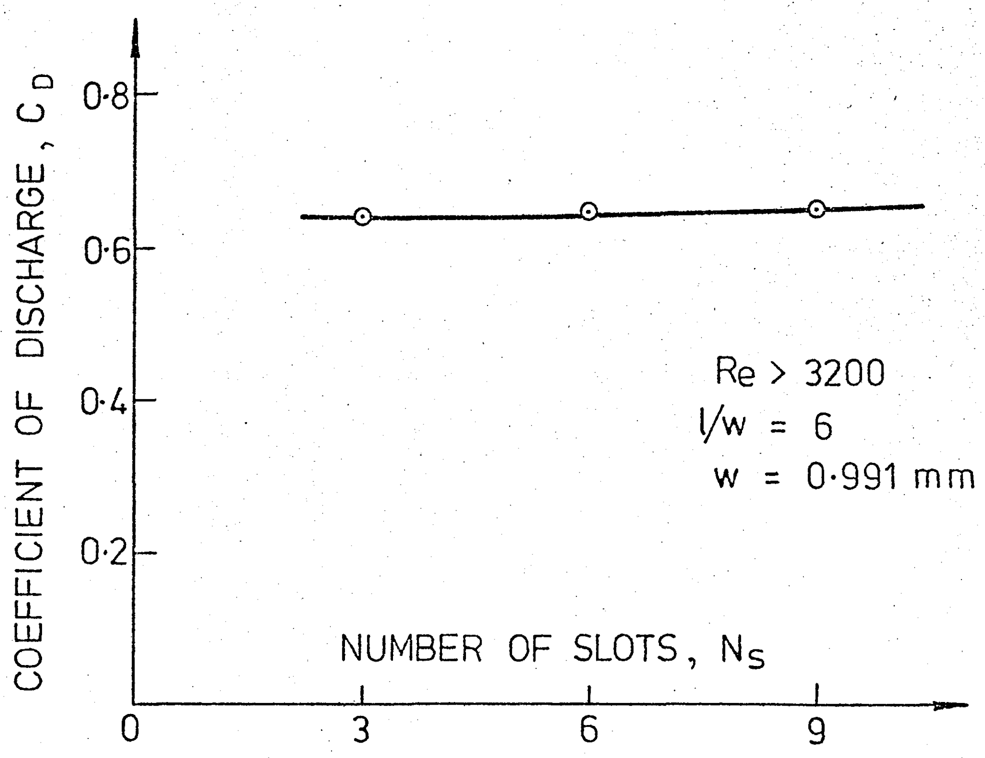


FIG. 62b EFECT OF NUMBER OF SLOTS ON C_D AT HIGH VALUES OF R_e

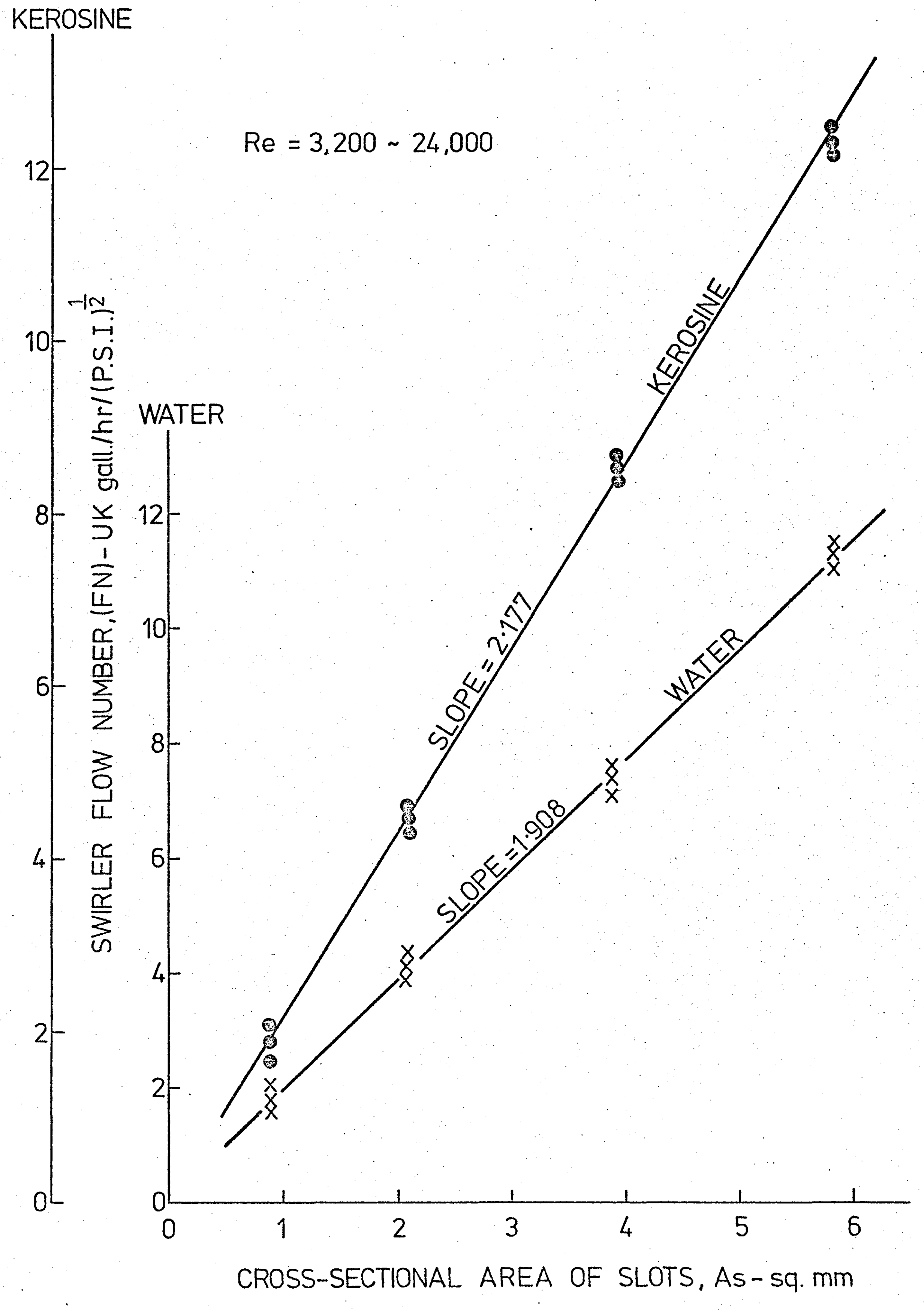


FIG. 63 CORRELATION BETWEEN SWIRLER FLOW NUMBER AND TOTAL DISCHARGE AREA OF TANGENTIAL LIQUID PORTS

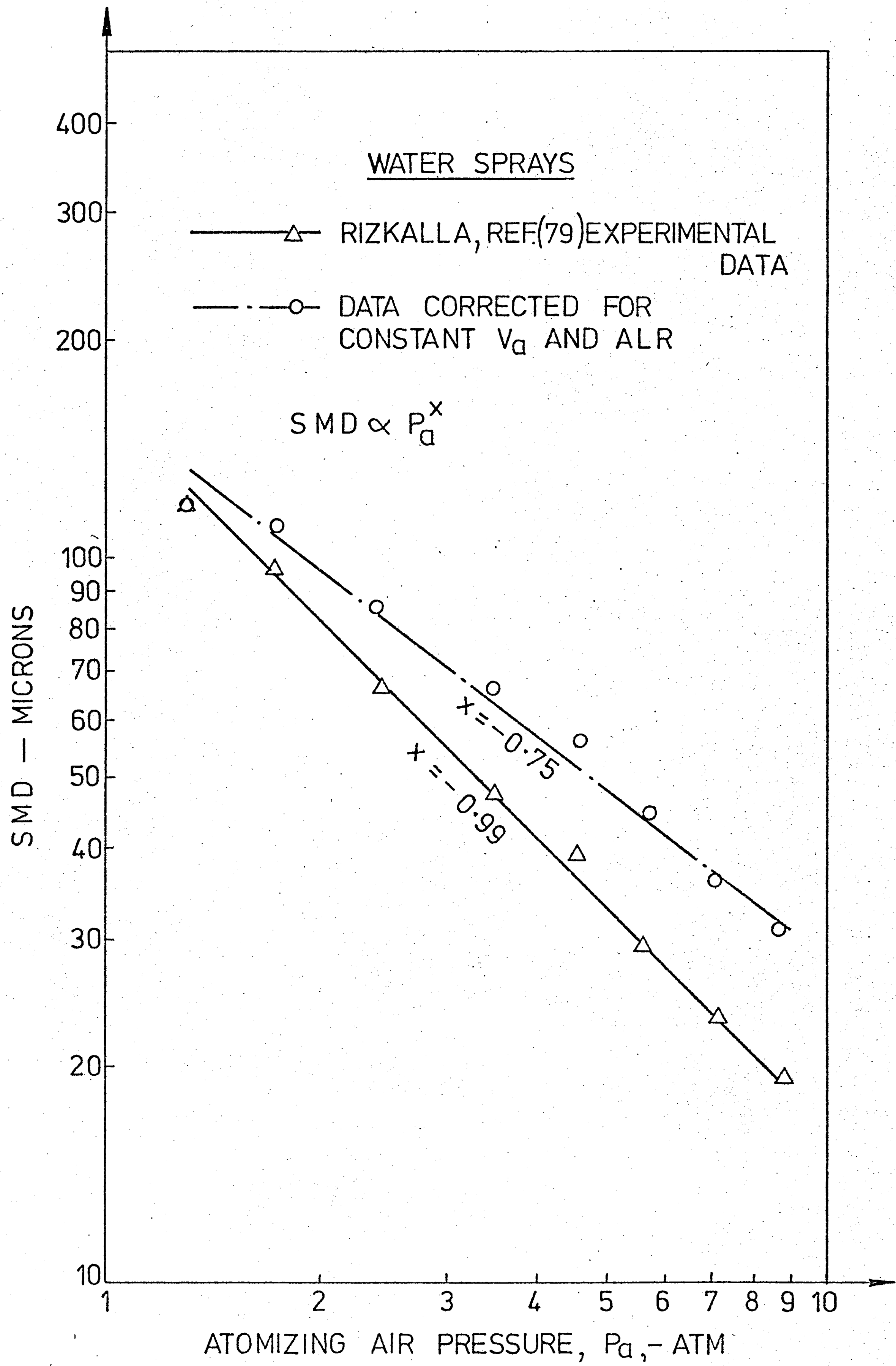


FIG. 64a. RELATIONSHIP BETWEEN SMD AND ATOMIZING AIR PRESSURE

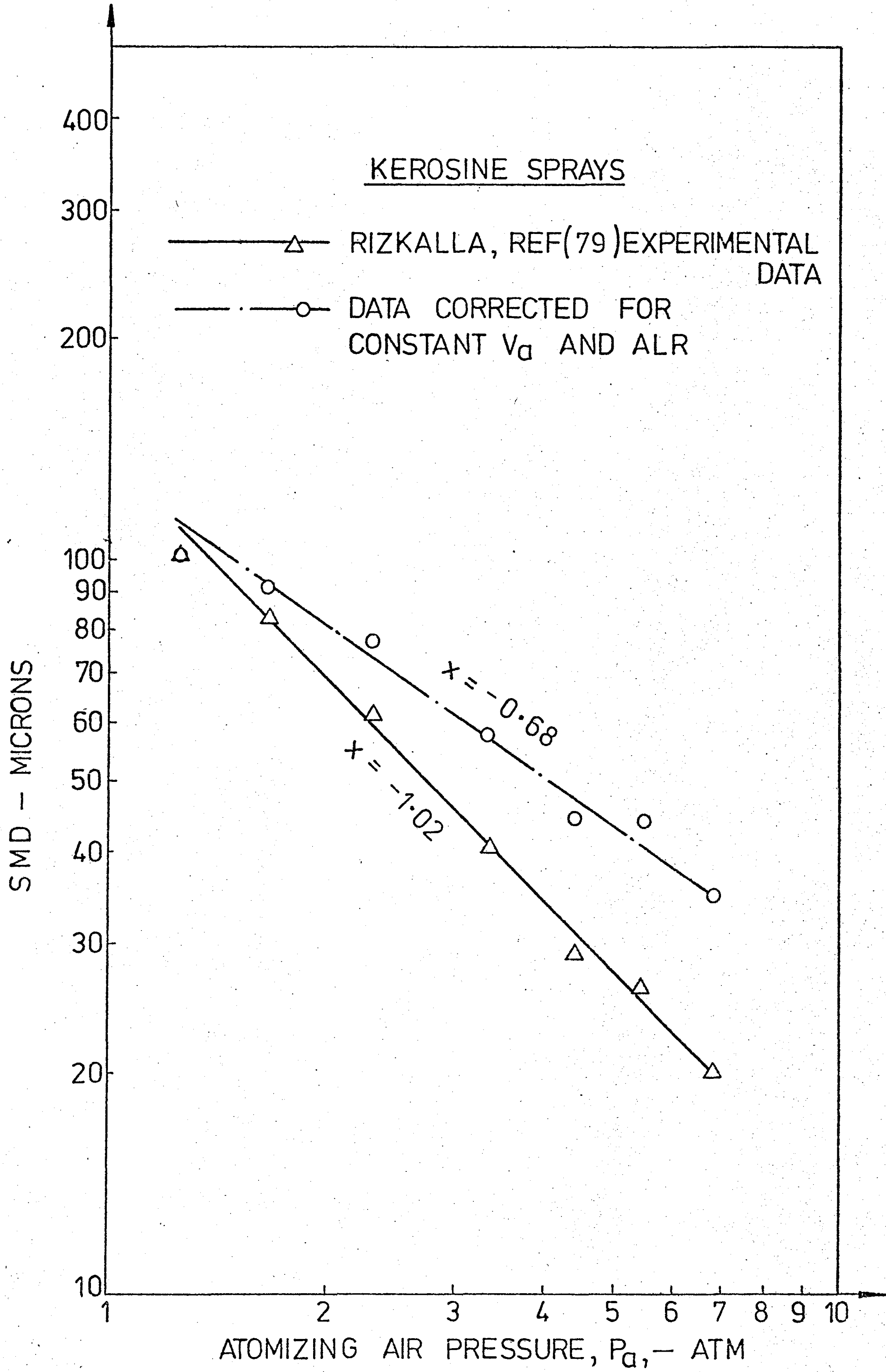


FIG. 64b. RELATIONSHIP BETWEEN SMD AND ATOMIZING AIR PRESSURE

