ANALISIS OF DROPLET SIZE DISTRIBUTION FOR SWIRL TYPE NOZZLES

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ABSTRACT

This paper presents a detailed investigation of the effect of swirl atomizer geometry on the droplet size distribution. This includes the investigation of the effect of pressure drop across the atomizer, length/diameter ratio of the swirl chamber, length/diameter ratio of the orifice, and the orifice, diameter upon the droplet size distribution. The slide sampling technique is used for the determination of the droplet size. A new analytical method for the Tanasawa-Tesima distribution equation is proposed. The Weibull distribution function is also tested for evaluation of the measured distribution. The dependences of the shape parameters, for the two distributions on the atomizer geometry and working pressure are summerized in useful empirical equations. These correlation equations can be used for the prediction of the atomizer geometry and the operating conditions which satisfy a specified liquid atomization quality.

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1- INTRODUCTION

The liquid spray has been the subject of considerable research [1,2,3] as it has wide applications in industry and every day activities. Since there is no explicit relations describing the spray droplet size distribution, could be found in literature,it was decided to perform detailed experimental investigation of all aspects of swirl atomization to clarify the atomization quality for a wide range of atomizer geometry and operating pressures.

The first phase of this investigation, which was reported in ref. [5] , was concerned with the effect of: pressure drop across the atomizer Δp, length/diameter ratio of the swirl chamber L/D, length/diameter ratio of the orifice l/d and the orifice diameter upon the spray cone angle α , the rate of discharge Q, the droplet size distribution and mean droplet diameter D_{32}. The obtained experimental results were used to derive three empirical relations describing the dependence of Q, α and D_{32} upon the operating conditions and atomizer geometry.

In this paper the theoretical analysis is continued to correlate the measured droplet size distribution and to establish a more suitable size distribution function. Empirical relations were developed based on Tanasawa-Tesima and Weibull distribution functions.

The previous method for determining the shape parameters of the used spray distribution functions, such as Tanasawa-Tesima [2] , Rosin-Rammler [2] , attempts to fit the experimental data adequately. Abou Ellail [1] used the mean droplet diameter D_{32} together with shape parameters α and β to specify uniquely the Tanasawa-Tesima distribution equation. However the using of D_{32} in this stage is not suitable as a change in the order of 0.5 % in the number of biggest droplet $\frac{\delta n}{n}$ will change the value of D_{32} by 5-10 %.

In this work the determination of the distribution shape and scale parameters is based on the point of maximum percentage of droplets number $(\frac{\delta n}{n})_{max}$ with the corresponding droplet diameter D_{opt} (peak point) in addition to another two measured points of the distribution. The distribution peak point is determined by using the " spline fit " [4] for each measured distribution.
The calculated results of both Tanasawa-Tesima and Weibull distributions are used to derive empirical dependences of shape parameters upon the operating conditions and atomizer geometry (Δp , L/D , l/d and d). These empirical equations can be used for prediction of the atomizer geometry and operating conditions required to estabilish a specified atomization quality by a design engineer.

2- EXPERIMENTAL SET-UP

The Experimental set-up is described in detail in ref [5] . However, for the seak of completeness, it is found suitable to give a brief description of the experimental procedure. Nine variants of swirl spray nozzles were produced and tested with L/D = 0.25 - 2.75 , l/d = 0.5 - 2, d = 0.8 - 1.6 mm and all with three inlet parts of diameter d_{in} = 1 mm , Fig. 1. The basic dimensions of the manufactured atomizers are given in table 1. The range of injection pressure drop was Δp = 5 - 20 bar .

The droplet sizes were measured using the slide sampling technique. The sampling apparatus consisted of part of hollow cylinder 100 mm diameter and 150 mm length which prepared with five 2 mm holes 15 mm a part, Fig.2. The slide sampling apparatus was fitted at a distance 80 mm from the atomizer.

Table 1. Swirl Spray Nozzles Dimensions

Nozzle number	d mm	l mm	D mm	L mm	l/d	L/D
I	0,8	0,4	6	1,5	0,50	0,25
II	0,8	1,0	6	1,5	1,25	0,25
III	0,8	1,6	6	1,5	2,00	0,25
IV	0,8	0,4	6	9,0	0,5	1,50
V	0,8	1,0	6	9,0	1,25	1,50
VI	0,8	1,6	6	9,0	2,00	1,50
VII	0,8	1,0	6	16,5	1,25	2,75
VIII	1,2	1,5	6	9,0	1,25	1,50
IX	1,6	2,0	6	9,0	1,25	1,50

The soot coated glass slide was mounted on an axle fitted inside the cylinder ends and could be rotated around its axis by a special arm. Fluid sprays injected from the atomizer and passing through the holes on the rim of the slide sampling apparatus will leave impression on the soot layer deposited on the glass slide. The impression diameter d is equal to droplet diameter D with an error not more than 3 percent [2] .

The liquid impression on the slide were photographed under microscope and then by using the projector for the photographed film, a total magnification of 500 was reached. The

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number of droplets which have the same diameter are counted and classified into groups with size interval 10 μm. The total random summation of these groups gives the droplet size distribution for the whole fluid spray. The accuracy of the measured impressions is about ± 1 μm.

3. RESULTS AND ANALISIS

The nine nozzles were tested at three values of pressure drops (Δp = 5, 10 , 20 bar). Sample photographs of the spray droplets at various conditions are shown in Fig.3 [6] . Some examples of the measured droplet size distribution together with the calculated peak points by the spline fit are shown in Fig.4.

The calculation of the distribution peak points is done by application of the " Spline Fit " method [4] . It is a numerical method of interpolation which produces first derivatives of high quality. This approximation, which is essentially the numerical analogue of the draft-man's spline, consists of joining the assigned points by sections of cubics, requiring that slopes and curvature to be continous at the junction points.

In the present paper the Tanasawa-Tesima equation is used to describe the measured droplet size distribution of the swirl atomizer. The Tanasawa-Tesima equation, namely

$$\frac{\delta n}{n} = A\, D^{\alpha} \exp\left(-b\, D^{\beta}\right) \qquad (1)$$

where,

α , β ... distribution shape parameters.
A ,b ... scale-change parameters.

