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THE INFLUENCE OF THE INJECTION PROCESS ON THE OPERATING BEHAVIOR OF SMALL LIQUID ROCKETS

PART I: HYDRODYNAMIC VARIABLES IN THE FUEL INJECTION BY IMPINGING JETS

by

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THE INFLUENCE OF THE INJECTION PROCESS ON THE OPERATING BEHAVIOR OF SMALL LIQUID ROCKETS

PART I: HYDRODYNAMIC VARIABLES IN THE FUEL INJECTION BY IMPINGING-STREAM ELEMENTS

German Research Office for Air and Space Travel
Institute for jet propulsion units

Braunschweig, 5 February 1968

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ABSTRACT

Cold flow studies on doublet and triplet impinging jets were conducted to define the major variables affecting the mixing and distribution of injected propellants. The well known criteria for optimum mixing of the doublt impinging jets is confirmed by an analytical model of the mixing process.

Investigations on the triplet impinging jets show a similar relation for optimum mixing. But in this case the data indicate a clear effect of the included impingement angle.

1. *Formulation of the problem*

The characteristic operating properties such as the degree of energy conversion, wall loads, combustion stability of rocket combustion chambers, are shaped by the injection head and the individual injection elements forming it. At the present time knowledge of the influential vales is still so incomplete that the construction [design] of an injection system generally requires a long term and expensive experimental program.

Fundamentally, the injection elements, over whose spray field cross section the values are constant for the mass flow rate and the mixture ratio, permit us to obtain the best specific impulses and the volume-optimum combustion chambers. In the most practical cases, however, due to the limited thermal, chemical, and dynamic load capacity of the walls, profilings of the mixture and mass distribution must be presented. The natural non-uniformity [heterogeneity] of the distribution profiles of individual elements meets this requirement insofar as the elements are arranged in a practical manner.

Therefore, the problem exists of investigating the mathematical interrelationships [variables] in the formation of mixture-ratio and mass-flow-rate distribution of the remaining injection elements and of optimizing them first with respect to the degree combustion efficiency.

This report describes the results of hydrodynamic laboratory investigations on doublet and triplet impinging-stream elements.

Further investigations concerning the actual behavior of the injection elements in running propulsion units under various conditions and with different propellants have, for the most part, already been performed and are published in two further reports.

2. *Nomenclature*

A_a	[mm^2]	Cross sectional area of a collecting tube
A_d	[mm^2]	Cross sectional area of the orifices [nozzles]
A_M	[mm^2]	Cross sectional area of a measuring tube
D_1; D_2	[mm]	Nozzle diameter
E_m	[%]	Mixing efficiency of the components
H_x	[mm]	Height of liquid level in a graduated measuring glass
I_1; I_2	[p]	Momentum [amount of motion] of the emerging jets
J	[p]	Momentum with respect to the mixing process
m_x	[g]	Captured [collected] mass at position x
$\dot{m}_1$; $\dot{m}_2$	[g/s]	Mass throughput per second
$\dot{m}_{tot}$	[g]	Total collected mass
n		Number of samples
n′		Number of samples with $\Omega_x < \Omega_0$
n″		Number of samples with $\Omega_x > \Omega_0$
$p(x)$	$\left[\frac{g}{s \cdot mm^2}\right]$	Mass flow rate at position x
Δp_1; Δp_2	[p/mm]	Pressure gradient in the nozzles
t	[s]	Duration of a test
w_1; w_2	[mm/s]	Stream [jet] velocity
α		Angle between nozzle axis and the vertical
ρ	$[\frac{g}{mm}]$	Density
ρ_x	[g/mm]	Density at position x
δ		Mean deviation of mass distribution
Ω		Mixture ratio of the components
Ω_0		Mean mixture ratio
$\Delta\Omega_m$		Mean mixture ratio deviation

Subscripts

1, 2	Designation of the components: in a triplet 1 stands for the outer nozzle and 2 stands for the inner one
x	Any [arbitrary] point of the working plane

3. *Test equipment and measuring device*

It may be mentioned at the beginning that one component of the propellants in order to simplify the tests is replaced by water and the other by a colored [dyed] aqueous solution. Any influences due to viscosity, density, or surface tension are therefore eliminated.

The test apparatus consists of the storage tanks for the simulated propellants, the necessary measuring and control devices, and the clamps [supports] for the interchangeable nozzles. Figure 1.

Figures 2 and 3 show injection heads with doublet and triplet impinging jets as they arrived for investigation, respectively.

The sprayed liquid is collected 110 mm from the point of impingement in tubes with a 4 mm internal width and then fed further into the measuring tubes.

The mass-flow-rate distribution results from the volume determination of the liquid in the graduated measuring glasses and in the measurement of the test period.

The mixture ratio is determined by means of a photometer.

4. *Evaluation procedure*

Mass-flow-rate and mixture-ratio distributions in the cone of spray are shown as profile cross sections or as spray projection above the working plane.

The mass flow rate often used below is defined as the mass flowing at position x per second through a collecting tube with the cross-sectional area A_a.

$$P_{(x)} = \frac{m_x}{t} \cdot \frac{1}{A_a}$$

The quantity passed through the collecting cross section corresponds to the volume of liquid measured in the test glass with cross-sectional area A_M.

Hence the result for the local mass flow rate is:

$$P(x) = \frac{A_M}{A_a} \cdot \frac{\rho_x}{t} \cdot H_x \qquad (1)$$

where ρ_x is the density of the collected liquid and H_x the height of the liquid level in the graduated measuring glass at position x.

The ratio of measurement to collection cross section as well as the density are constant (both components are water). Thus, in order to determine the local mass flow rate, only the height of the liquid level in the graduated measuring glass and the test length [duration] need to be measured.

In order to judge the degree of uniformity [homogeneity] of the mass distribution of the propellant, the mean deviation of the local masses from the arithmetical mean of all individual quantities is obtained. The equation used for the calculation is:

$$\delta = \left[\sum_1^n \left(\frac{m_x}{m_{tot}} - \frac{1}{N}\right)^2\right]^{1/2} \qquad (2)$$

The definition of the mixture ratio that is to find general use in the hydrodynamic tests is:

$$\Omega = \frac{\dot{m}_2}{\dot{m}_2 + \dot{m}_1} \qquad (3)$$

The subscript 2 here always refers to the colored component.

The attainable degree of mixing of an individual element can be given as the mean percentage deviation of the gross or mean mixture ratios. A corresponding relationship that supplies well utilizable results and that is already generally used in the respective literature comes from J. H. Rupe [ref. #4]:

$$E_m = 100\left[1 - \left(\frac{\sum_0^{n'} m_x(\Omega_0 - \Omega_x)}{\Omega_0 \cdot m_{tot}} + \frac{\sum_0^{n''} m_x(\Omega_0 - \Omega_x)}{(\Omega_0 - 1) \cdot m_{tot}}\right)\right] \qquad (4)$$

Complete mixing of the components means $E_m = 100\%$, no mixing at all $E_m = 0\%$.

In order to make possible comparisons with other authors, this equation will also be used here. In the future, however, the mean deviation of the gross mixture ratio corresponding to the simple equation

$$\Delta\Omega_m = \sum_1^n \frac{m_x |\Delta\Omega_x|}{m_{tot}}$$

should be better obtained since the results are clearer and sources of error are excluded in extreme mixture ratios.

5. Investigations on doublet impingement elements

A large number of tests have been performed with doublet impinging jets of the most diverse configurations where first the explanation of the effects of the pressure level, nozzle diameter, and the included impingement angle had to be made.

Fundametally in doing this, the observation can be made that the jets penetrate appreciably into one another. This generally known phenomenon is always present no matter what spray conditions are set up. Other details concerning the shape of the spray profiles and projections under various injection conditions are to be taken from figures 4-7.

In order to illustrate the mass-flow-rate distribution setup, figure 8 contains the local mass flow rate for an asymmetric element in perspective. An asymmetric impinging doublet is to be understood here as an element with different jet diameters or different jet impulses.