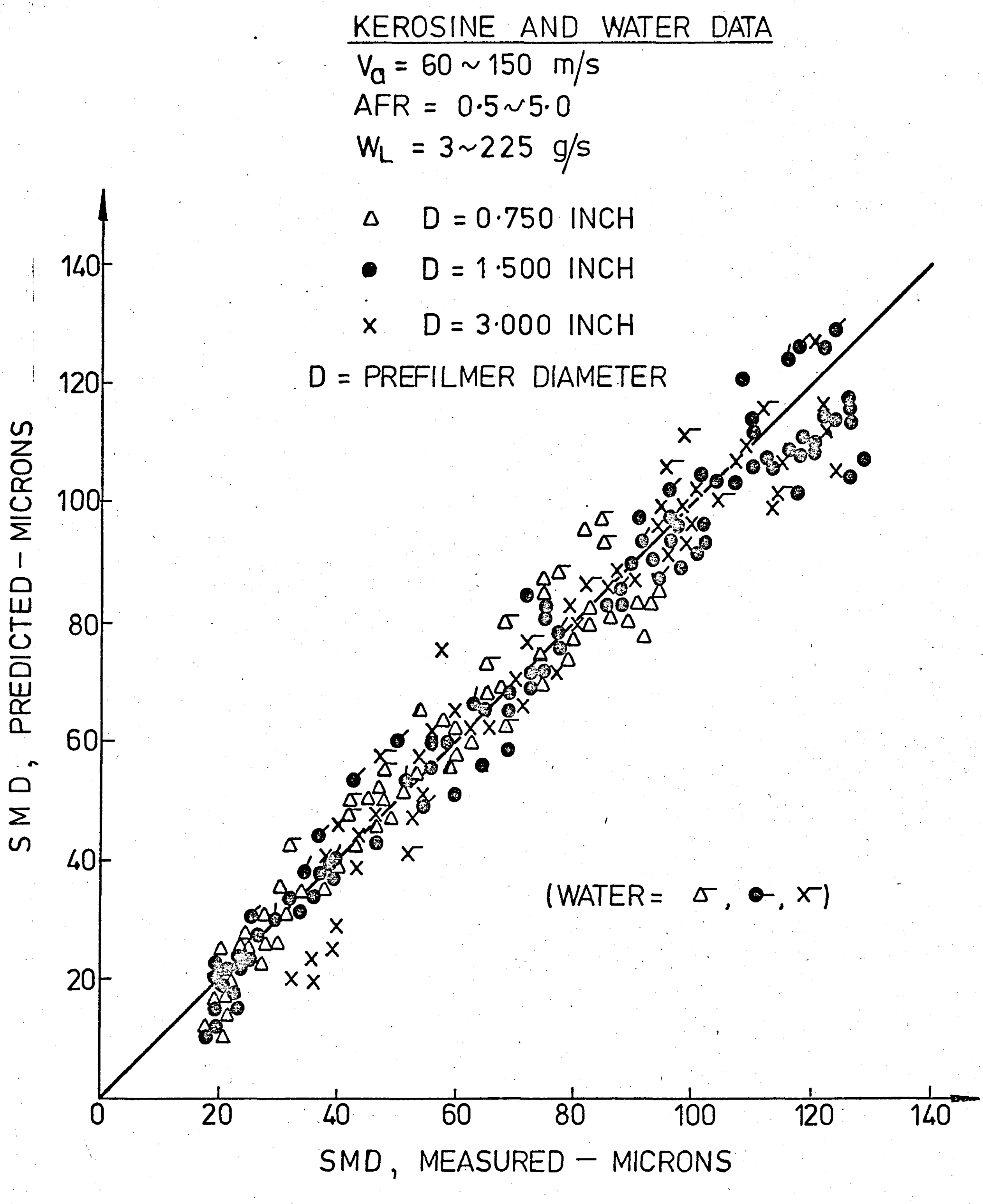


FIG 65a COMPARISON OF SMD VALUES MEASURED V/S. PREDICTED BY EQ^{N}·(6·5) FOR DIFFERENT SIZE BUT GEOMETRICALLY SIMILAR ATOMIZERS

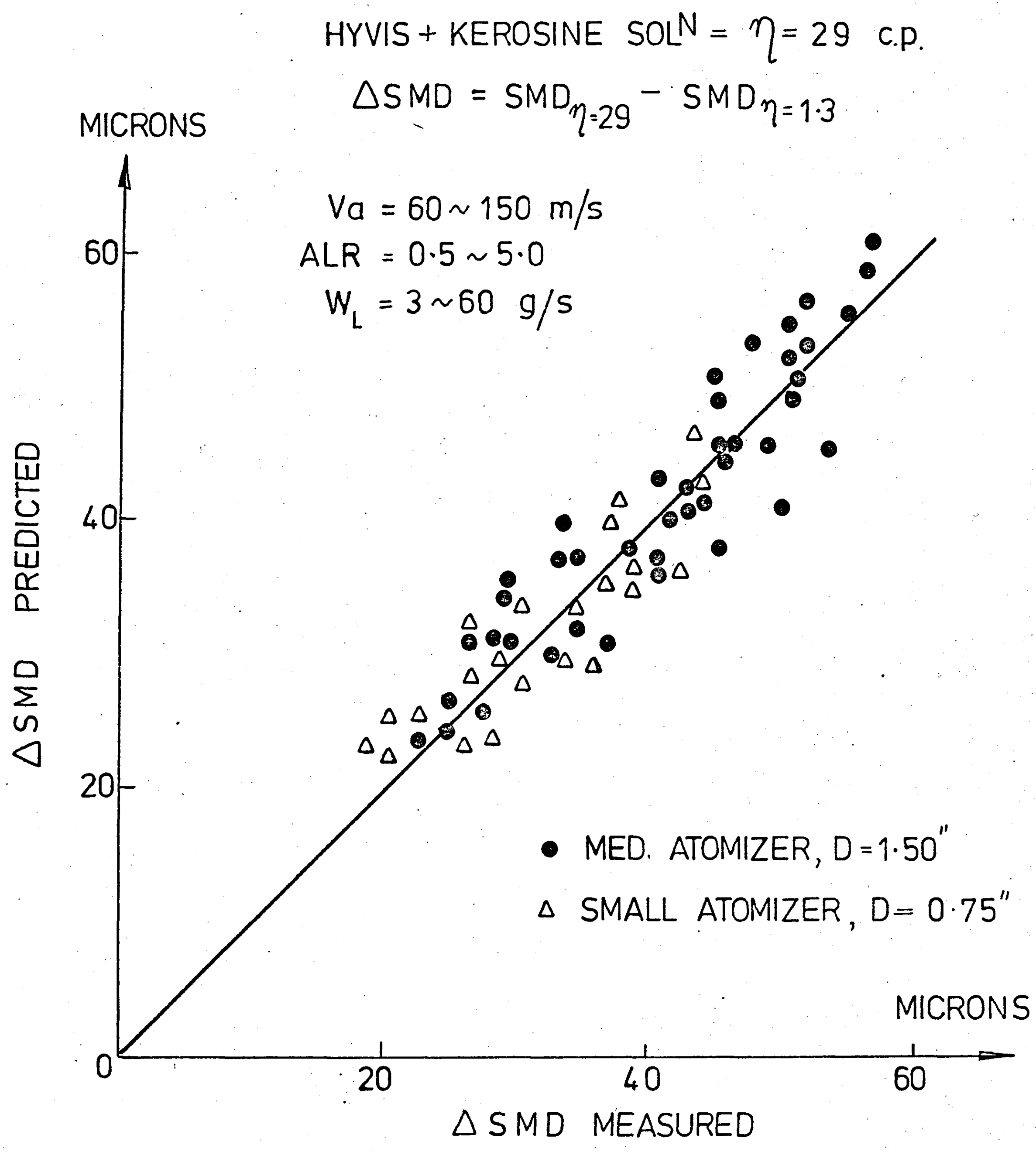


FIG. 65 b. COMPARISON OF ΔSMD VALUES MEASURED VIS PREDICTED, FOR DIFFERENT SIZE BUT GEOMETRICALLY SIMILAR ATOMIZERS

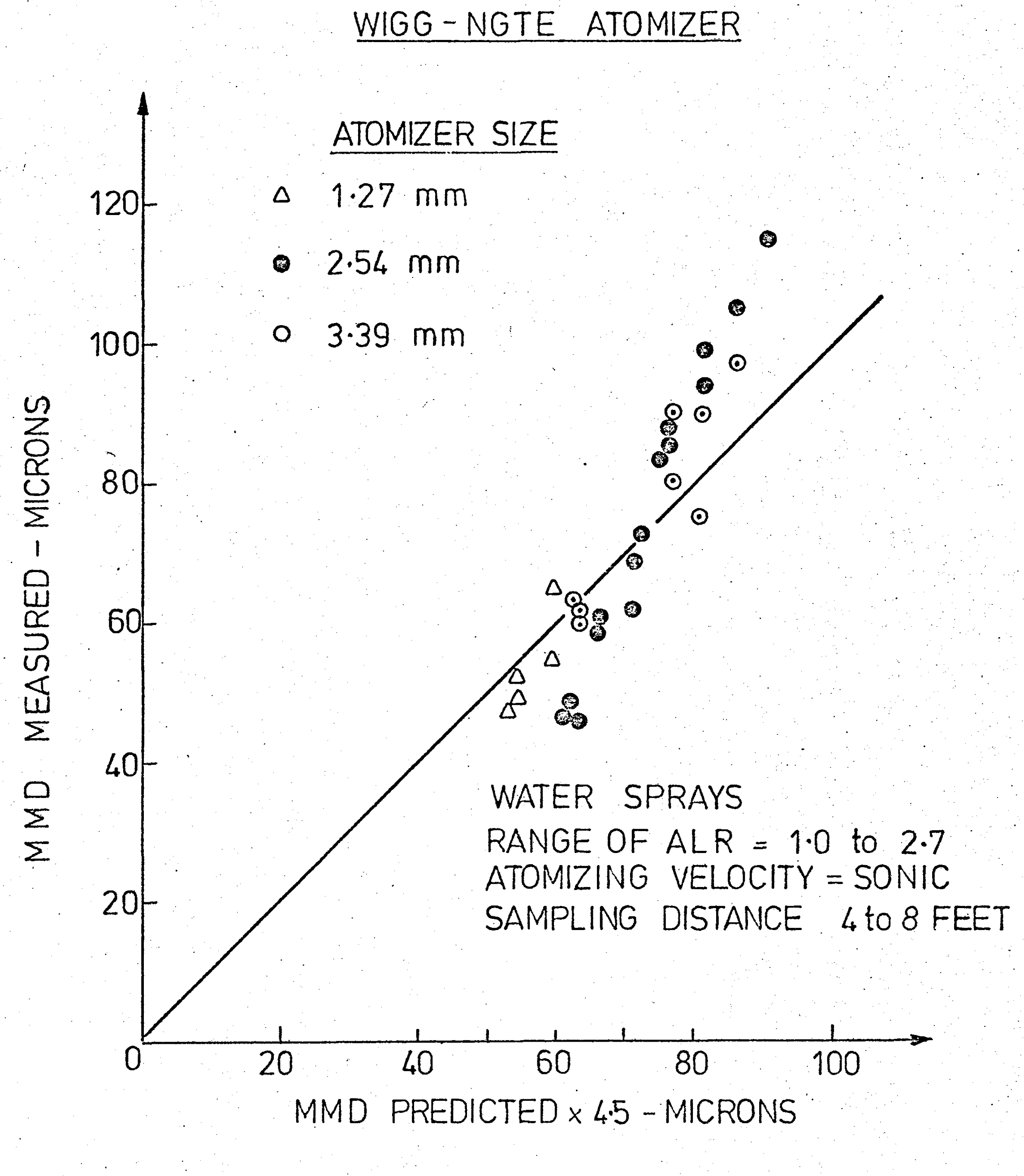


FIG. 66. CORRELATION OF THE DATA OF WIGG REF(96), FOR WATER SPRAYS, BY EQUATION (6·5)