The determination of the distribution shape and scale parameters is based on the point of maximum percentage of the droplet diameter and the corresponding droplet diameter

(peak point), together with another two measured points of the distribution $(\frac{\delta n}{n})_1 = \frac{\delta n}{n}(D_1)$ & $(\frac{\delta n}{n})_2 = \frac{\delta n}{n}(D_2)$.
The importance of using the peak point of the distribution to define the spray atomization is that it is an important criterion in many practical application of industry and agriculture.
Theoretical analysis was done to evaluate the distribution parameters as function of the above selected three points which gives the following relations,

$$A = \frac{(\delta n/n)\max}{D_{opt}^{\alpha}} \exp\left(\frac{\alpha}{\beta}\right) \tag{2}$$

$$b = \frac{\alpha}{\beta}\left(\frac{1}{D_{opt}}\right)^{\beta} \tag{3}$$

$$\alpha = \frac{\ln\left[(\frac{\delta n}{n})_1 / (\frac{\delta n}{n})_2\right]}{\ln(\frac{D1}{D_2}) + \frac{1}{\beta}\left[(\frac{D2}{D_{opt}})^{\beta} - (\frac{D1}{D_{opt}})^{\beta}\right]} \tag{4}$$

$$\frac{(\delta n/n)_1}{(\delta n/n)_{max}} = \left(\frac{D_1}{D_{opt}}\right)^{\alpha} \exp\left\{-\frac{\alpha}{\beta}\left[\left(\frac{D_1}{D_{opt}}\right)^{\beta} - 1\right]\right\} \tag{5}$$

The solution of the above set of equations is done by itteration on a P.C. Figs.5,6,7 and 8 show the suitability of the used Tanasawa-Tesima equation to describe the droplet size distribution and also the applicability of the used method for prediction of distribution shape parameters. The variation of the calculated distribution shape parameters α and β with the pressure drop across the atomizer Δp, the geometrical parameters L/D, l/d and the orifice diameter d are presented in Figs 9,10.

The Weibull equation has been considered for the representation of the measured droplet size distribution. The Weibull equation is given as follows,

$$\frac{\delta n}{n} = K\ D^{m}\ \exp\left(- \frac{K}{m+1}\ D^{m+1} \right) \qquad (6)$$

where m is the distribution shape parameter and K is a scale change parameter.

The determination of the Weibull parameters is done by help of the known value of $(\delta n/n)_{max}$ with corresponding value of Dopt which gives

$$K = m / (D_{opt})^{m+1} \qquad (7)$$

$$\left(\frac{\delta n}{n}\right)_{max} = K\ D^{m}_{opt}\ \exp\left(- \frac{m}{m+1} \right) \qquad (8)$$

The variation of the calculated Weibull distribution shape parameter m with Δp, L/D, l/d and d are represented in Fig.11. The comparison between the measured, Weibull and Tanasawa-Tesima distributions for different working conditions is shown in Fig.12.

4. CORRELATION OF EXPERIMENTAL DATA

The previous analysis shows that the distribution shape parameters of the Tanasawa-Tesima and Weibull distributions depend on the operating conditions and the atomizer geometry. The practical use of these results require the correlation of the calculated data in suitable emperical equations.

In order to obtain these equations the " Graphical and Numerical Method of Partial Relations " was used [5]. The introduced method is at present time the most general one for deriving the empirical dependences of the function of

more independent variables.
The following three emiprical equations for the distribution shape parameters were derived using the mentioned method.
For Tanasawa-Tesima distribution:

$$\alpha = 30{,}247\,[-1 + 0{,}37181\ \Delta p - 12{,}616\,.10^{-3}\ \Delta p^2] \times$$
$$\times [1 + 0{,}17514\ (L/D) - 0{,}10366\ (L/D)^2]\ [1-0{,}20508\ (l/d)] \times$$
$$\times [1 - 1{,}35358\ d + 0{,}52583\ d^2] \qquad (9)$$

$$\beta = 655{,}44\,[1-0{,}12675\ \Delta p + 4{,}3737.10^{-3}\ \Delta p^2]\ \left[\frac{(L/D)}{96{,}461(L/D)-1}\right] \times$$
$$\times\ [1-0{,}087522\ (l/d)]\ [\,1 - 0{,}34096\ d\,] \qquad (10)$$

For the Weibull distribution

$$m = 4{,}454\ [1-0{,}087343\ \Delta p + 3{,}3458.10^{-3}\ \Delta p^2]\ [1+0{,}60032(L/D)-$$
$$- 0{,}22434\ (L/D)^2]\ [\,1-0{,}0701(l/d)]\ [\,1-0{,}46766\ d] \qquad (11)$$

These relations are accurate within ± 8 percent over the investigating range of $L/D = 0.25 - 2.75$, $l/d = 0.5 - 2$, $d = 0.8 - 1.6$ mm and $\Delta p = 5 - 20$ bar. The above equations together with equations (2), (3) and (7) for the distribution scale parameters give the droplet size distribution.
The droplet mean diameter D_{32} from Tanasawa-Tesima equation is given in the form [1] ,

$$D_{32} = \frac{\Gamma[(\alpha+4)/\beta]}{b^{1/\beta}\,\Gamma[(\alpha+3)/\beta]} \qquad (12)$$

The calculated D_{32} from equation (12) will give lower value than that estimated by the measured distribution, that is due to the neglection of small percentage of big droplets. In spite of the small percentage of the big droplet, they have great effect on the value of D_{32} as mentioned before. Therefore, the mean droplet diameter is calculated according to the empirical relation derived in ref. [5] , considering the measured droplet size distributions. This relation takes the form:

$$D_{32} = 107,38 \left[\Delta p^{-0,3884} \right] \left[(L/D)^{-0,1129} \right] \left[1 + 1,3596(l/d) - 0,5835(l/d)^2 \right] \left[d^{0,671} \right] \qquad (13)$$

5. CONCLUSIONS

A quantative variation of the atomization characteristics with atomizer geometry and operating pressures can be easily deduced from the derived empirical equations.

The droplet size distribution is best represented by Tanasawa-Tesima equation which is uniquely dependent on the distribution shape parameters (α, β) and the distribution peak point. Also the Weibull distribution can be used to give the first approximation of the droplet size distribution knowing only the peak point.