5.1 Influences of hydrodynamic values on the mixing efficiency of symmetric doublets

Hydrodynamic values, such as pressure gradient, nozzle diameter, and the included impingement angle, have an effect on the resultant mixture in addition to the shape of the spray field.

Here the following statements can be made:

a) If the pressure gradient of both jets varies in impinging jets of equal diameter and equal density, then a slight decrease in the mixing efficiency is set up as the pressure gradient increases. Figure 9.

b) If with symmetric impinging jets there is a variation in the diameter of the jet, then the degree of mixing decreases as the diameter of the jet increases. Figure 10.

c) Especially interesting is the effect of a variation of the impingement angle. The degree of mixing exhibits a very pronounced minimum at an angle of $2\alpha = 90°$, while it reaches higher values rapidly at angles deviating from this. Figure 11.

Of practical significance here is only the influence of the impingement angle since a variation can cause an appreciable improvement in the degree of mixing.

5.2 Optimization of spray conditions of individual elements

The densities of the components different in most propellant combinations and the only slightly variable mean mixture ratios do not frequently permit the use of symmetric impinging jets.

An exhaustive investigation of the degree of mixing in asymmetric jets is therefore absolute necessary. These types of investigations ha\
already been performed by Rupe [ref. #4], Elverum and Morey [ref. #
and others. A systematic variation of all effects [limiting quanti 1
finally led to the result that the degree of mixing always reaches maximum if the relationship

$$\frac{\rho_1 \cdot w_1^2 \cdot D_1}{\rho_2 \cdot w_2^2 \cdot D_2} = 1 \qquad (5)$$

is obtained.

Our own investigations confirm this result. Figure 12.

Relationship (5), however, can also be found in an analytic manner; i.e., if the jet impulse that become effective [active] in the time unit is introduced into equation (5), then the result is:

$$\frac{I_1}{I_2} = \frac{D_1}{D_2} \qquad (6)$$

This means the momenta [amounts of motion] of the jets must behave like the jet diameters if the degree of mixing is to reach a maximum value.

It can therefore be assumed that the momenta alone are decisive for the mixing of both components.

In visual observation of the "impinging point," an impinging area can be clearly perceived. Its inclination to the angle bisector between the jets essentially appears to be determined by the jet diameters.

It is now to be assumed that the exchange [replacement] of both components takes place perpendicular to this impinging area. The resultant mixture will be the greatest if the actually effective impulse components that must be directed perpendicular to the resulting direction of spray are the greatest. This is the case if the major axis of the impinging area and the resultant jet direction coincide. Figure 13.

If this model is correct, then equation (5) must be confirmed by means of the impulse equation and simple geometric relationships.

The inclination of the impinging area that is formed in the impingement of two jets is established with respect to the angle bisector between the jet directions by the two jet diameters D_1 and D_2.

According to figure 13 the following is true:

$$\begin{aligned} \sin(\alpha - \beta) &= \frac{D_2}{2l} \\ \sin(\alpha + \beta) &= \frac{D_1}{2l} \end{aligned} \qquad (7)$$

By combining both equations and solving for the ratio of the jet diameters, we obtain:

$$\frac{D_2}{D_1} = \frac{1 - \mathrm{tg}\beta(1/\mathrm{tg}\alpha)}{1 + \mathrm{tg}\beta(1/\mathrm{tg}\alpha)} \qquad (8)$$

for the angle β the result from this is:

$$\mathrm{tg}\,\beta = \frac{1 - (D_2/D_1)}{1 + (D_2/D_1)} \cdot \mathrm{tg}\,\alpha \qquad (9)$$

Therefore, the inclination of the impinging area is defined with respect to the angle bisector of the impingement angle.

The resulting direction of spray is obtained by means of the jet impulse. It is:

$$\operatorname{tg} \varphi = \frac{1 - (I_2/I_1)}{1 + (I_2/I_1)} \cdot \operatorname{tg} \alpha \tag{10}$$

If the amount of motion [momentum] existing for the mixing process is designated by J, then the portion of J becoming active on mixing is, according to figure 13:

$$J_{act} = J \cdot \cos (\beta - \varphi) \tag{11}$$

The mixing vector is the greatest for the case cos $(\beta - \varphi) = 0$, thus for $\beta = \varphi$.

Therefore, equations (9) and (10) can be set equal [to one another] and we obtain:

$$\frac{I_2}{I_1} = \frac{D_2}{D_1} \tag{6}$$

thus, the result found by Rupe in an experimental manner.

It is interesting here that in the optimization of the degree of mixing with doublet jets, the angle between the two jets is without significance.

5.3 Mean deviation of the mass distribution

The mean deviation of the mass distribution in the impinging doublets has been obtained only within the framework of a limited investigation. In doing so it was shown that the symmetric elements exhibit the smallest deviations.

The asymmetric doublet jets show the smallest deviations if Rupe's mixing criterion is just fulfilled.

The mean deviation of the optimized jets with respect to mixing efficiency having a spray angle of $2\alpha = 90°$ amounted generally to $\delta = 0.09$-0.13.

6. *Triplet impinging jets*

6.1 *Spray profile and spray projection*

The spray projection of impinging triplets is similar to an ellipse whose major axis is perpendicular to the plane that is covered by the nozzle axis. It is generally true that the spray ellipse is quite elongated and the sprayed mass is concentrated along the major axis.

Typical spray projections of the triplet jets are shown in figure 14 (here it is observed that the two axes have different scales). Spray field shape and size as well as the mass-flow-rate and mixture-ratio distributions are considerably more strongly affected by variations in the pressure or diameter ratios than with the doublets.

The comparison of two spray projections in the already mentioned figure 14 shows the influence of the pressure ratio $\Delta p_1/\Delta p_2$ on the shape of the spray field. In general, the following can be inferred from the figure:

The middle jet is split into two partial flows with large pressure ratios where both partial flows move to the outside along the major axis of the spray ellipse and are therefore responsible for the elongated shape. The angle between the two partial flows is a function of the pressure ratio. It becomes smaller as the pressure ratio decreases.

The division of the middle jet is explained by the perspective representation of the mass-flow-rate distribution in figure 15.

6.2 *Mass distribution of triplet elements*

The mean deviation of mass distribution has been obtained for impinging triplets under various spray conditions.

The results are plotted in figure 16 and show the mean deviation of the mass distribution as a function of the diameter ratio and of the impulse ratio.

The curves show pronounced maxima whose location with respect to the diameter ratio is determined by the impulse ratio. At diameter ratios that are greater than 1.5, the mean deviations practically correspond to those of the doublets and they are then almost independent of the impulse ratio. At diameter ratios below 1, the effect of the impulse ratio on the other hand becomes very strong.

The broken line drawn in the diagram connects points of optimum mixing efficiency. It makes clear the fact that the triplets cannot be optimized with small diameter ration of $\frac{D_1}{D_2} < 1$. An arrangement [interpretation] that would be optimum with respect to the mixing efficiency causes large mean deviations in the mass distribution while the selection of large jet impulse ratios and hence smaller deviations of mass distributions lead to a poor mixing efficiency.

6.3 Optimization of spray conditions

It can first be assumed that for the optimization of the spray process with respect to the mixing for the impinging triplets, similar conditions are true as for the doublets.

The results published by Morey and Elverum [ref. #5] support this suspicion.

Both authors found that the relationship

$$\frac{\rho_1 \cdot w_1^2}{\rho_2 \cdot w_2^2} \left(\frac{2A_1}{A_2}\right)^{0.25} = k' \qquad (12)$$

corresponded to their test results. The constant k′ is still a function of the spray angle α, i.e., when 2α = 90°, k′ = 0.42, while when 2α = 60°, the constant k′ will be equal to 0.66. The tests were performed in the range of diameter ratios from $\frac{D_1}{D_2} \approx 0.71$ to $\frac{D_1}{D_2} = 1.29$. However, it is restrictively stated that the equation should be used if possible only in the vicinity of diameter ratios of $\frac{D_1}{D_2} = 1.22$.