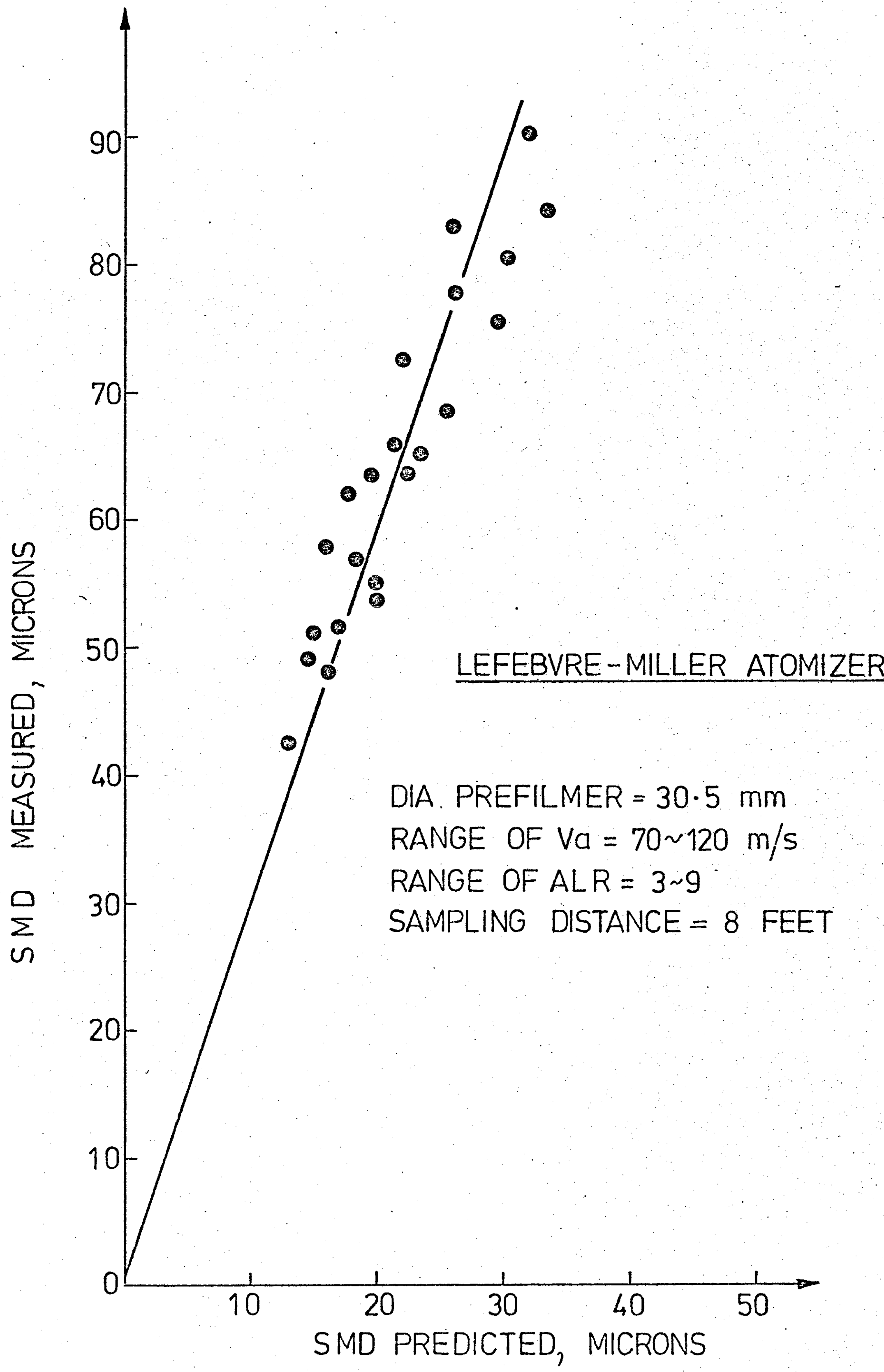


FIG. 67. CORRELATION OF LEFEBVRE MILLER DATA FOR WATER AND KEROSINE SPRAYS, REF (48), BY EQUATION (6·5)

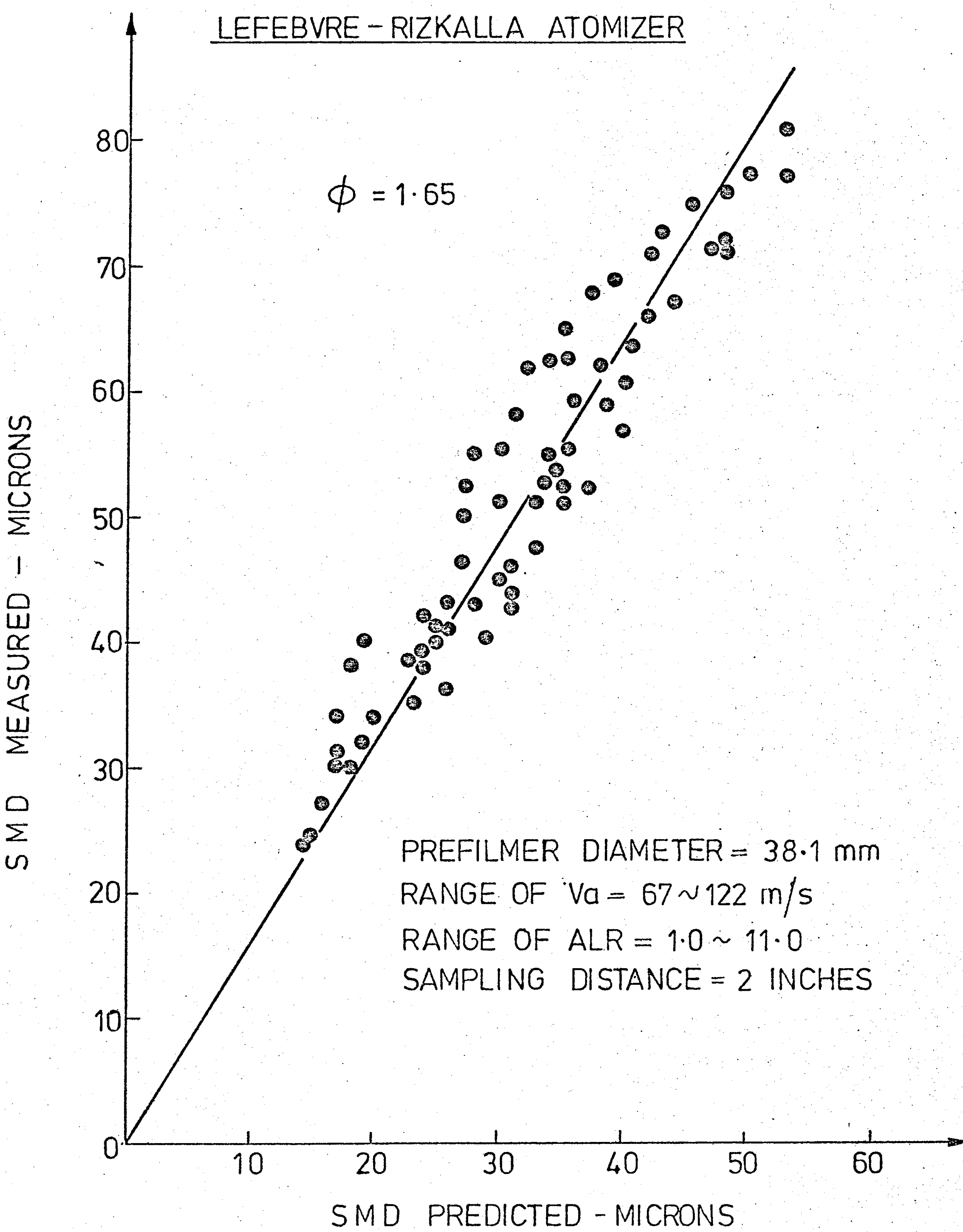


FIG. 68a. CORRELATION OF THE DATA OF RIZKALLA REF. (79) FOR WATER AND KEROSINE SPRAYS, BY EQUATION (6·5)

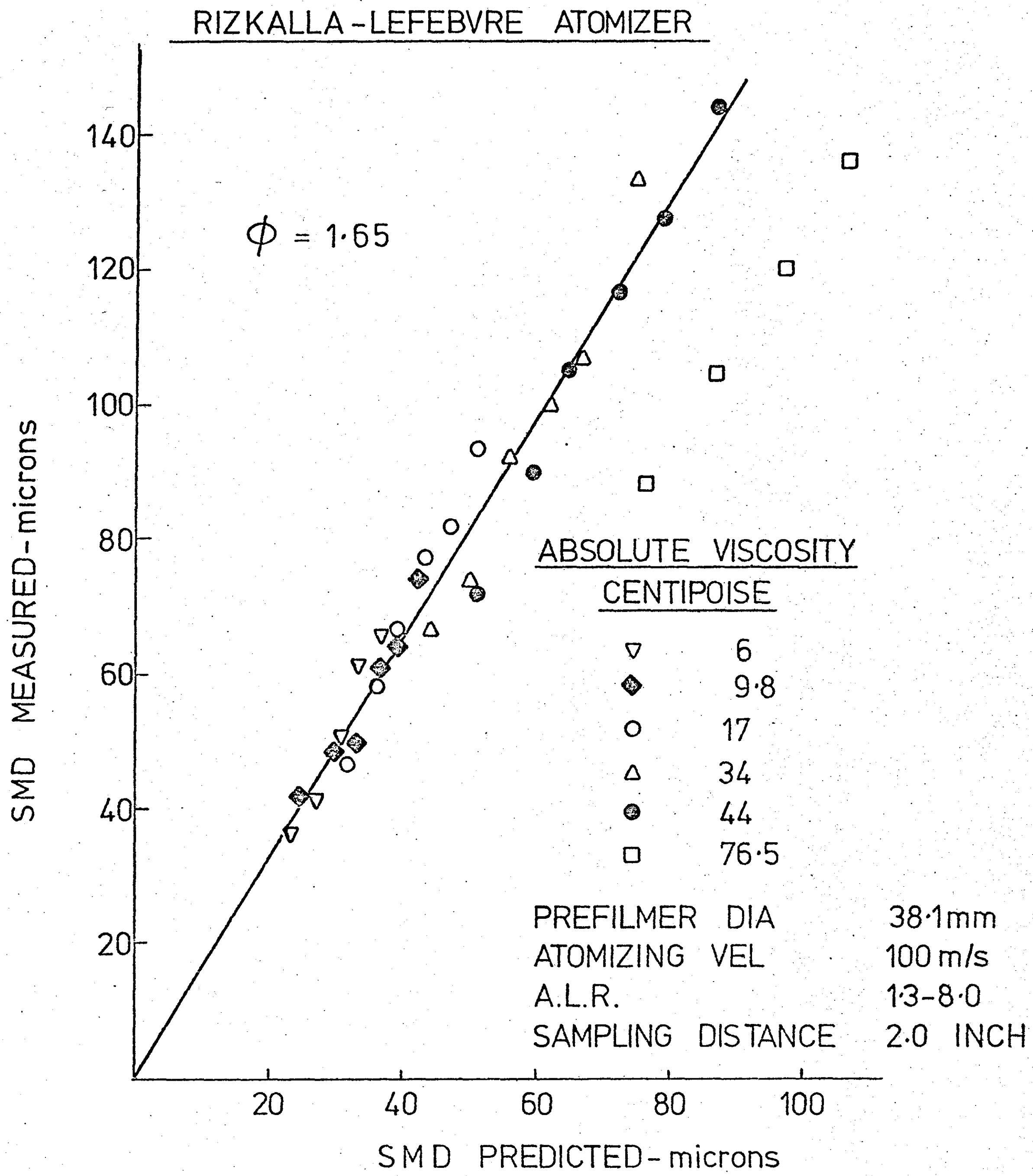


FIG. 68b. CORRELATION OF THE DATA OF RIZKALLA-LEFEBVRE FOR SPRAYS OF VARIOUS HIGH-VISCOSITY SOLUTIONS BY EQUATION (6·5)