These correlation equation can be used either to determine The atomizer geometry and the operating pressure drop for a give atomization quality or to determine the atomization characteristics of a given atomizer.

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NOMENCLATURE

A	Tanasawa-Tesima scale change parameter
b	Tanasawa-Tesima scale change parameter
d	orifice diameter, mm
d_{in}	diameter of the inlet swirl ports, mm
D	diameter of the swirl chamber, mm
D	droplet diameter, μm
D_{32}	surface-volume mean diameter (Sauter mean diameter, or mean droplet diameter), μm
K	Weibull scale change parameter
l	orifice diameter, mm
L	Length (width) of the swirl chamber, mm
m	weibull distribution shape parameter
n	number of inlet ports
Δp	pressure drop across the atomizer, bar
α , β	Tanasawa-Tesima distribution shape parameters

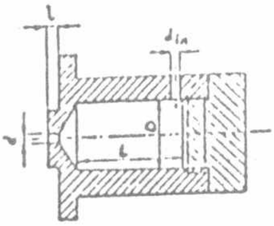


Fig.I. Cross-sectional view of swirl atomizer

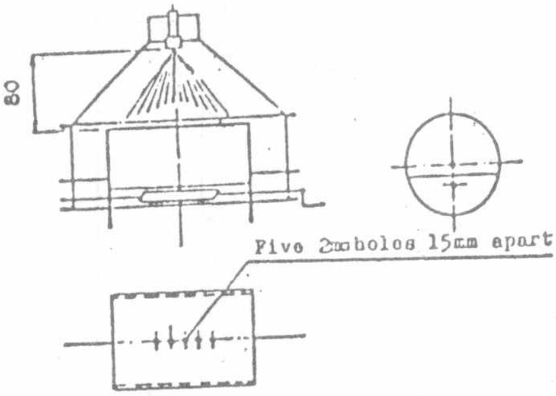
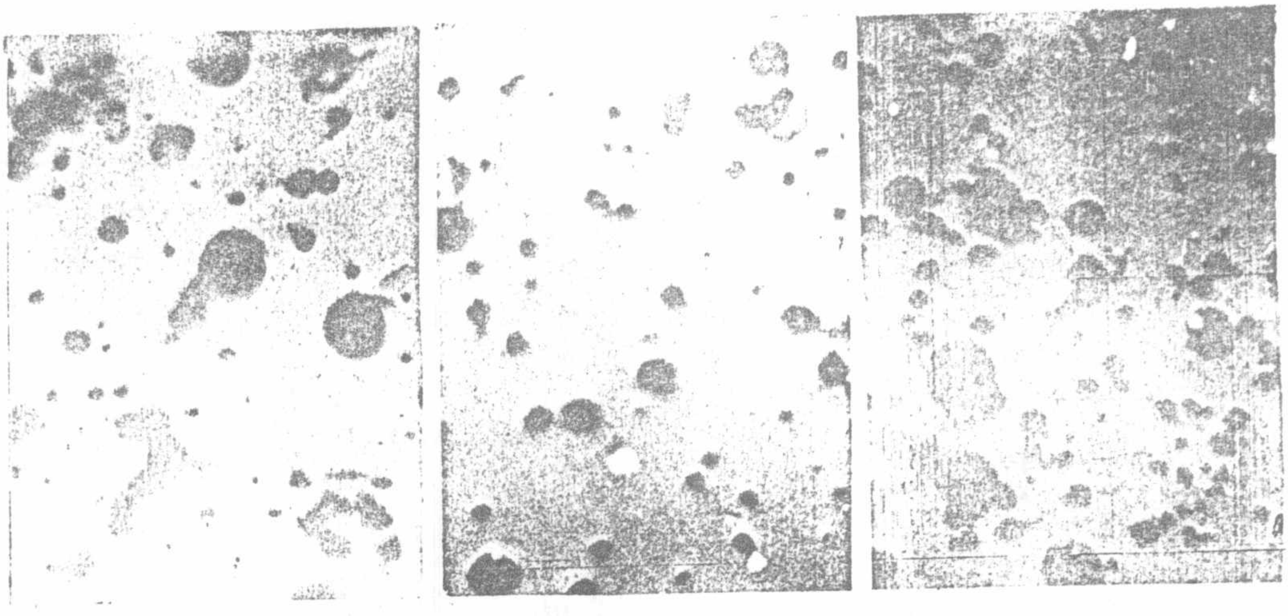