Our own tests showed that the triplets are extraordinarily sensitive to differences in the mean mixture ratio as well as the slightest errors in the finishing and alignment of the nozzles.

This sensitivity makes it necessary for example to base the evaluation on the measured mean mixture ratio, since the evaluation on the pressure gradient also leads to considerable errors in only slight different flow coefficients of the nozzles.

The equation to be expected then is:

$$\frac{A_1}{A_2} = k\left[\frac{\rho_2}{\rho_1}\left(\frac{\dot{m}_1}{\dot{m}_2}\right)^2\right]^q \qquad (13)$$

The tests were performed in the range of nozzle surface ratios of $\frac{A_1}{A_2}$ = 0.25 to $\frac{A_1}{A_2}$ = 2.75 and with spray angles of 2α = 60°, 90°, and 120°. The results are plotted in figure 17. The tests show that for each injection element an optimal mean mixture ratio exists with respect to the degree of mixing, the value of which is a function of the diameter ratio $\frac{D_1}{D_2}$ and of the area ratio $\frac{A_1}{A_2}$ of the elements respectively. The optimum values of the mean mixture ratio for the area ratio with respect to the degree of mixing were plotted on double log paper. Figure 18 shows that the lines result here whose inclination is only a function of the spray angle α.

The constant in equation (13) can be taken from the diagram in figure 18 and one then obtains the following relationships:

$$\frac{A_1}{A_2} = 0.81\left[\frac{\rho_2}{\rho_1}\left(\frac{\dot{m}_1}{\dot{m}_2}\right)^2\right]^{0.525} \quad \text{when} \quad 2\alpha = 60° \text{ and } 120° \quad \text{and}$$

$$\frac{A_1}{A_2} = 0.83\left[\frac{\rho_2}{\rho_1}\left(\frac{\dot{m}_1}{\dot{m}_2}\right)^{\cancel{2}}\right]^{0.453} \quad \text{when} \quad 2\alpha = 90°.$$

An essential difference in the behavior of the impinging doublets and triplets is the clear effect of the spray angle in the latter. Furthermore, it is striking that the exponent at the 60° and 120° elements differ from that of the 90° elements by a factor of $\frac{1}{\sin 60°}$. If the exponent for the 90° elements is assumed to be exactly q = 0.453, then the following general relationship can finally be inserted for the exponent:

$$q = \frac{0.453}{\sin 2\alpha}$$

If the obtained values are compared with those of Elverum and Morey [ref. #5], then considerable differences are partially established. The two authors found the value 0.571 for the exponent q, i.e., this value is independent of the spray angle. For the constant K, the values K = 0.634 for 60° and K = 0.821 for 90° are named.

Whether these differences are possibly to be attributed to the effect of the density could not be previously explained (Elverum and Morey used water in kerosene as simulated propellents). Investigations are being performed concerning this.

7. *Summary*

The hydrodynamic variables in propellant injection by means of impinging doublets and triplets are being thoroughly analyzed.

A model that confirms the relationship for optimizing the degree of mixing found by Rupe [ref. #4] in an experimental manner is given and described for the mixing process for the doublet elements.

From the test results for the triplet elements, an analogous relationship can be derived, but where the included impingement angle represents an additional effect in contrast to the doublet elements.

8. *Conclusion*

The systematic investigation of the hydrodynamic variables of injection elements was begun in 1960 at the Trauen Field Office by Mr. Buschulte. It was first report on at the Third European Space Flight Congress at Munich in 1963 [ref. #1].

In this literature the relationship between the effects resulting from the injection system and the propulsion unit performance under various internal and external conditions is analyzed in a theoretical consideration and simultaneously the path is shown for the many investigations to be done.

The preliminary work led to the formulation of a research contract of BMwF on "Investigations on Orbital and Control Propulsion units" in the framework of which investigations of the mixing heterogeneity of various injection elements were first performed by Mr. Schadow [ref. #2].

9. *Documentation*

1. W. Buschulte: Considerations on minimum propulsion units. Paper at the Third European Spaceflight Congress, 1963.

2. K. Schadow: Experimental deterimination of the mixture distribution of different injection systems in minimum rocket propulsion units. Paper at the annual meeting of WGLR, Munich 1963.

3. Rupe, J.H.: The Liquid Phase Mixing of a Pair of Impinging streams. Progress Report, No. 20-195, Pasadena, Jet Propulsion Laboratory, August 1953.

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5. G.W. Elverum, Jr. T.F. Morey: Criteria for Optimum Mixture-ratio Distribution Using Several Types of Impinging Stream Injector Elements. Jet Propulsion Lab., California, February 1959.

6. G.W. Elverum, Jr. P. Staudhammer: The Effect of Rapid Liquid Phase Reactions on Injector Design and Combustion in Rocket Motors. Jet Propulsion Lab., Report 30-4, August 1959.

7. Somogyi, D. Feiler, Ch.E.: Mixture Ratio Distribution in the Drops of Spray Produced by Impinging Liquid Streams, ARS Journal, February 1960, p185.

8. Porter, R.N. Evans, D.D.: Advanced Propulsion Systems for Unmanned Spacecraft, Astronautics and Aeronautics, No. 6, 1965.

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10. Stanford, H.B. Tylor, W.H.: Injector Development, in Space Programms Summary, No. 37-31, Vol. IV. Jet Propulsion Lab., Pasadena, California, February 1965, pp. 192-196.

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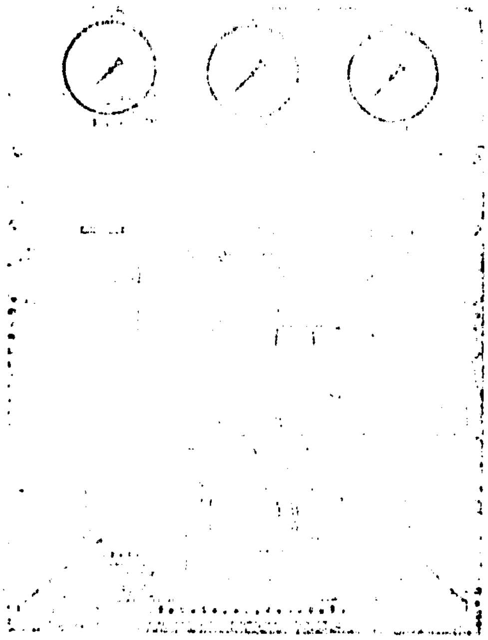