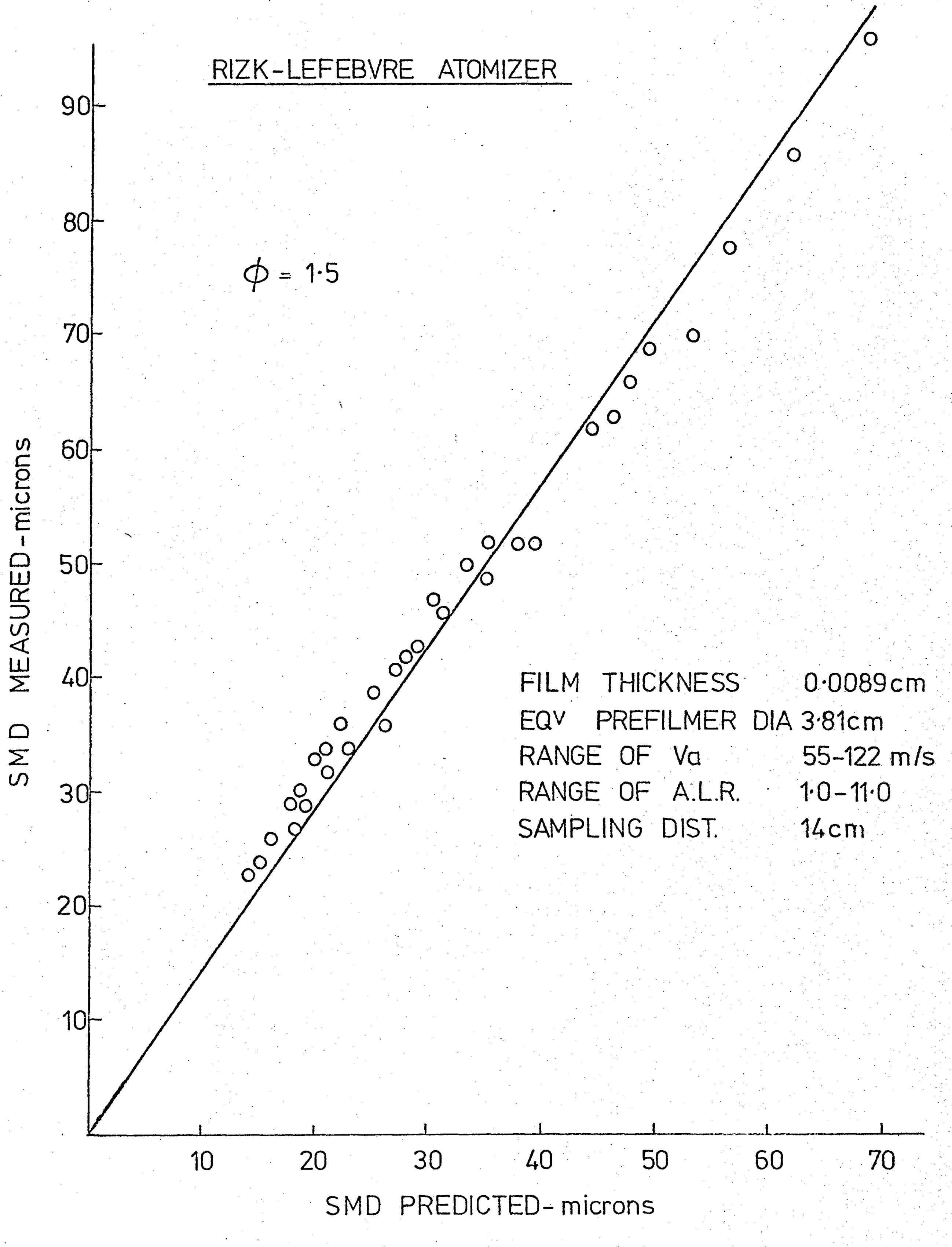


FIG. 69a CORRELATION OF THE DATA OF RIZK (REF 77) FOR KEROSINE SPRAYS, BY EQUATION (6·5)

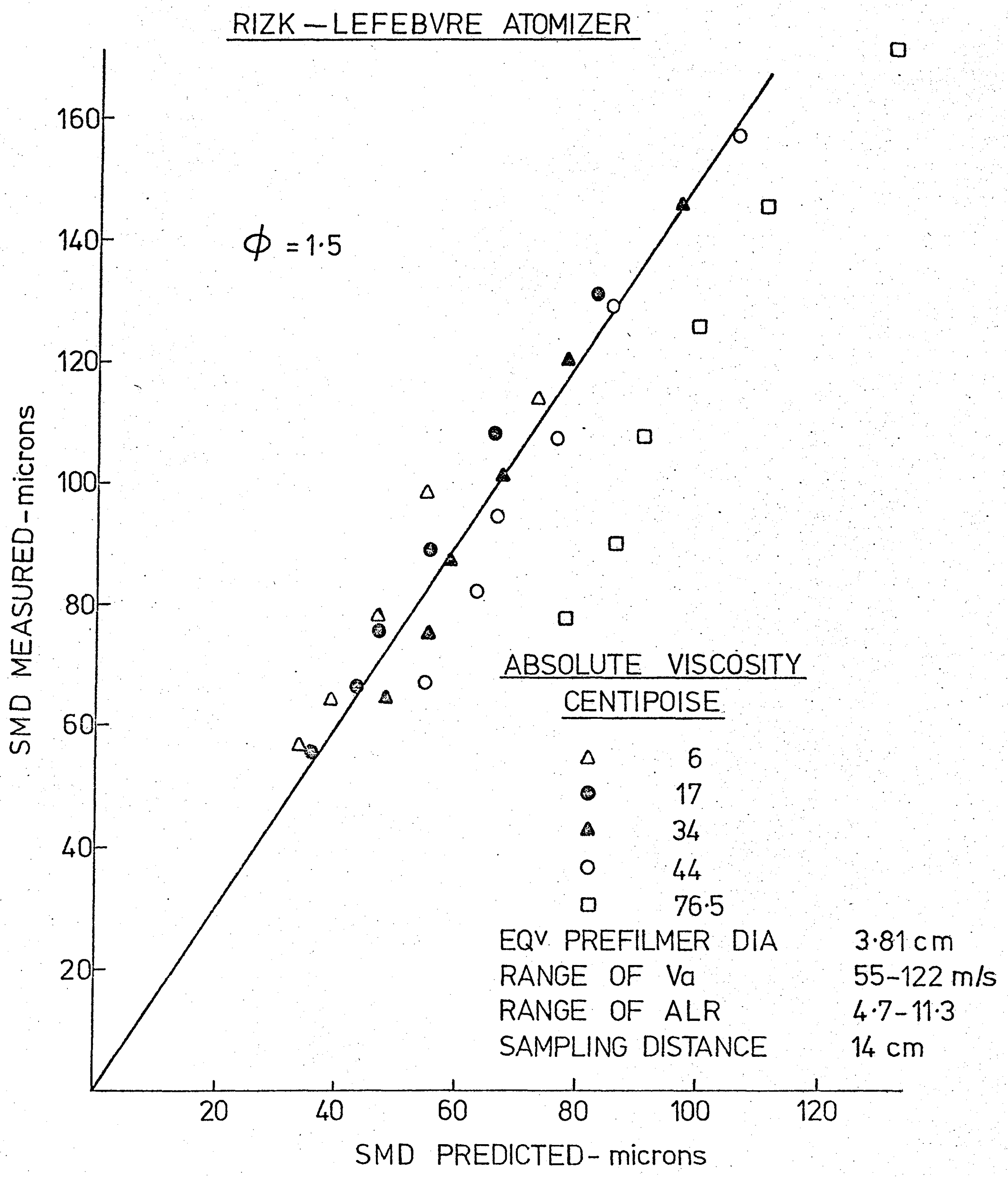


FIG 69b CORRELATION OF THE DATA OF RIZK (REF 77) FOR SPRAYS OF VARIOUS HIGH VISCOSITY SOLUTIONS BY EQUATION (6·5)