Fig.2. Diagramatic sketch of the slide sampling apparatus

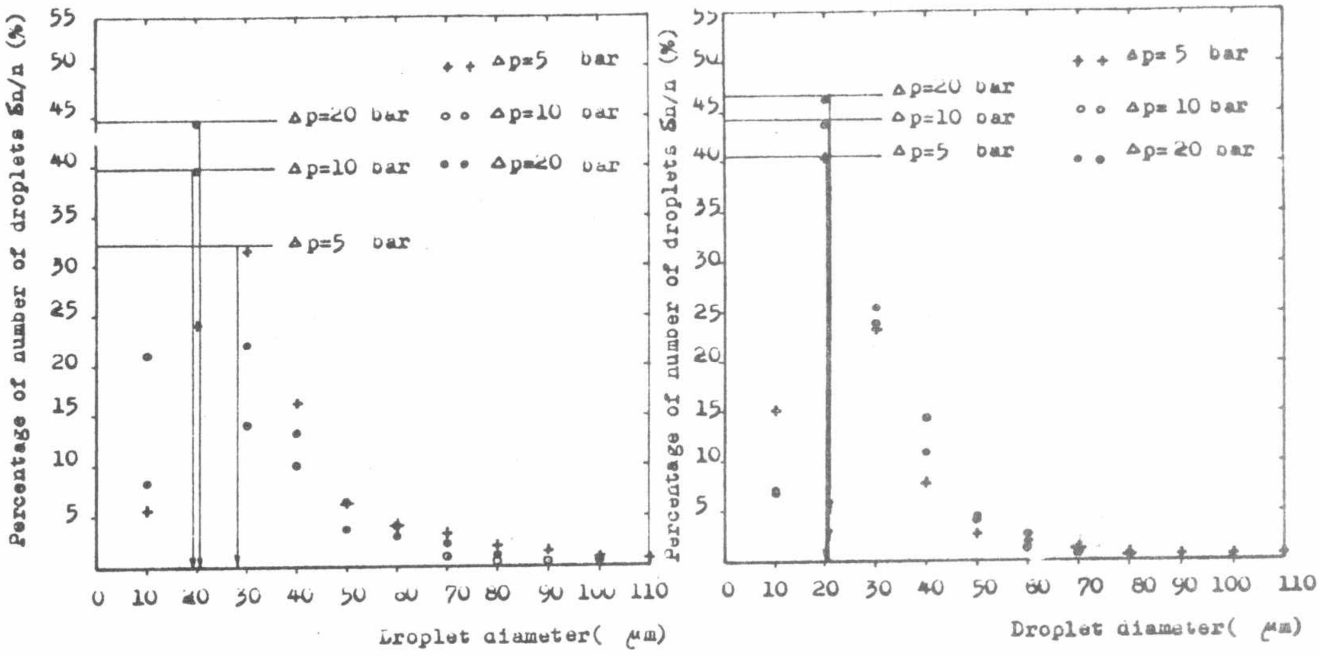


$\Delta p = 5$
$L/D = 1.5$
$l/d = 1.25$
$d = 0.8$

$\Delta p = 10$
$L/D = 1.5$
$l/d = 1.25$
$d = 0.8$

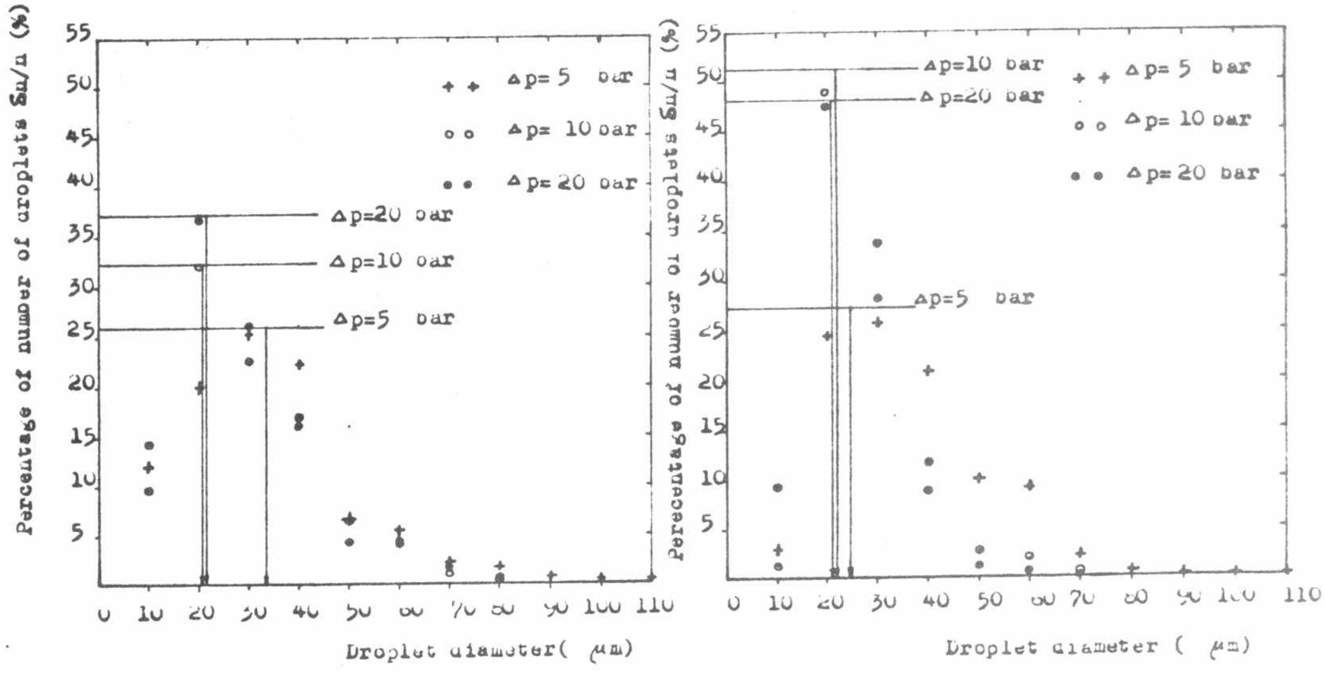
$\Delta p = 10$
$L/D = 2.75$
$l/d = 1.25$
$d = 0.8$

Fig.3. The photographed impression of the spray at different conditions



a- Nozzle I

b- Nozzle II



c- Nozzle III

d- Nozzle IV

Fig.4 Some examples of the measured droplet size distribution showing the calculated peak points