Fig. 1: Test equipment for hydrodynamic investigations

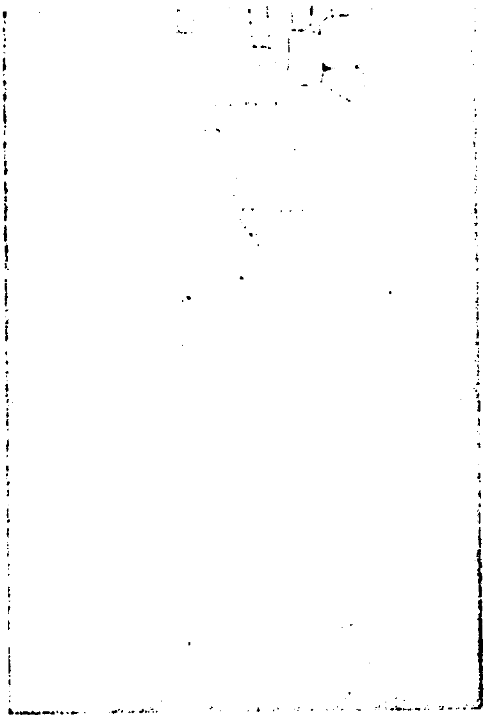


Fig. 2: Doublet impinging-stream injection head

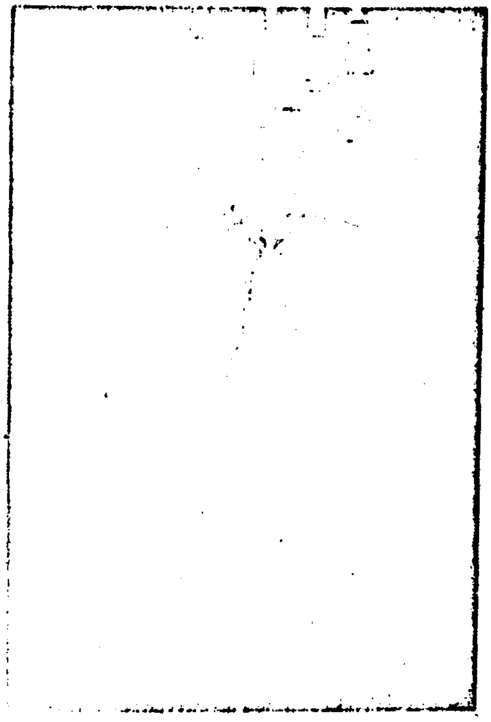


Fig. 3: Triplet impinging-stream injection head

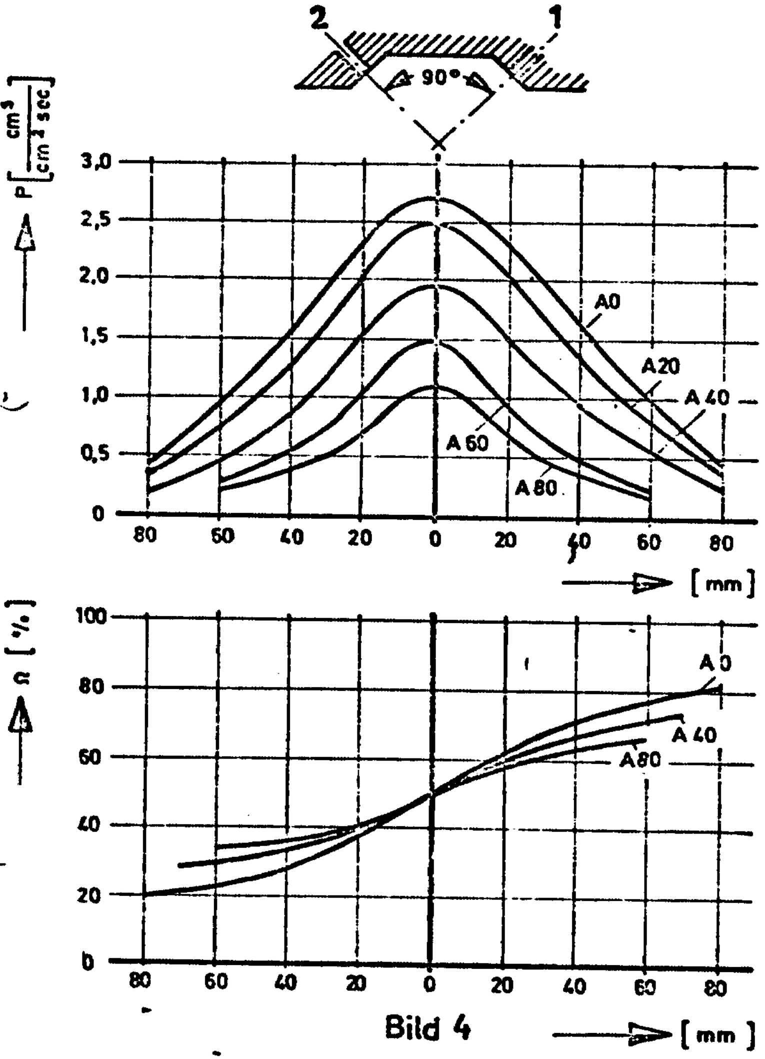


Fig. 4: Spray profile