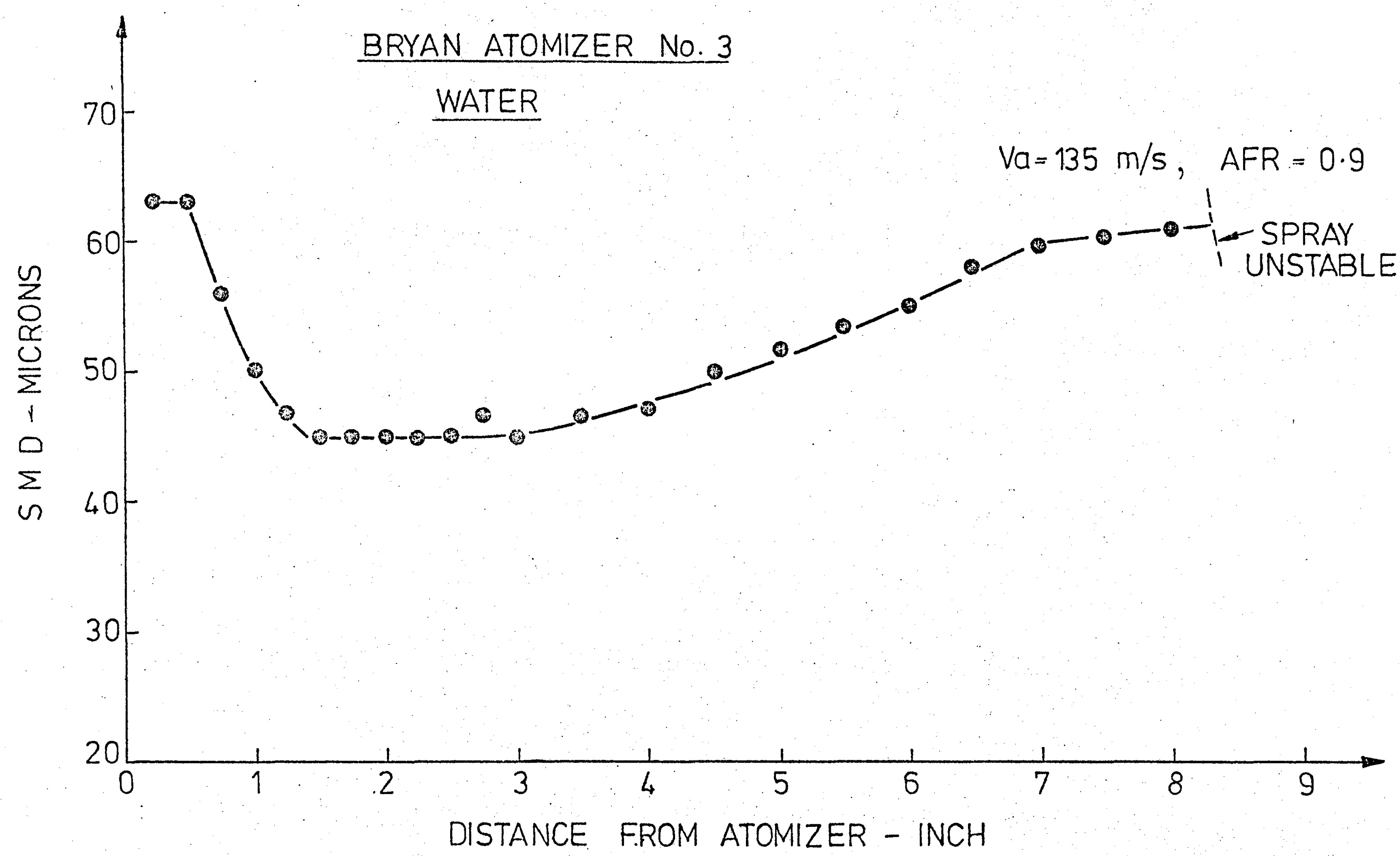


FIG 70a BRYAN ATOMIZER No. 3 - WATER VARIATION OF S M D WITH DISTANCE ALONG AXIS OF SPRAY

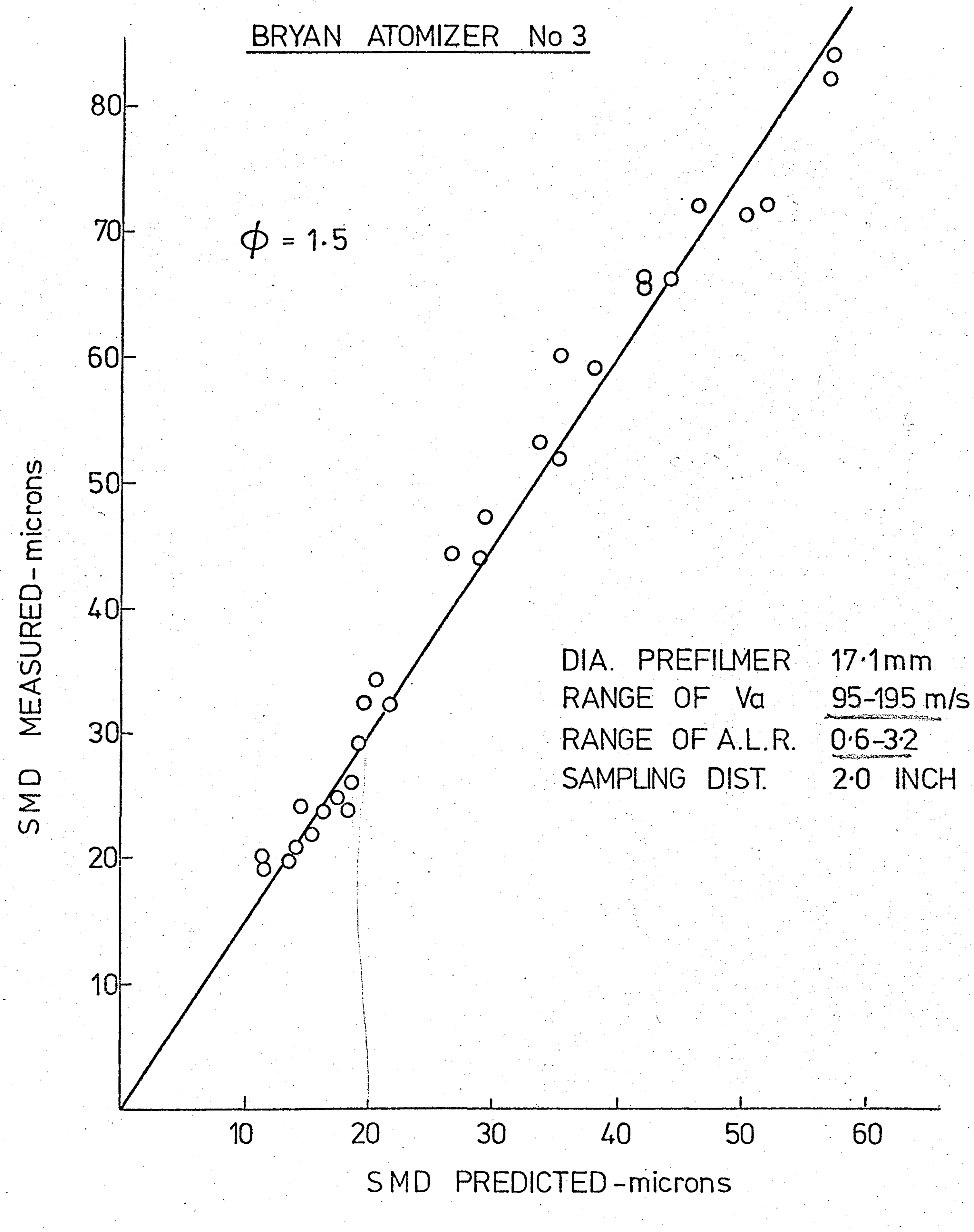
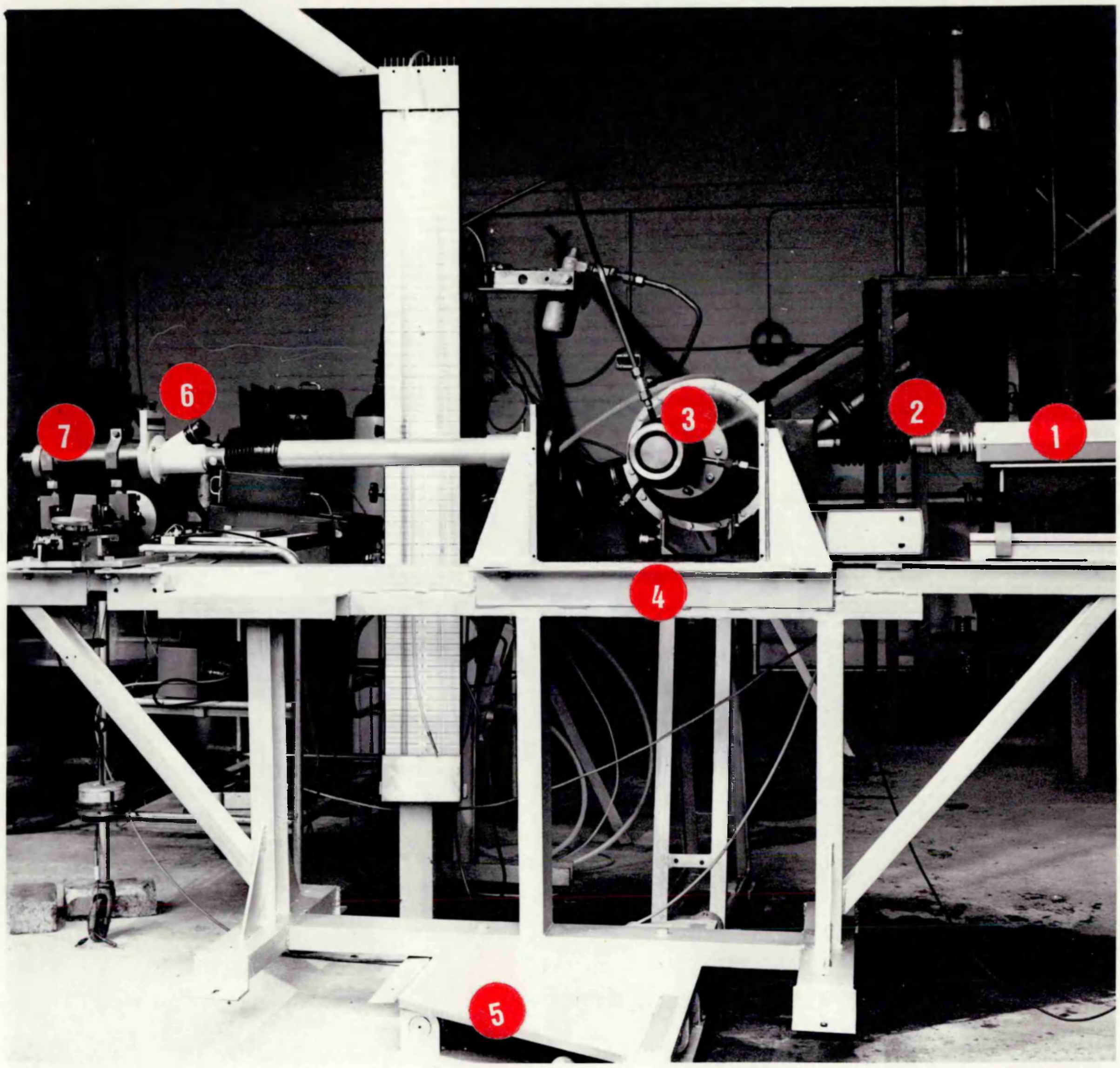


FIG. 70b CORRELATION OF THE DATA OBTAINED WITH BRYANS ATOMIZER SPRAYING WATER, BY EQUATION (6·5)

PLATES

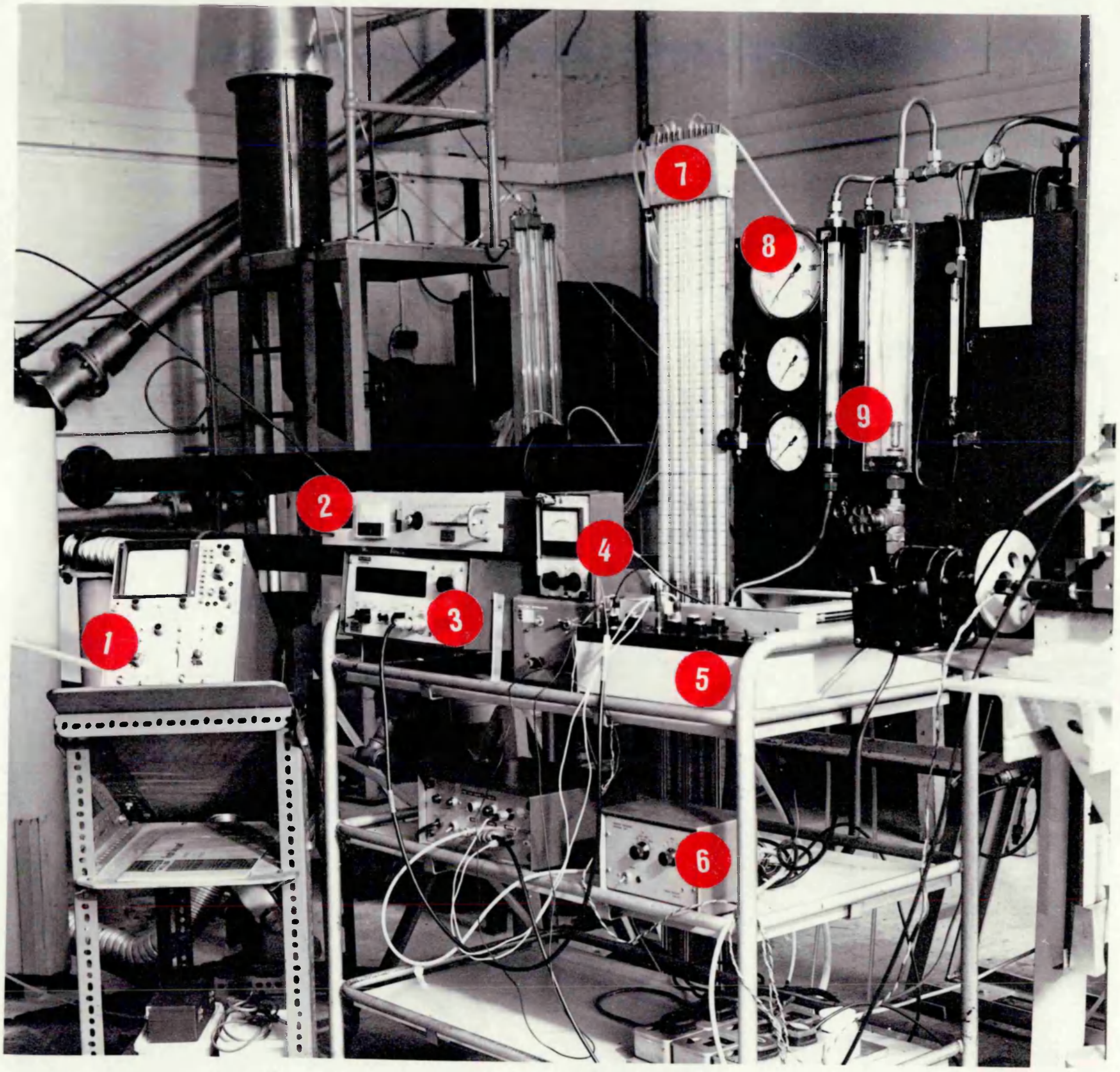
PLATE 1



OPTICAL SYSTEM

1. Laser Head
2. Beam Expanding Assembly
3. Airblast Atomizer
4. Bench
5. Carriage
6. Eye-piece and Shutter
7. Photomultiplier