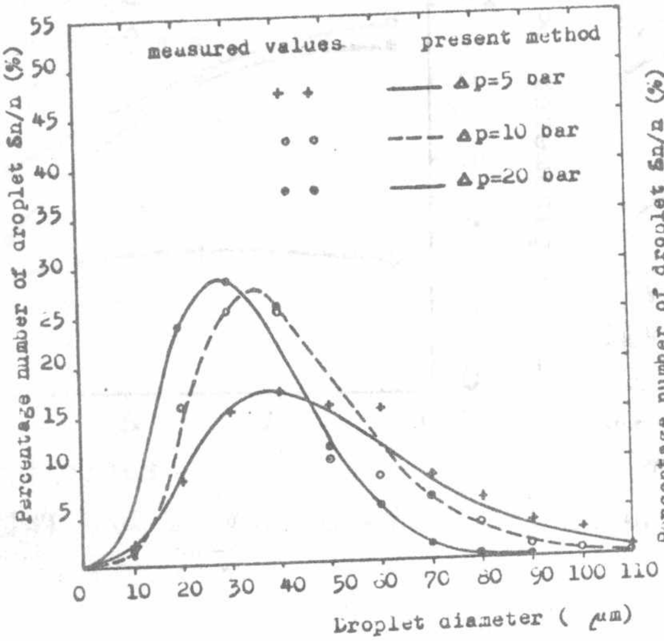


Fig.5 Effect of pressure drop on the droplet size distribution nozzle VII

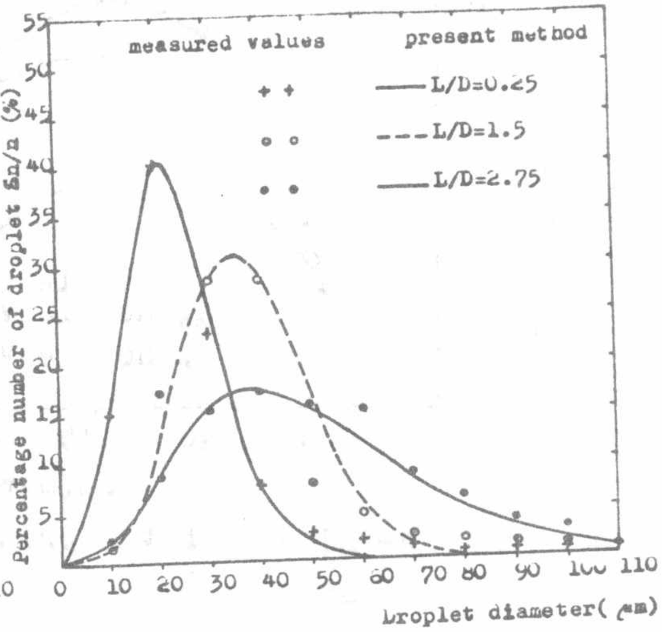


Fig.6 Effect of L/D variation on the droplet size distribution for Δp = 5 bar and l/d = 1.25