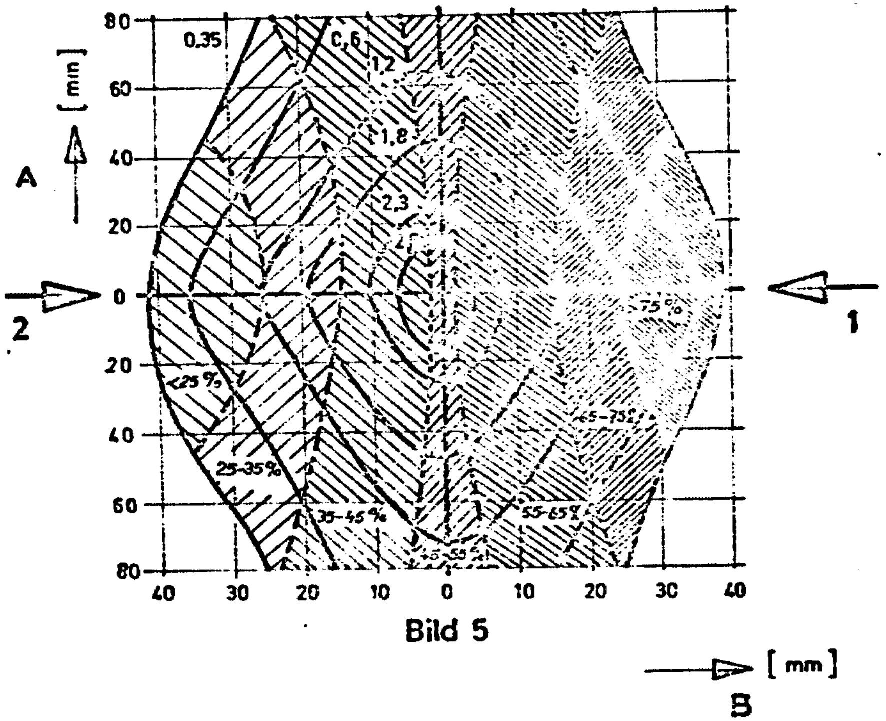


Fig. 5: Spray projection symmetrical impinging doublet

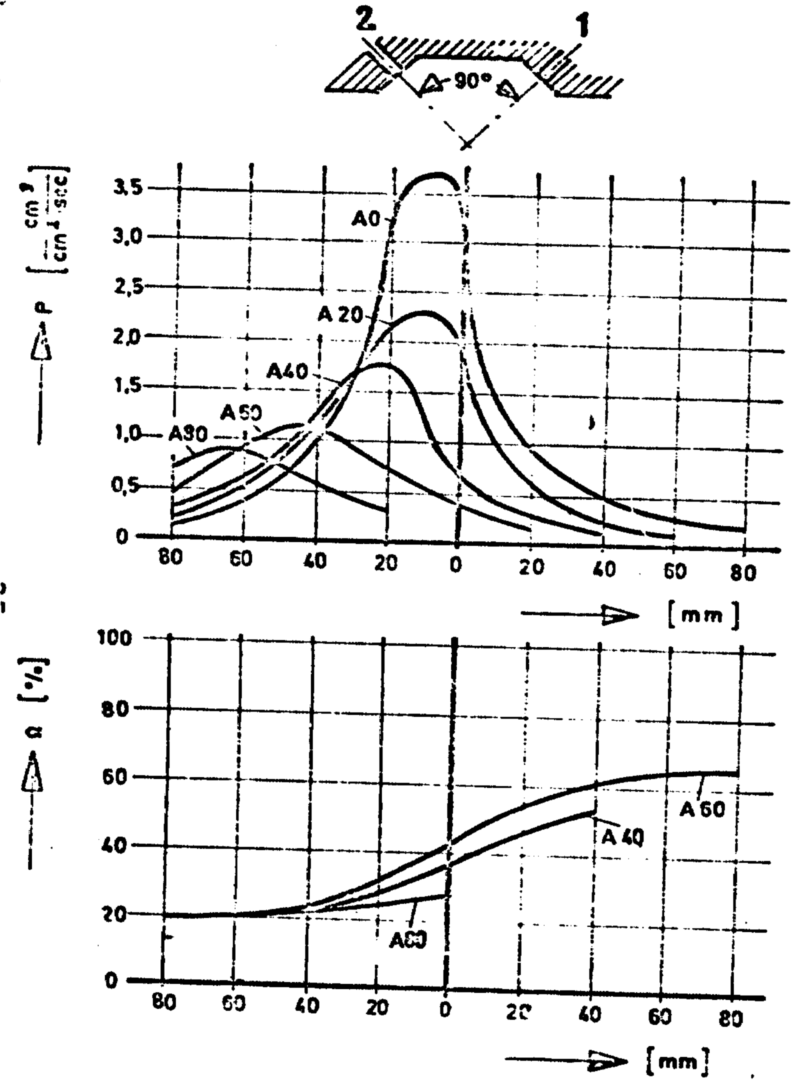


Fig. 6: Spray profile

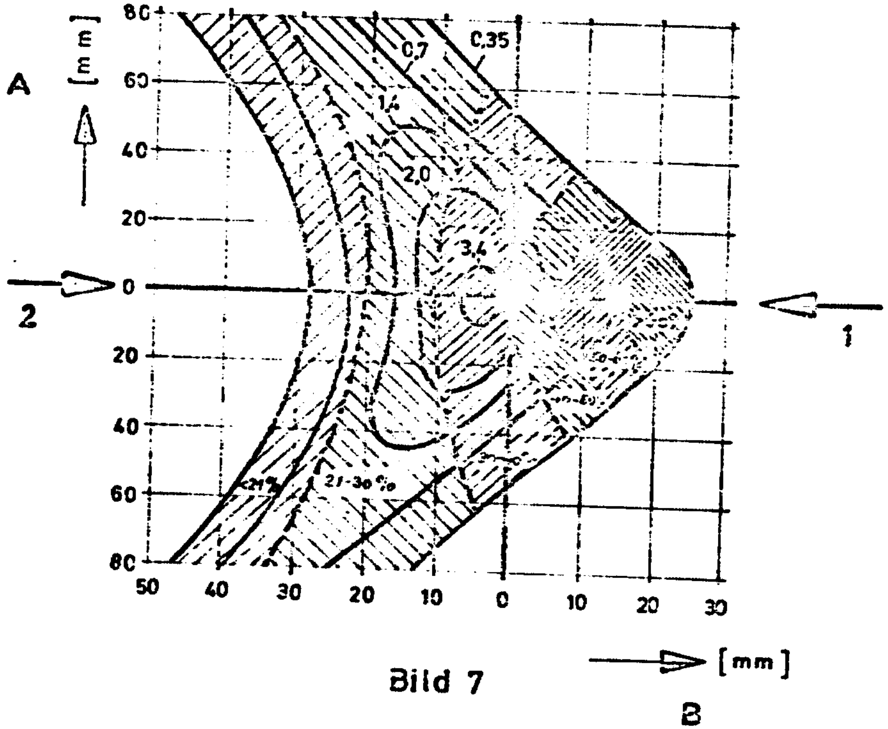


Fig. 7: Spray projection
asymmetrical impinging doublet

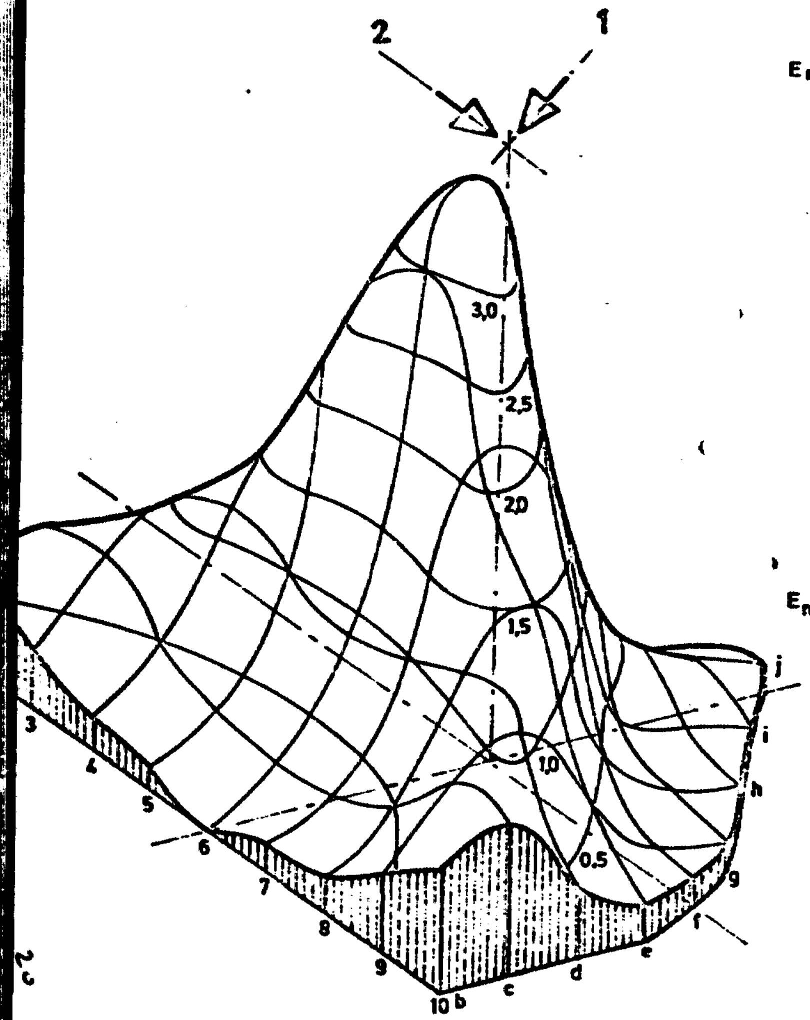
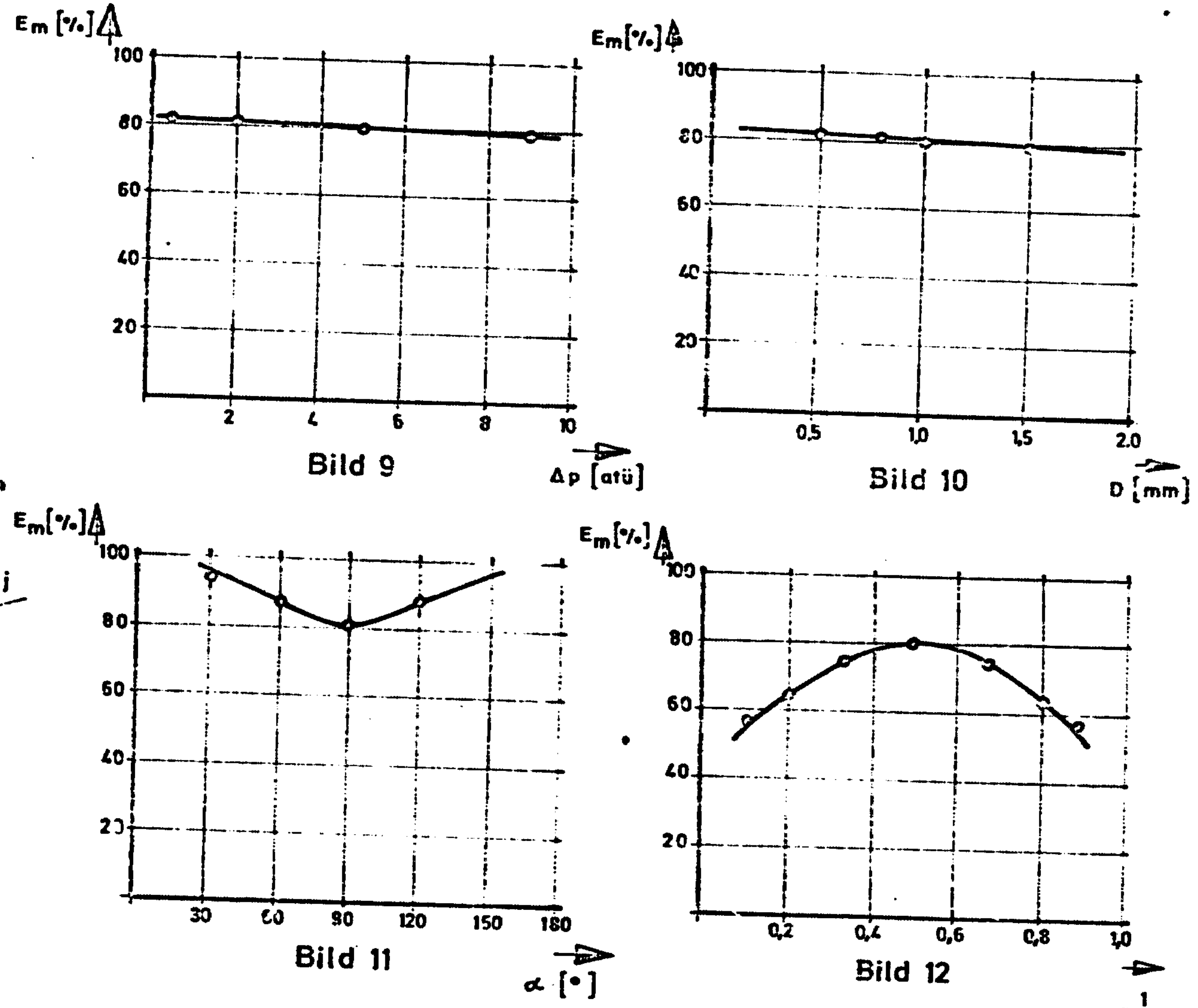