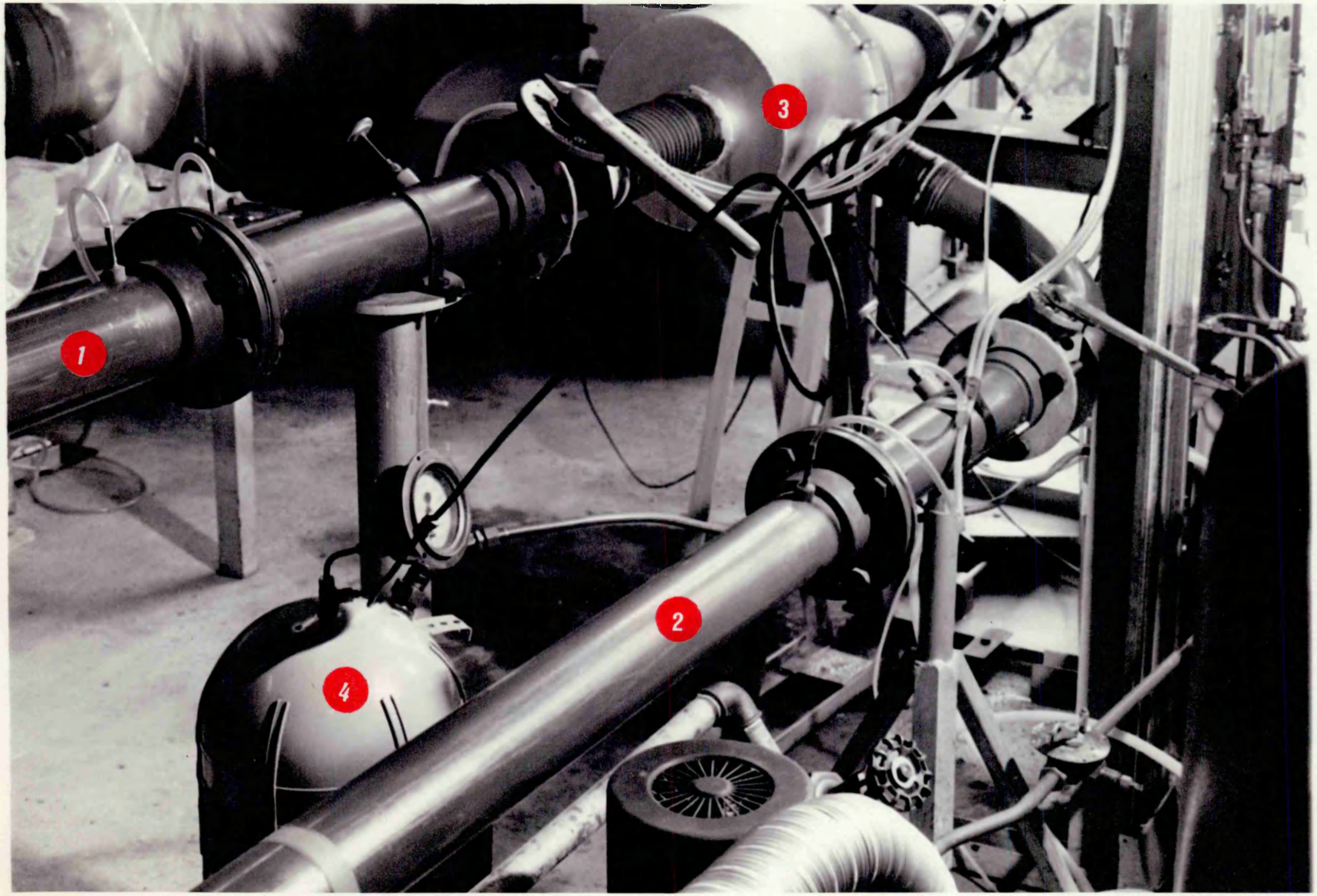
PLATE 2



INSTRUMENTATION

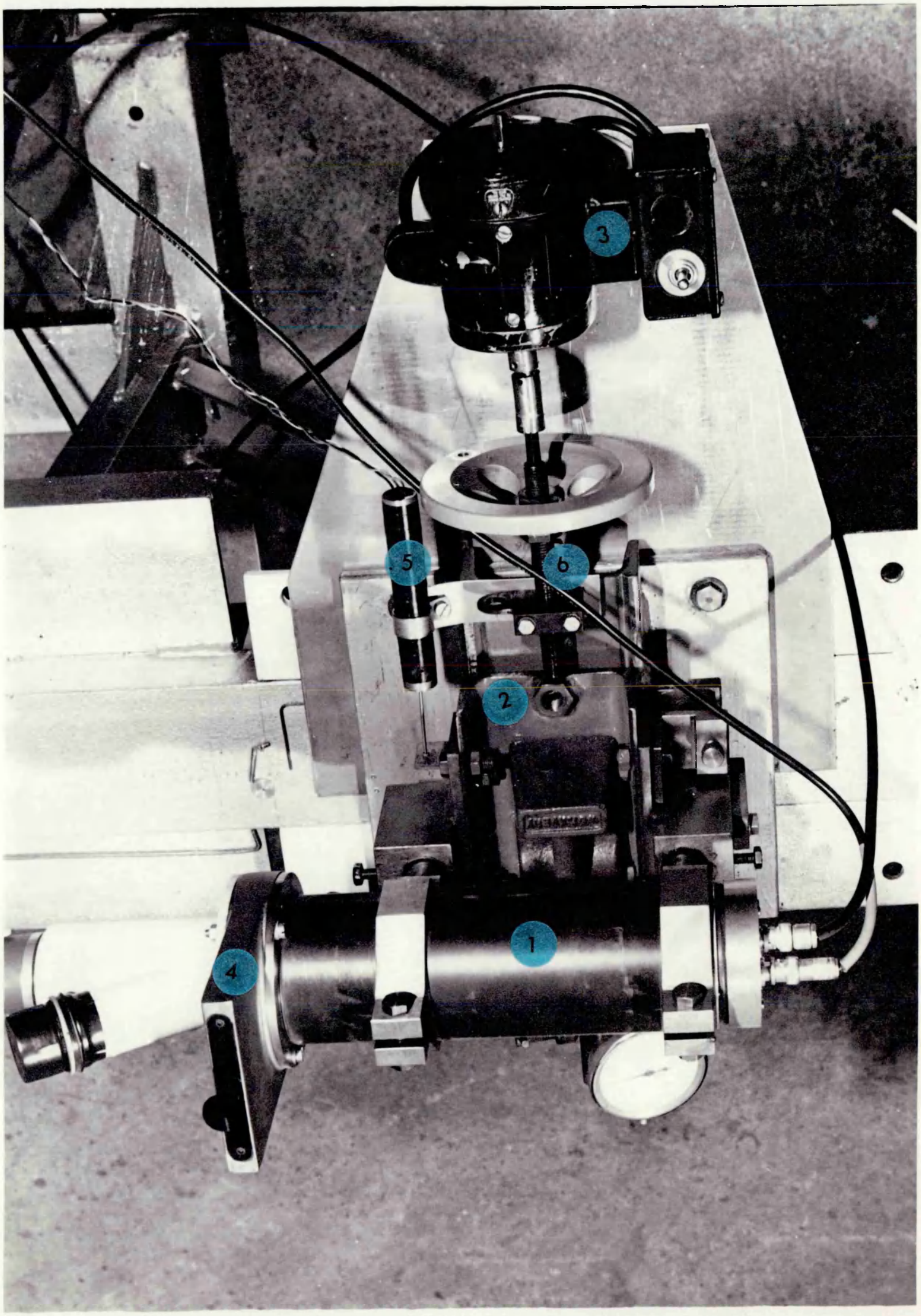
1. Oscilloscope
2. H.T. Supply to Photomultiplier
3. Digital Voltameter
4. Air Temperature Indicator
5. X-Y Plotter
6. Chopper Control Unit
7. Manometers to Orifice Plate
8. Liquid Pressure Gauges
9. Flowmeters

PLATE 3



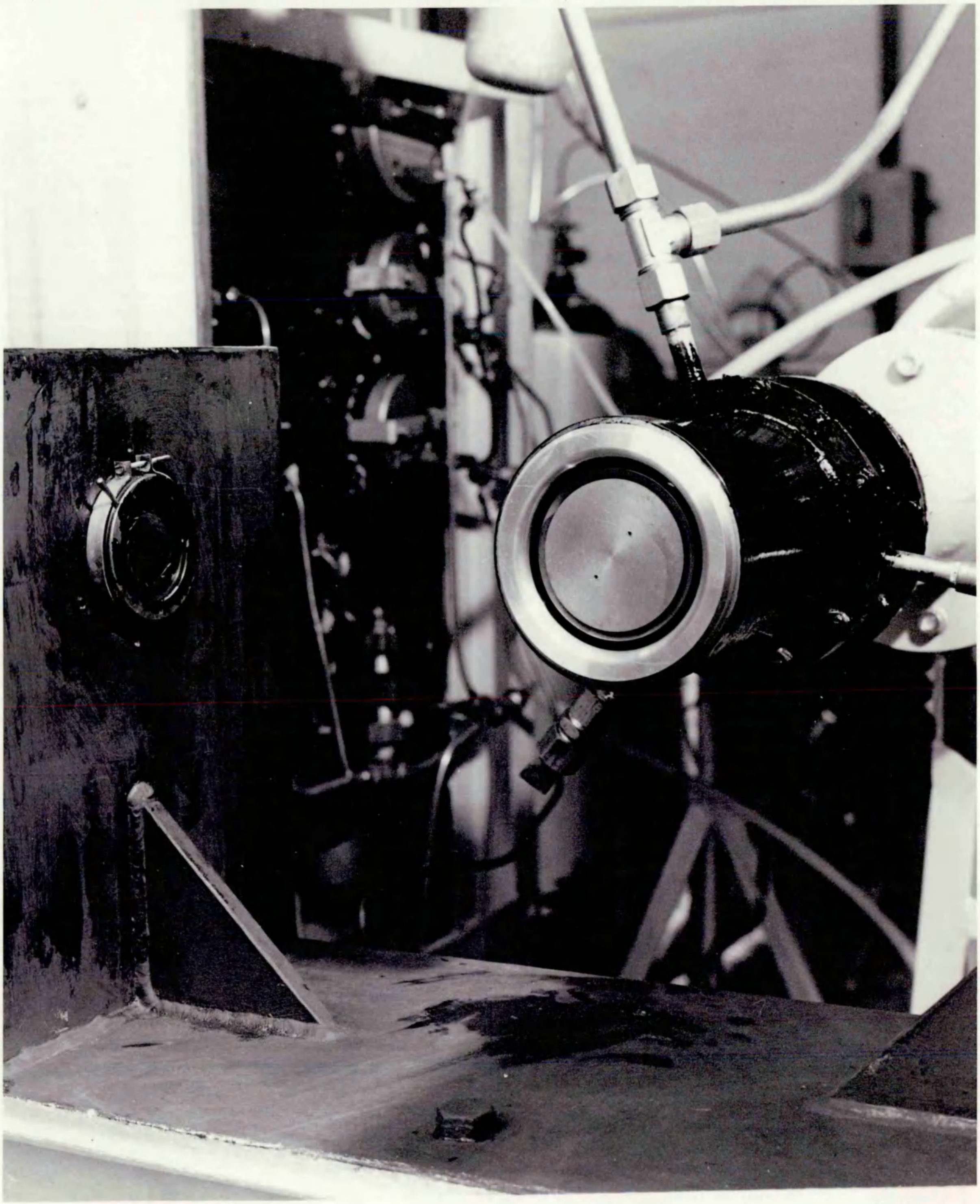
1. Shroud Air Duct
2. Pintel Air Duct
3. Plenum Chamber
4. Liquid Tank