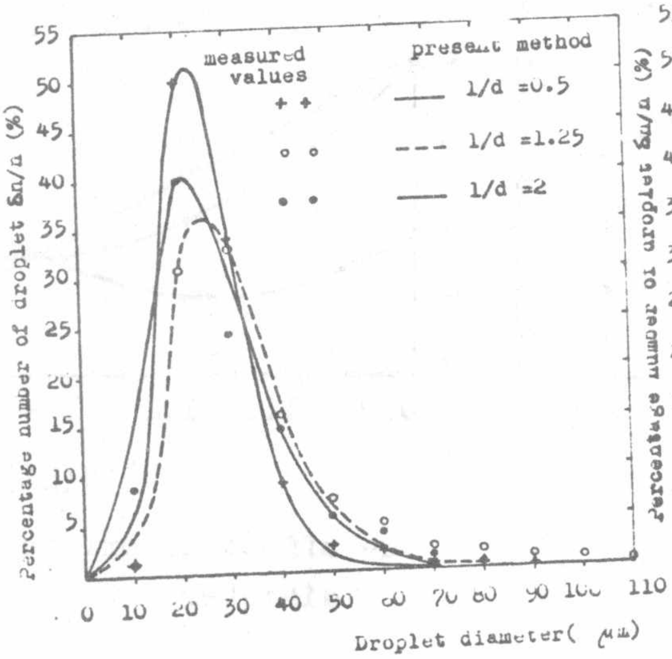


Fig.7 Effect of l/d variation on the droplet size distribution for Δp = 10 bar and L/D = 1.5

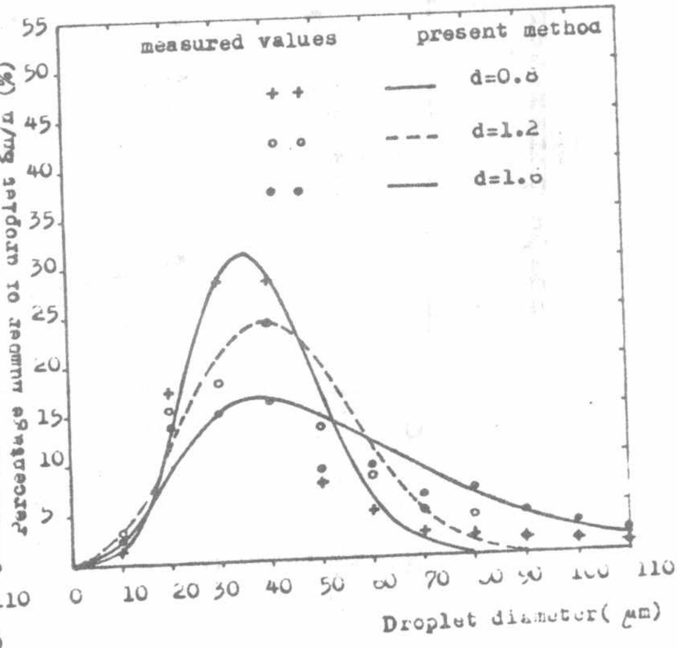
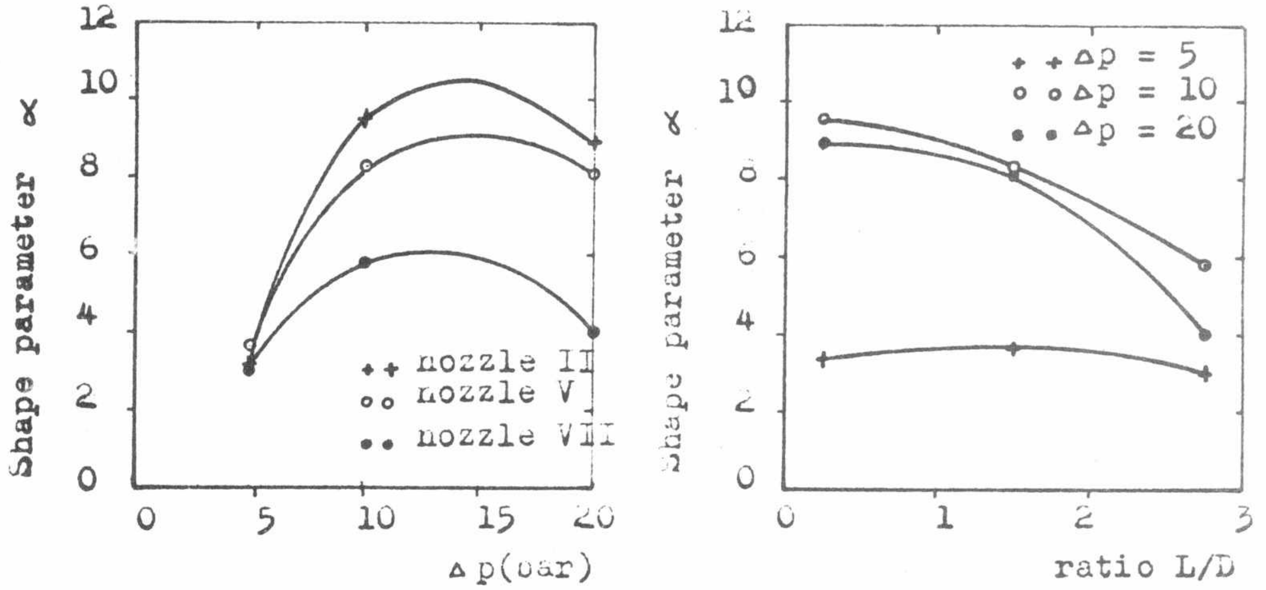
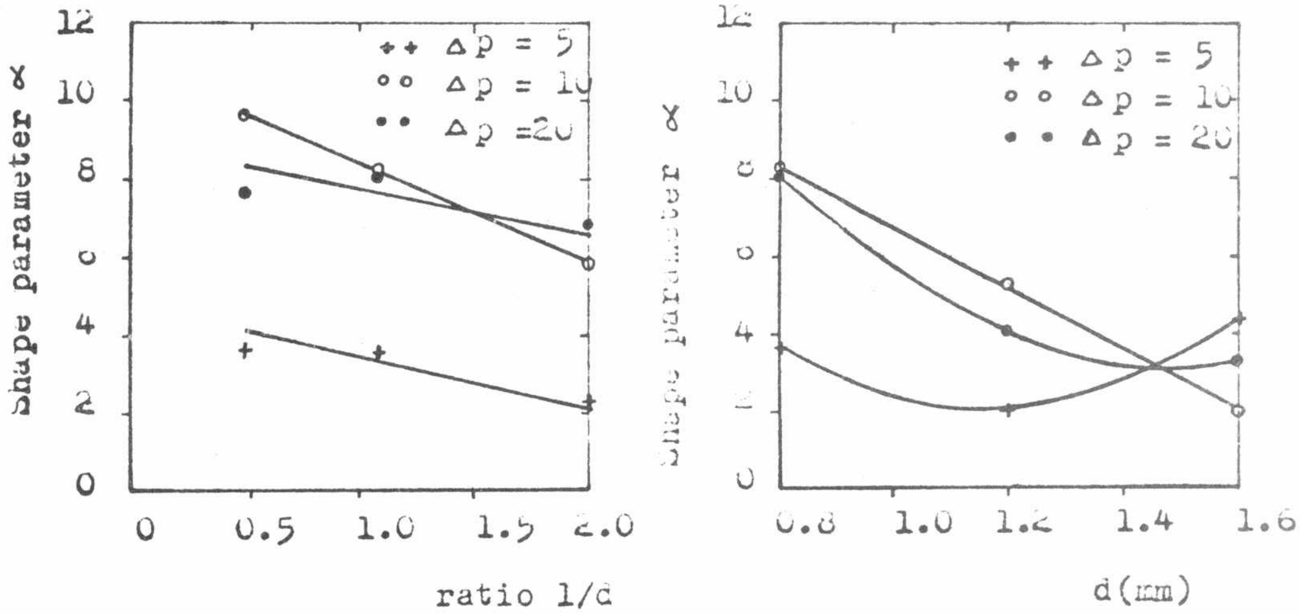