Bild 8

Fig. 8: Mass flow rate of asymmetric doublet in perspective



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$$k = \frac{\rho_1 \cdot w_1^2 \cdot D_1}{\rho_2 \cdot w_2^2 \cdot D_2}$$

Mixing efficiency as a function of individual parameters in symmetric nozzles

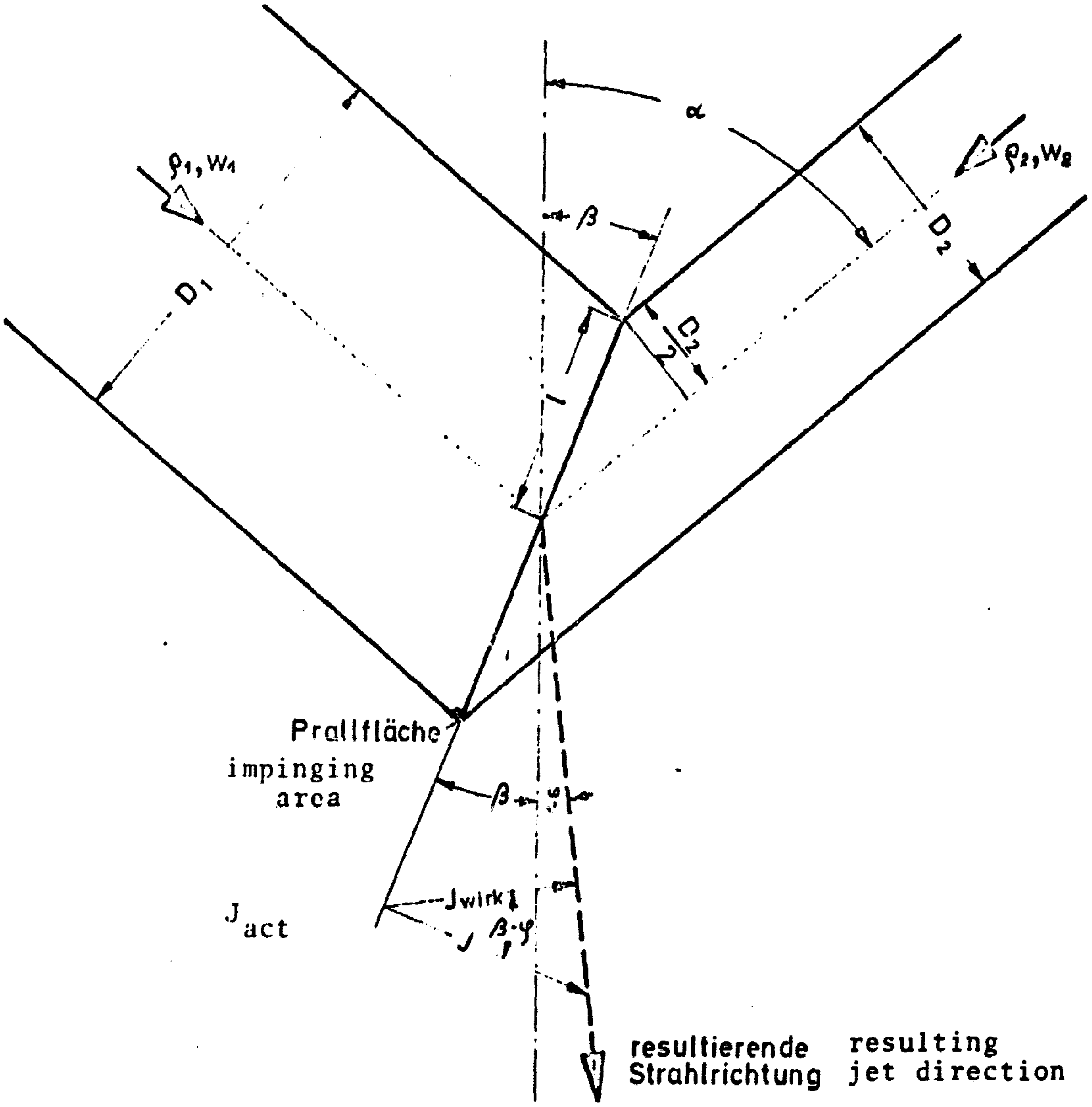