PLATE 4



1. Photomultiplier
2. Trolley
3. Motor
4. Shutter
5. Position Transducer
6. Screw-jack

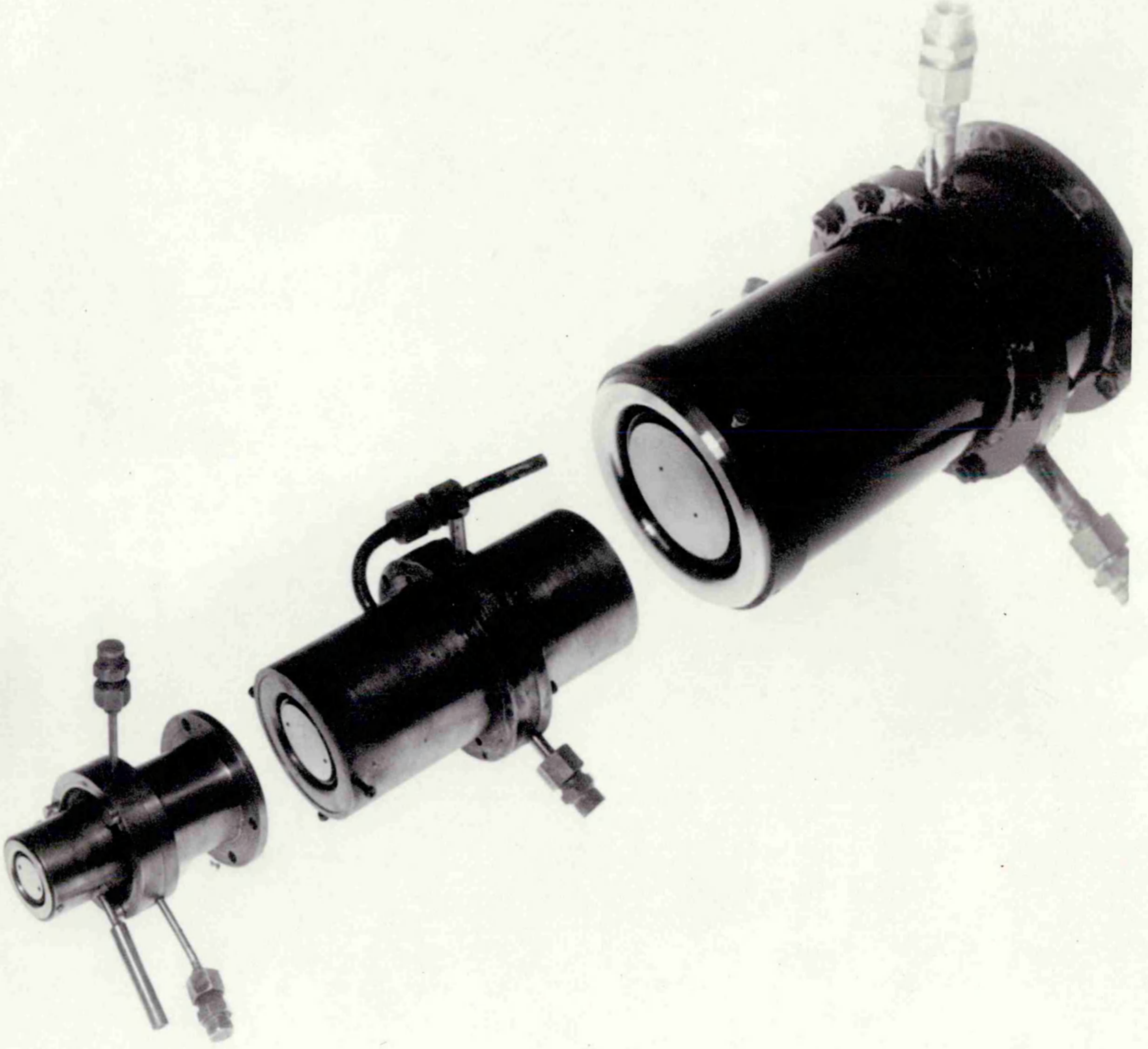
PLATE 5



THE LARGE AIRBLAST ATOMIZER

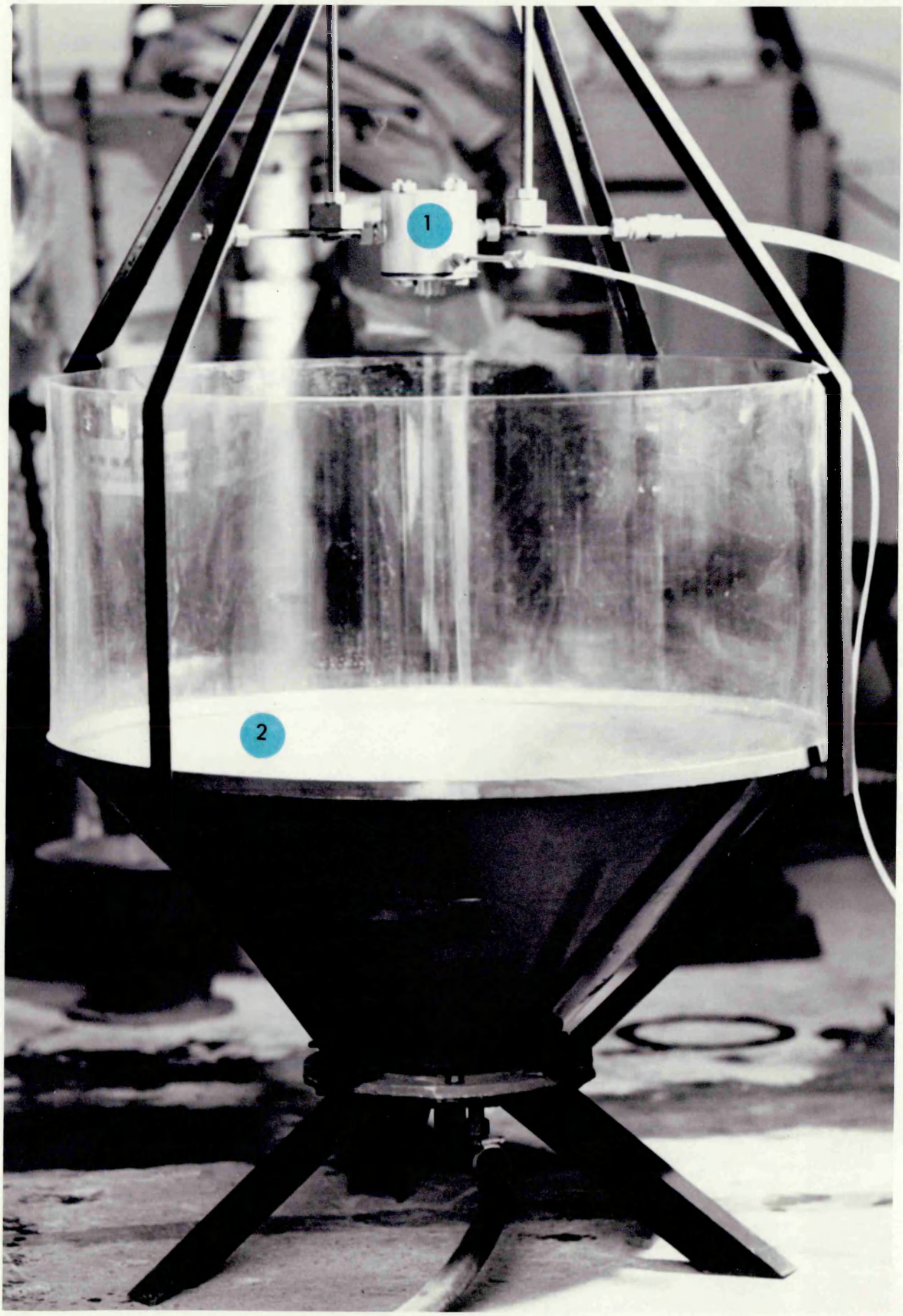
6

PLATE 6



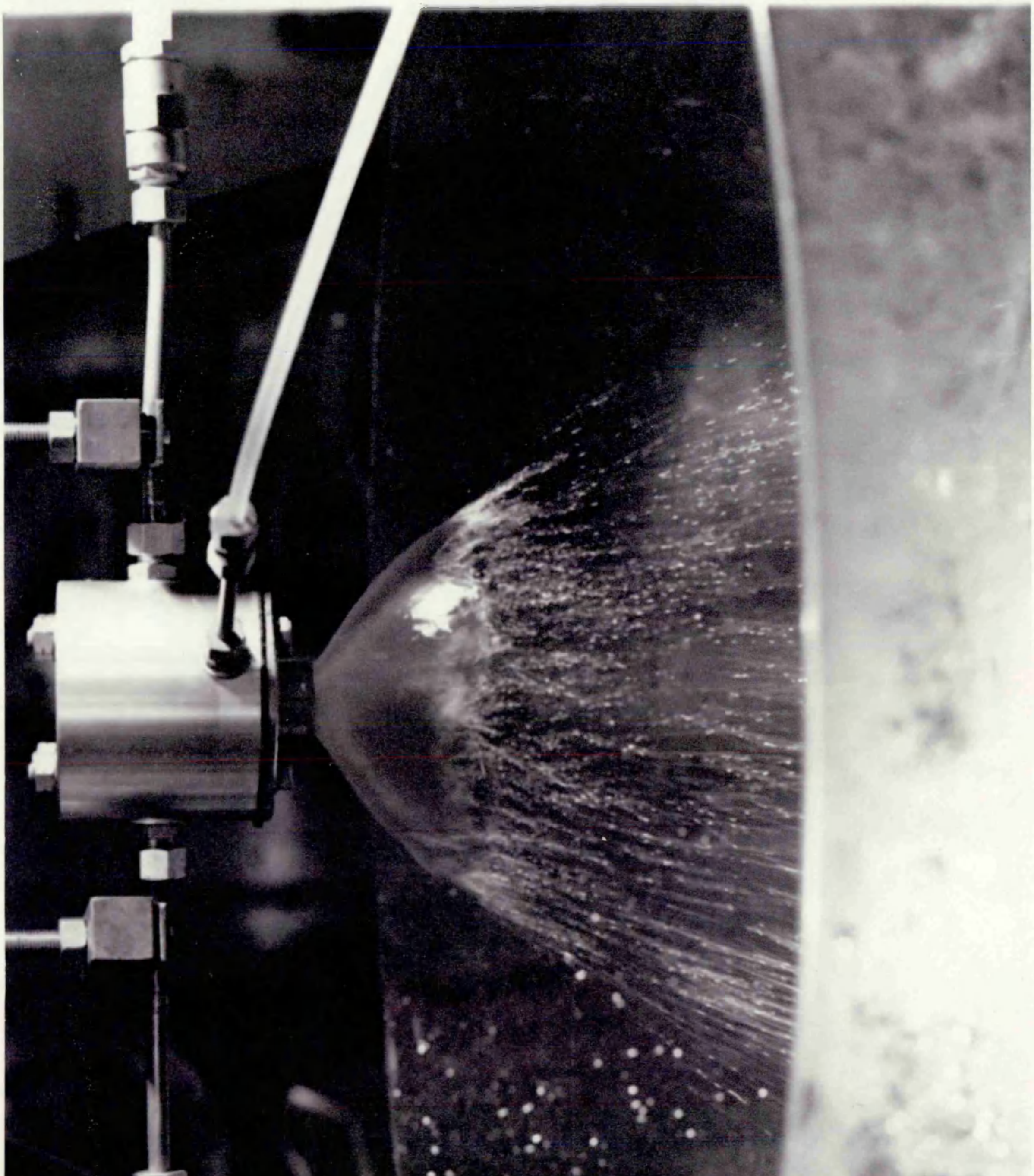
THE THREE GEOMETRICALLY
SIMILAR AIRBLAST ATOMIZERS

PLATE 7



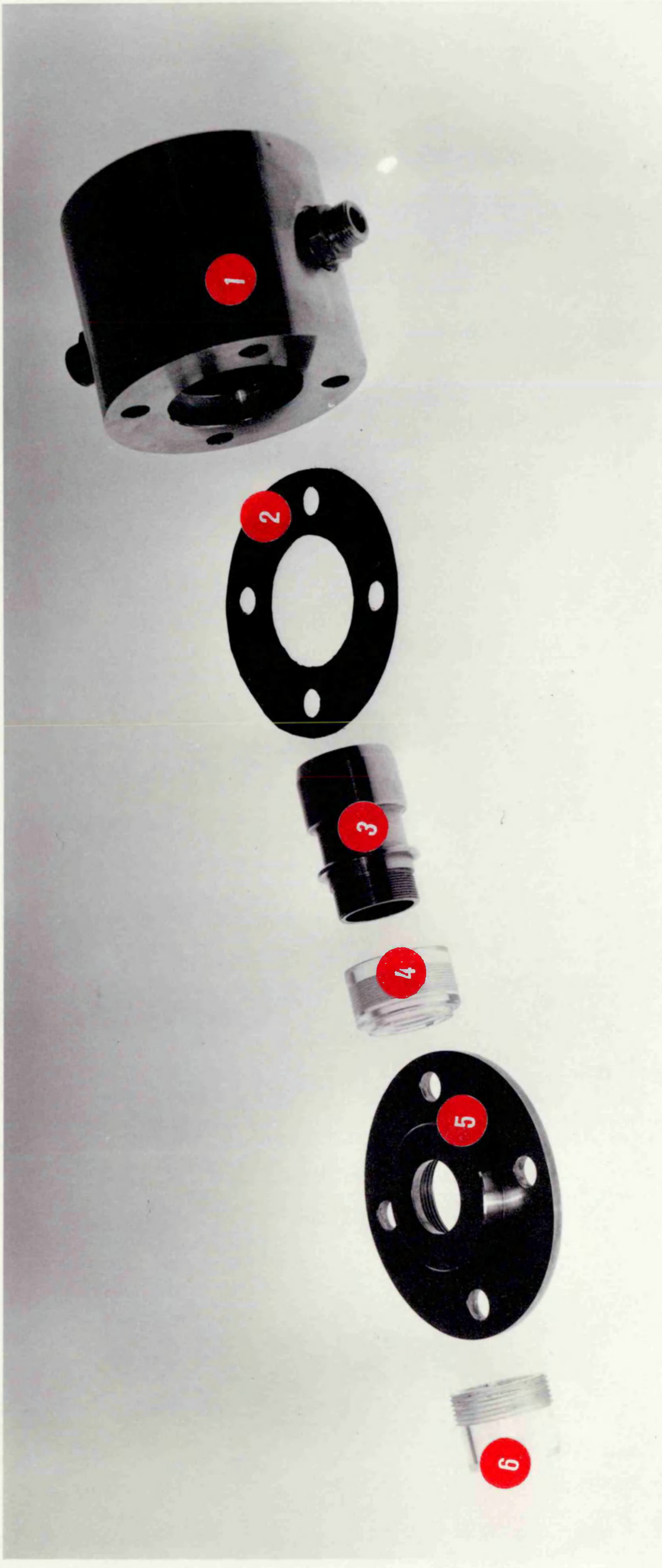
1. Liquid Swirler's Test-Section
2. Liquid Collector