Fig.8 Effect of orifice diameter variation on the droplet size distribution for Δp = 5 bar, L/D=1.5 & l/d=1.25



a- Effect of the pressure drop

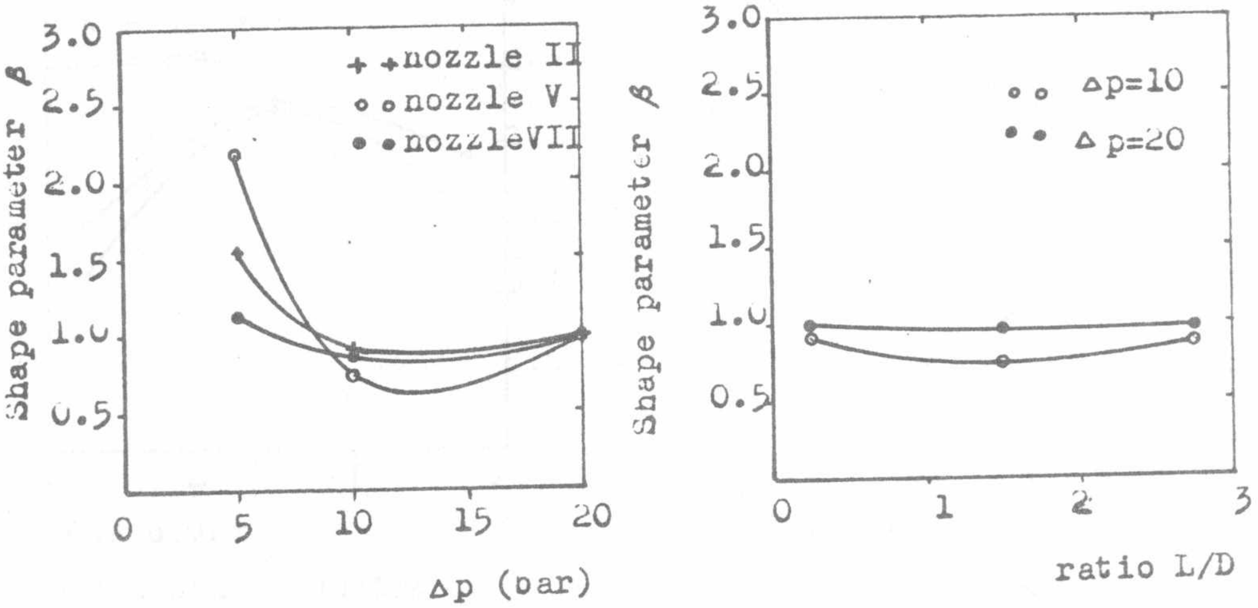
b- Effect of L/D ratio



c- Effect of l/d ratio

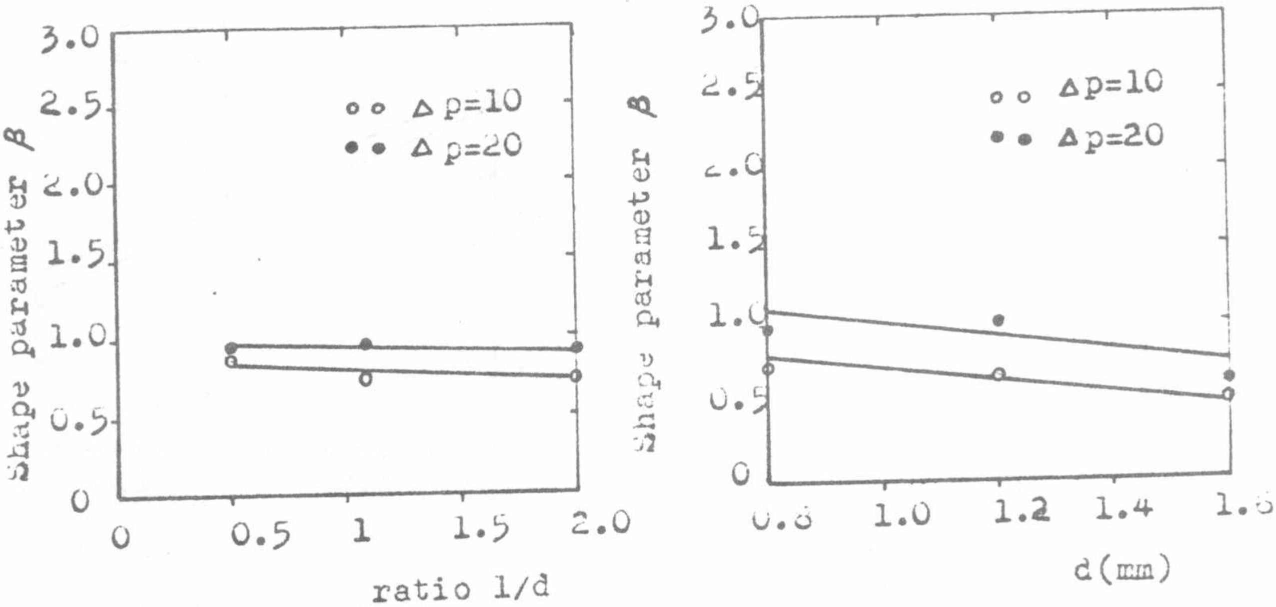
d- Effect of orifice diameter

Fig.9 The calculated Tanasawa-Tesima distribution shape parameter ∝ by the proposed method