Figure 13
Formation of the impinging area with doublet impinging elements

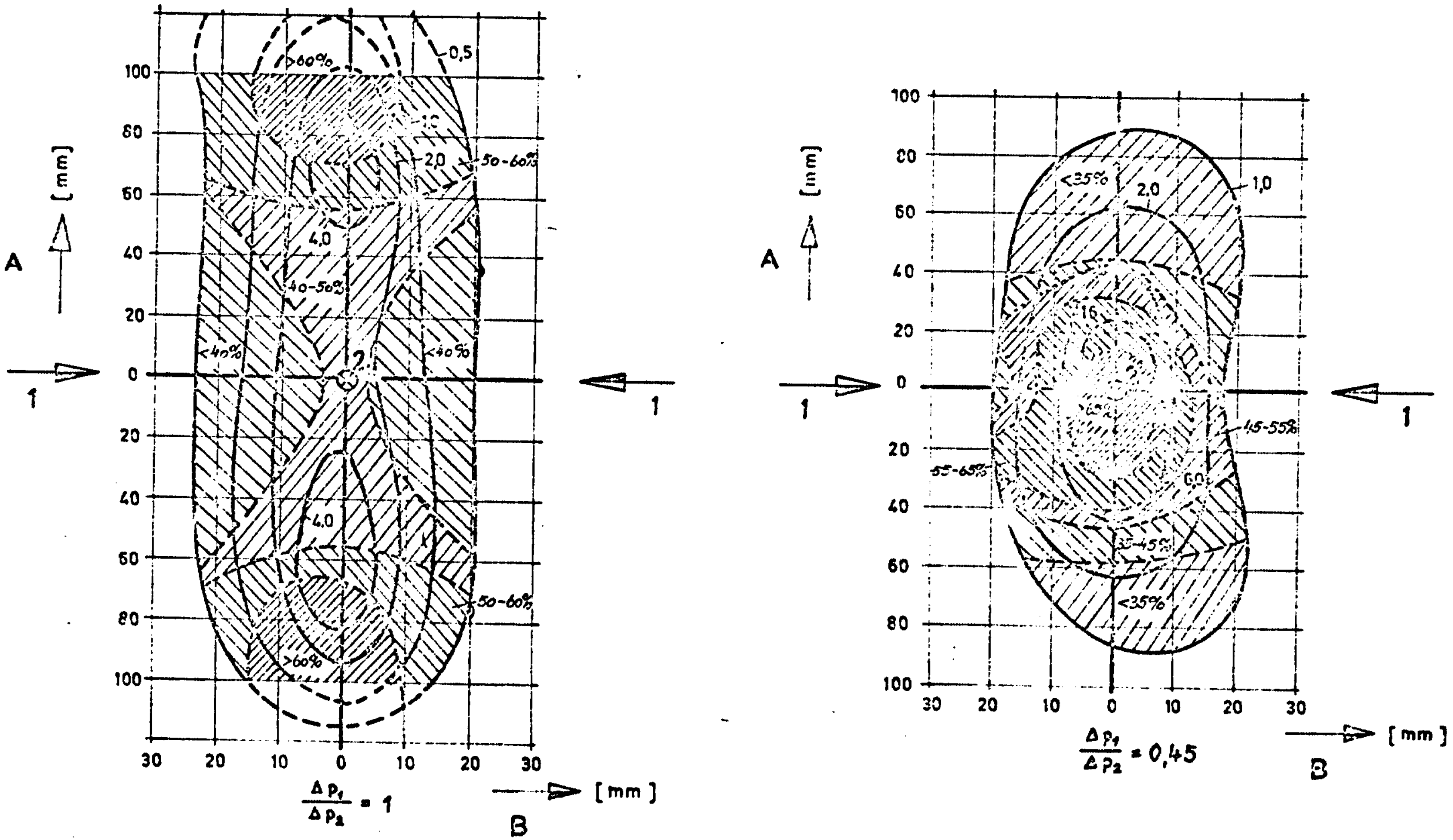

Figure 14
Effect of the pressure ratio on the spray projection

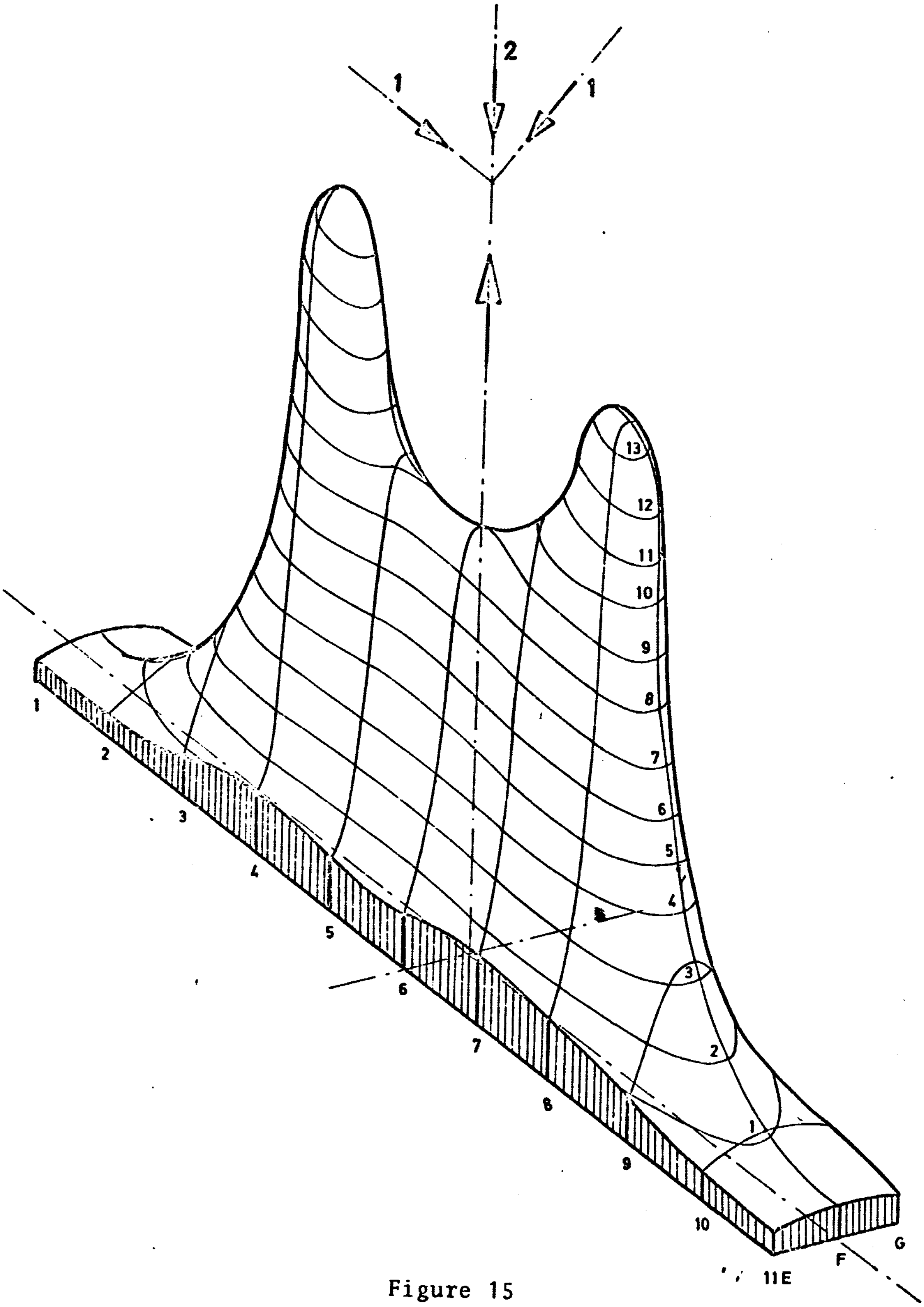

Figure 15
Perspective representation of the mass-flow-rate distribution of triplet impinging elements