PLATE 8



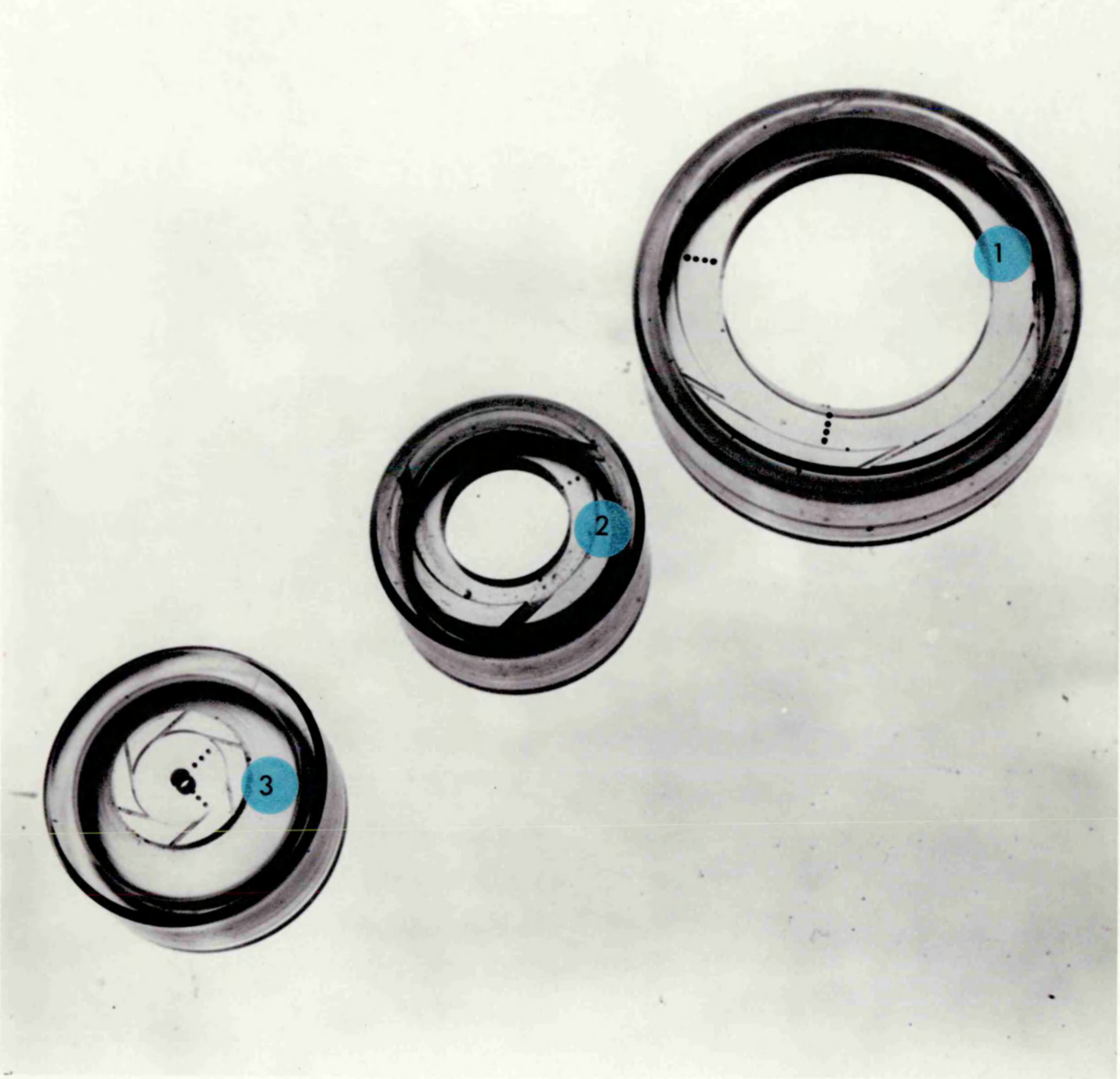
SWIRLERS' TEST-SECTION

PLATE 9



1. Housing
2. Gasket
3. Holder
4. Swirler
5. Cover Plate
6. Cup

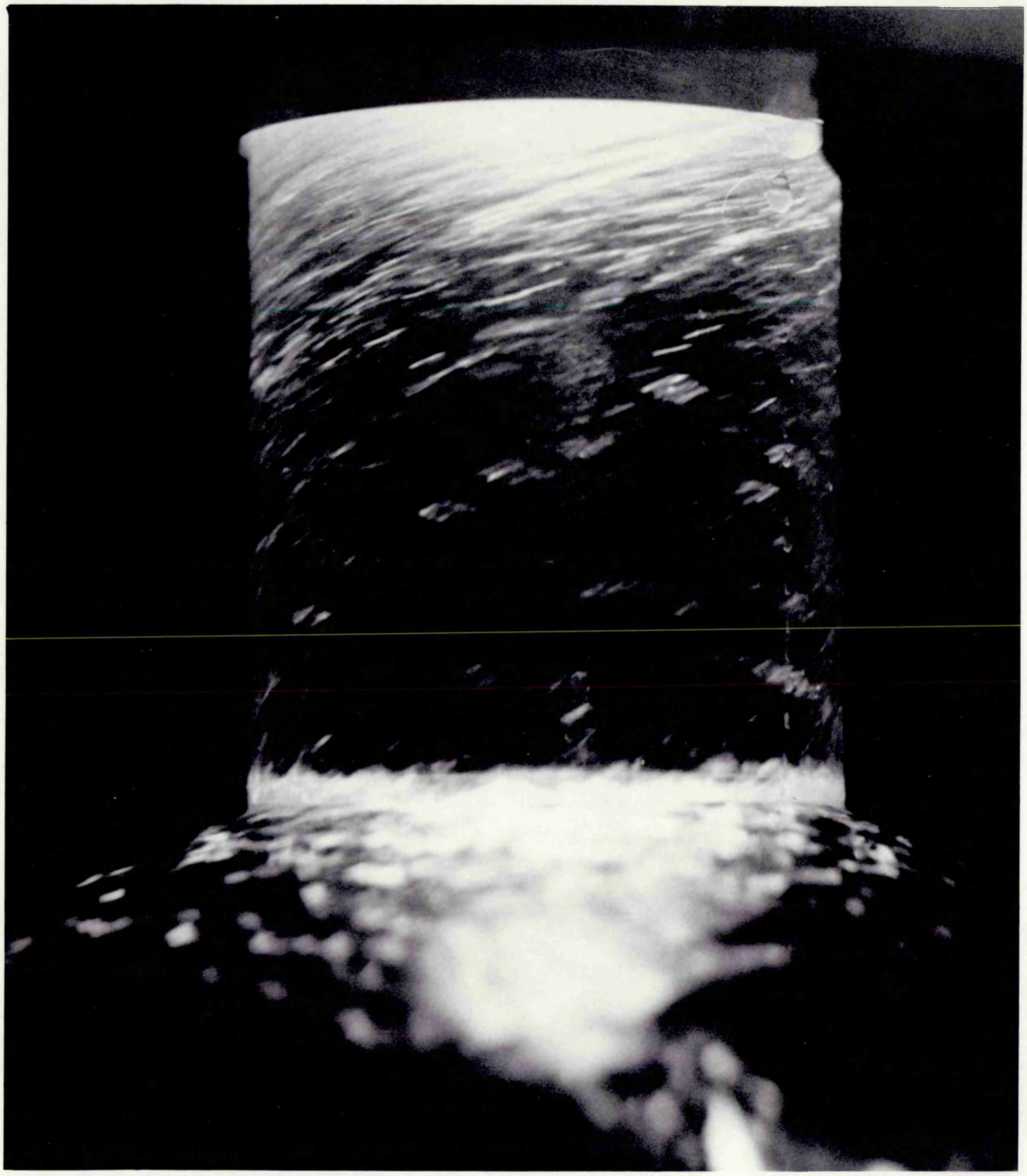
PLATE 10



SWIRLERS

1. 6 slots tengential to 50.8mm. diameter
2. 3 slots tangential to 25.4mm. diameter
3. 6 slots tangential to 12.7mm. diameter

PLATE 11

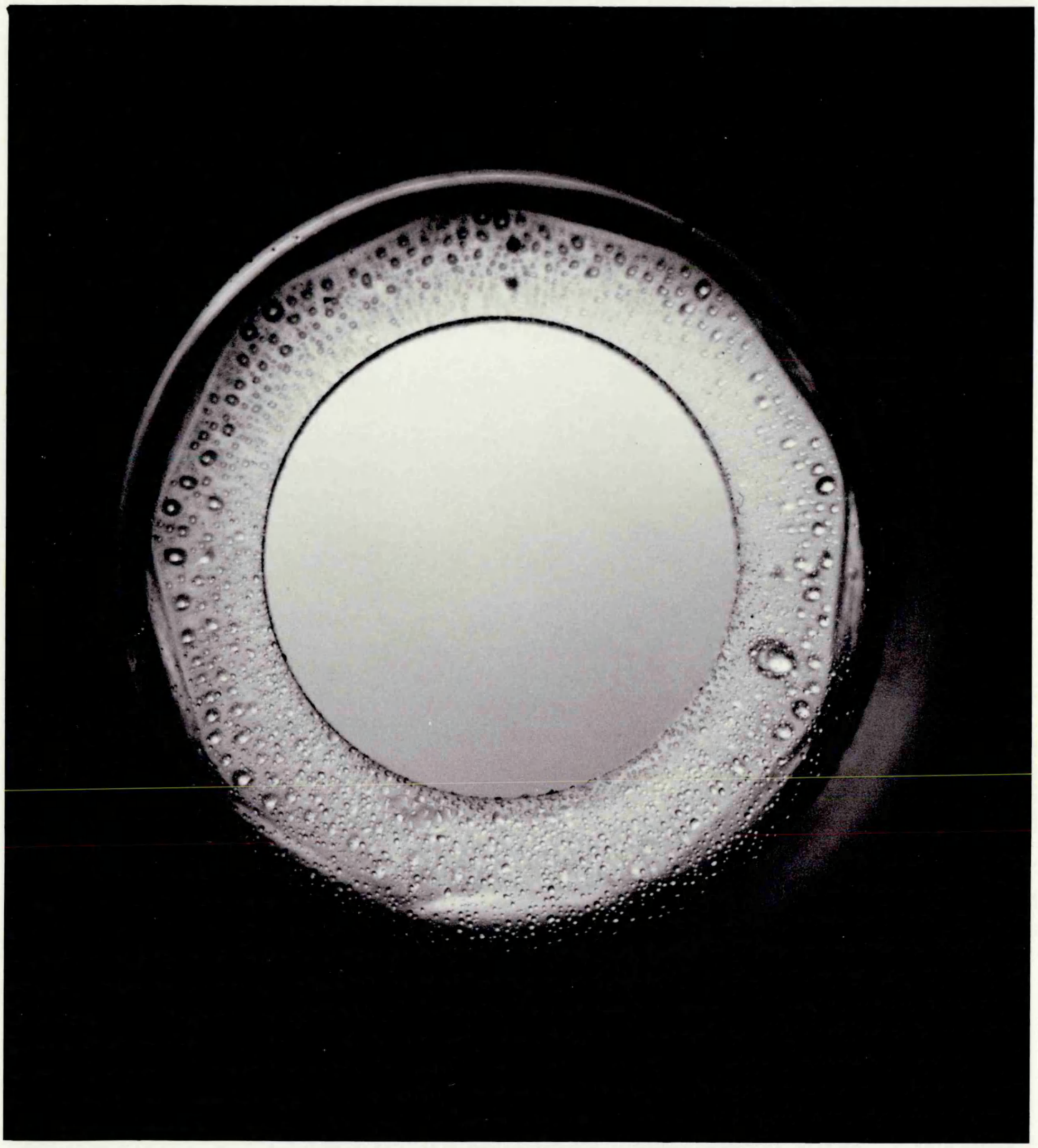


Liquid swirling over pre-filming surface

PLATE 12

6-slot SWIRLER: Liquid formation against back-weir

PLATE 13



9-slot SWIRLER: Liquid formation against back-weir