a- Effect of the pressure drop

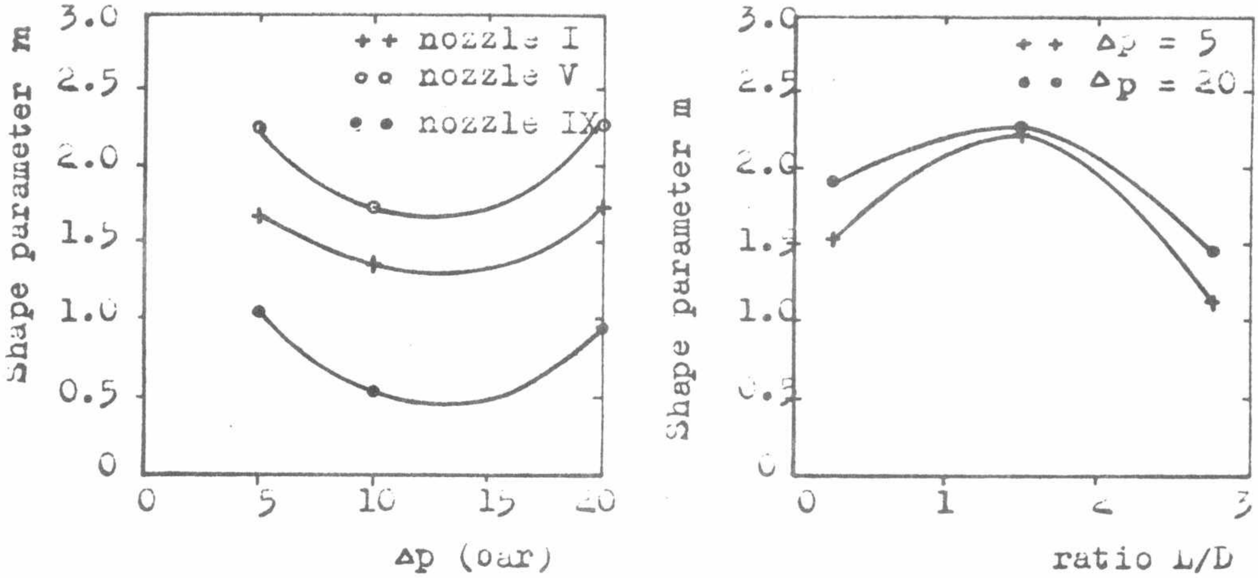
b- Effect of L/D ratio



c- Effect of l/d ratio

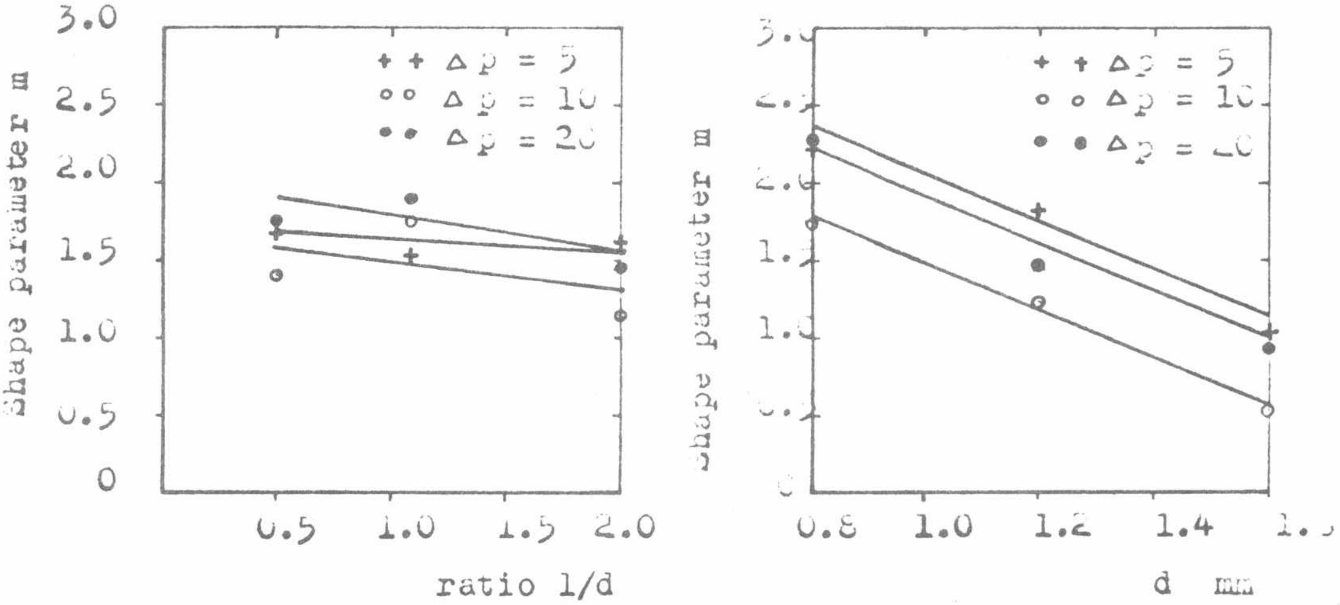
d- Effect of orifice diameter

Fig.10 The calculated Tanasawa-Tesima distribution shape parameter β by the proposed method



a- Effect of the pressure drop

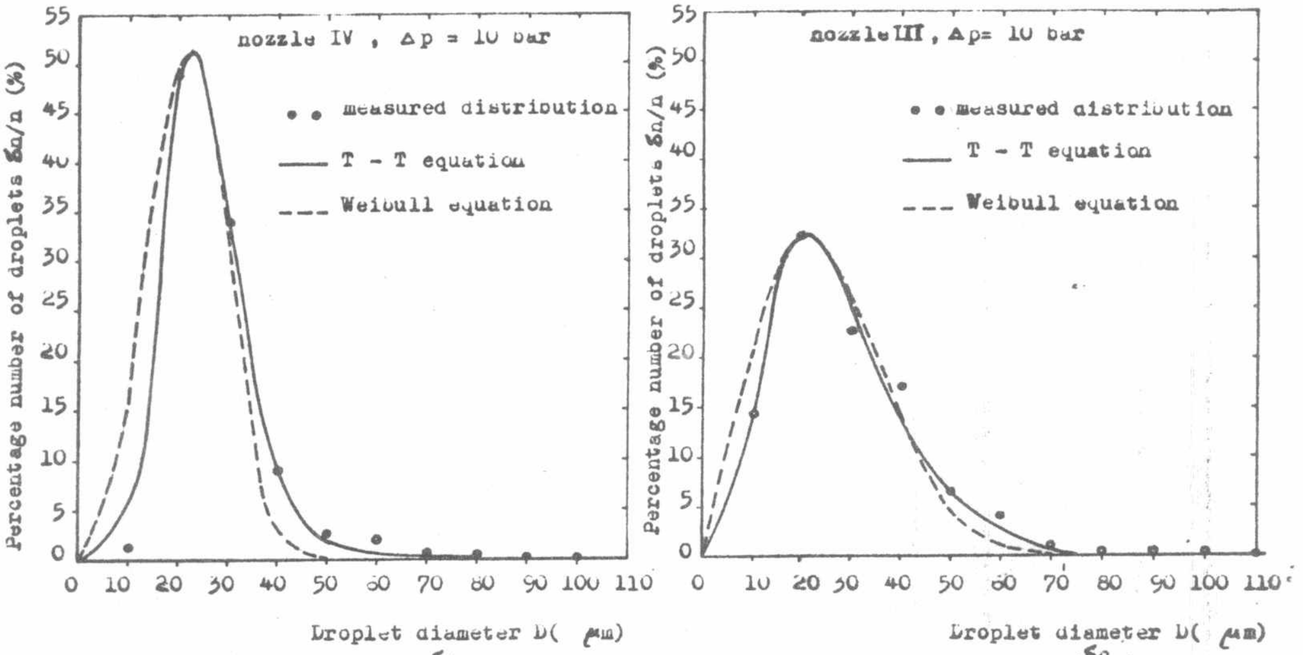
b- Effect of L/D ratio



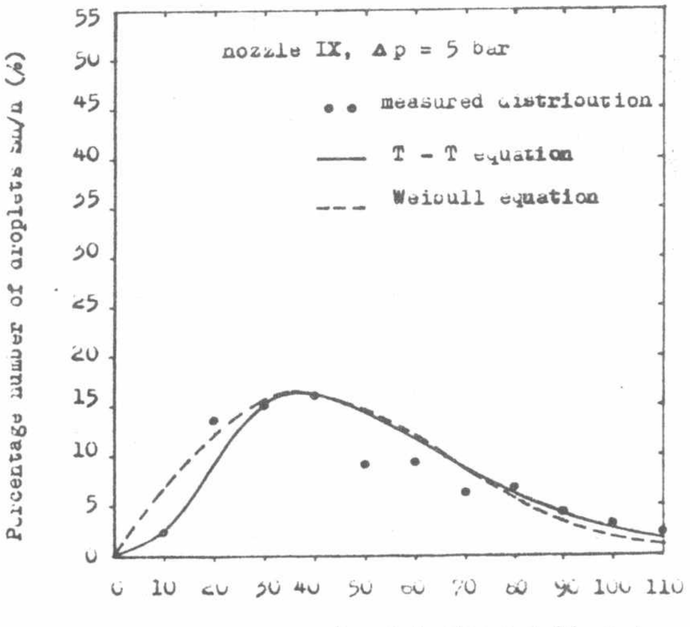
c- Effect of l/d ratio

d- Effect of orifice diameter

Fig.11 The calculated Weibull distribution shape parameter m by the proposed method



a- high value of $(\frac{\delta n}{n})_{max}$ b- medium value of $(\frac{\delta n}{n})_{max}$



c- Low value of $(\frac{\delta n}{n})_{max}$

Fig.12 Comparison between Tanasawa-Tesima,Weibull and the measured droplet size distribution for different working conditions