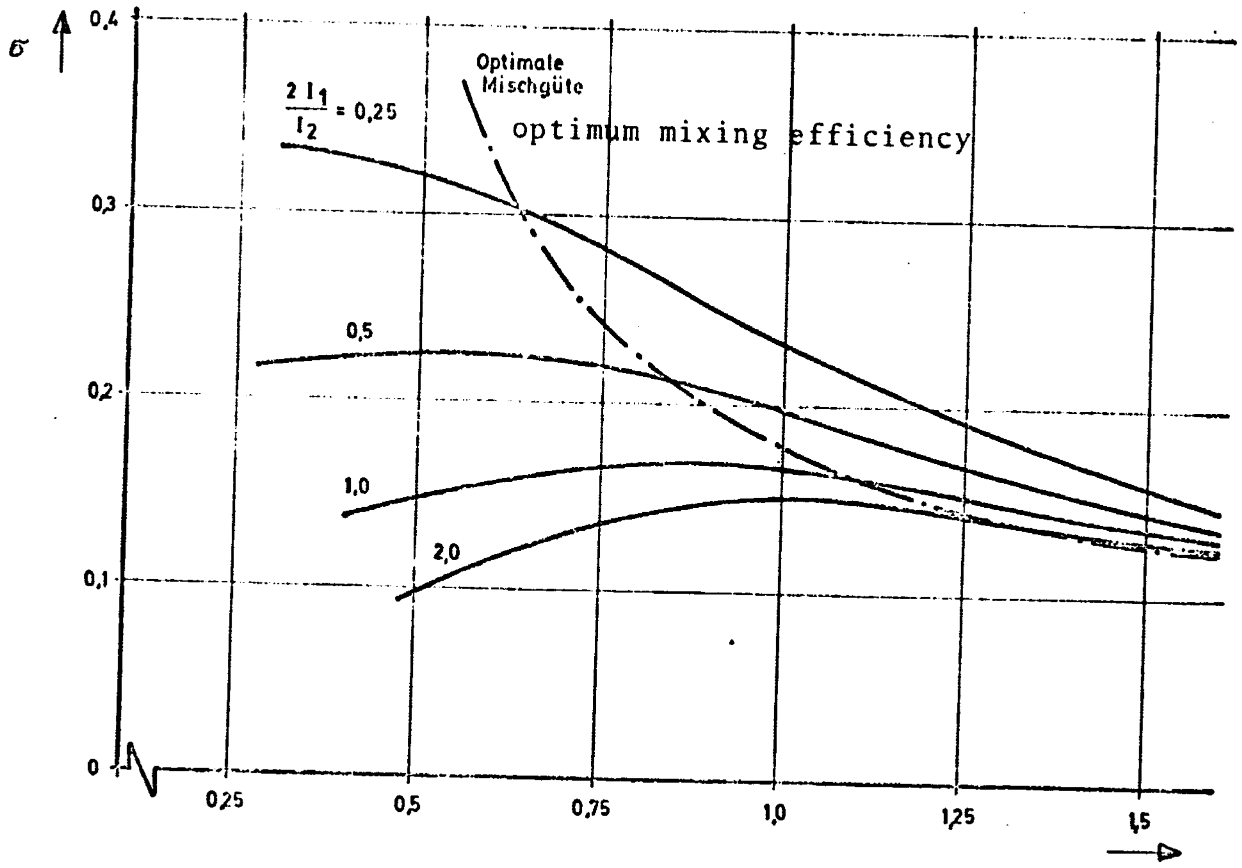

Fig. 16: Mean deviation of the mass distribution against the diameter ratio

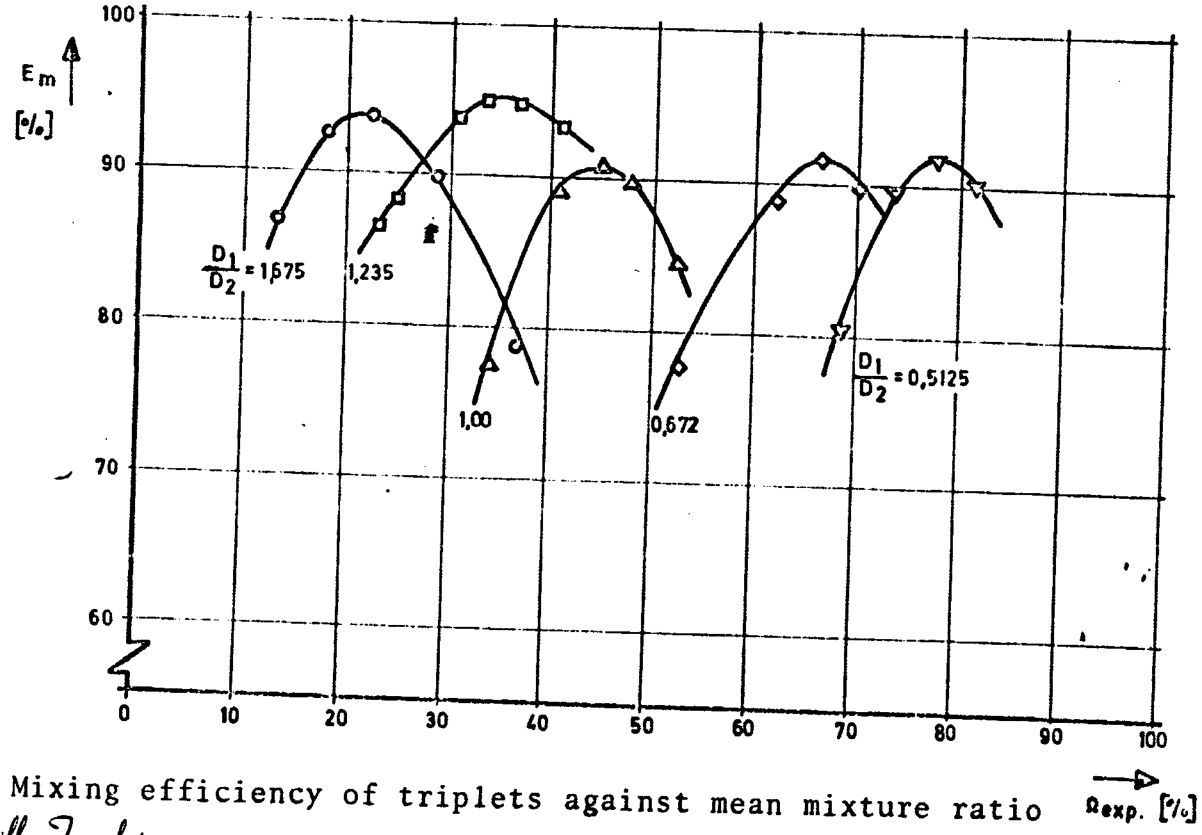

Fig. 17: Mixing efficiency of triplets against mean mixture ratio

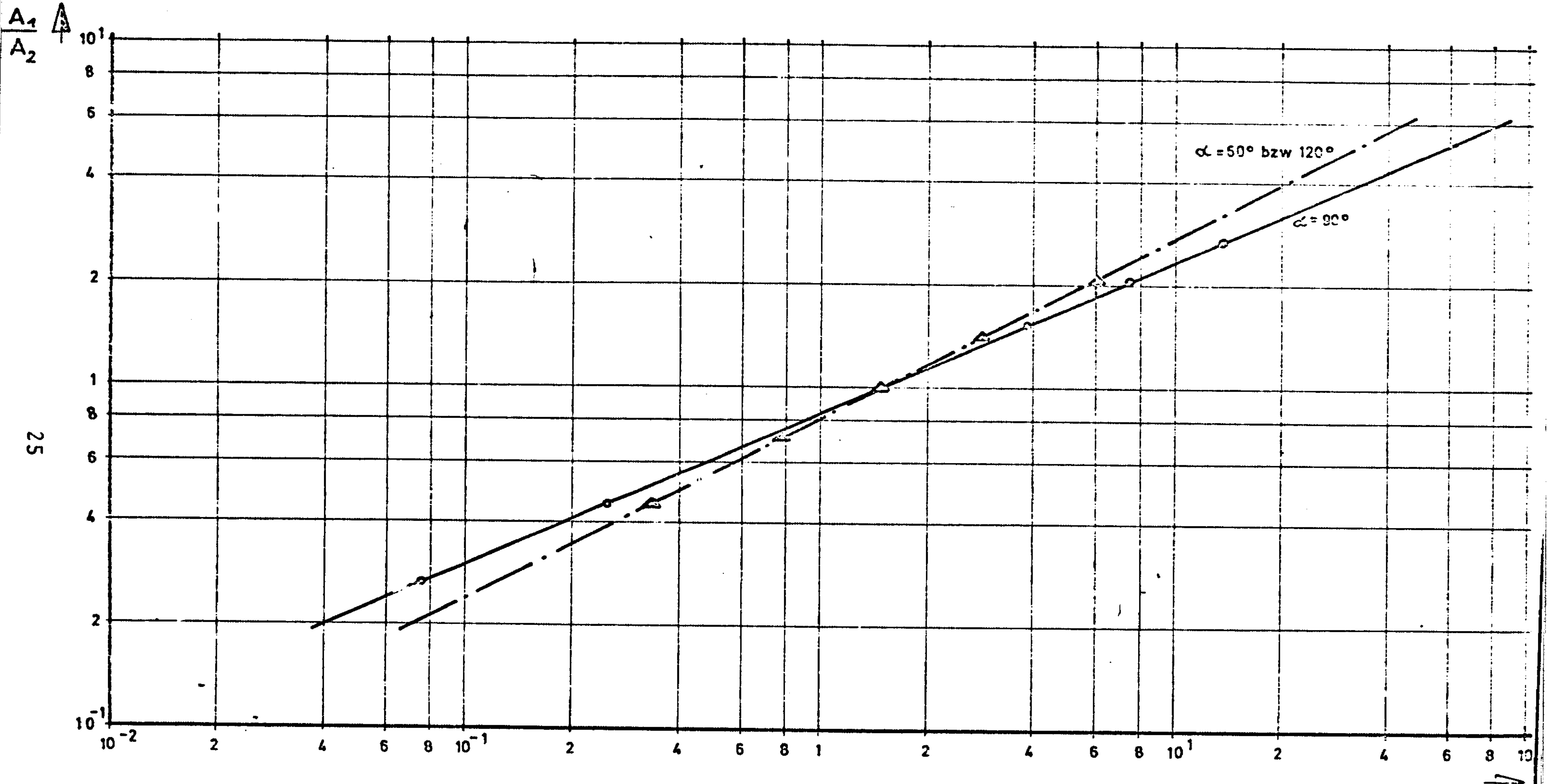

Fig. 18: Optimum mean mixture ratios as a function of the area ratio of triplet impinging elements