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THE HYDRODYNAMICS OF A FREE, LIQUID JET AND THEIR INFLUENCE ON DIRECT CONTACT HEAT TRANSFER—I

HYDRODYNAMICS OF A FREE, CYLINDRICAL LIQUID JET

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Abstract—The present paper is concerned with the hydrodynamics of a free, cylindrical liquid jet and forms the first part of a set of papers on the influence of jet hydrodynamics on direct contact heating. In the present paper the available literature is discussed and special attention is paid to existing differences between the cited authors' conclusions. On the basis of our own experiments the influence of individual variables on the jet hydrodynamics was analysed qualitatively. Correlations, which hold in the investigated area, are proposed. The phenomenon of hysteresis in the case of flow through short nozzles ($L/d < 2$) having sharp inlet edges was observed.

INTRODUCTION

The process of direct contact condensation on a free liquid jet takes place in a variety of industrial equipment. Barometric condensers, feed water heaters, thermal deaerators in power stations or in sea water desalination plants are examples. Direct contact allows high heat transfer intensity and applicability of the process to the heating of slurries and solutions. As a result of the research presented by Iciek & Ciesielski (1977; 1978) the application of the process to thermal sterilization of solutions or slurries was proposed.

The study of direct contact condensation on a free jet is interesting both theoretically and practically and thus has led to much research work.

On the basis of an analysis of the available literature, e.g. Isachenko & Solodov (1972), Benedek (1976), Kutateladze (1979), Iciek (1977), the following conclusions can be drawn:

There are serious differences between the various descriptions of the process,

In most of the papers too little attention is paid to hydrodynamics and their influence on direct contact heat transfer.

At the same time an analysis of the papers by Grant & Middleman (1966), McCarthy & Molloy (1974) and other on the hydrodynamics of free jets has shown a number of problems to be solved, for example the influence of nozzle geometry. For the above reasons it is evident that further investigations are required on both the heat transfer and hydrodynamic aspects of the subject. The present investigations are mainly carried out for: cylindrical nozzles which suffer less from clogging than nozzles with other geometry; short nozzles ($L/d < 2$) having sharp inlet edges which are specially interesting both from the point of view of hydrodynamics according to Gavis & Modan (1967) and Tikhonenko *et al.* (1979) and heat transfer (e.g. Iciek (1977) and Isachenko *et al.* (1976)).

The wide range of the investigations results in the findings being published in a series of three papers. The aims of the individual papers are:

(I) to review the literature data and to present our own conclusions on the hydrodynamics of the free, cyclindrical jet,

(II) to analyse the phenomenon of hysteresis which takes place during the outflow through short sharp edged nozzles,

(III) to analyse the influence of jet hydrodynamics on its direct contact heating by vapour.

The present paper is the first of this series.

PREVIOUS WORK

The hydrodynamics of a cylindrical, liquid jet involves the following aspects: the mode of disintegration, the character and length of the continuous segment and the jet diameter. The individual parameters are dependent on the flow velocity, the physical properties of liquid, the nozzle geometry and the physical properties of the environment into which the jet enters. In most of the papers these parameters are discussed separately despite their evident interaction.

Many studies have been performed on jet hydrodynamics, e.g. Grant & Middleman (1966), Phinney (1975) and others. McCarthy & Molloy (1974) gave a vast analysis of the literature on this topic concluding that many problems associated with jet hydrodynamics remained unsolved. Let us now discuss the following jet parameters.

The mode of breakup of cylindrical liquid jets

Ohnesorge distinguished three typical modes of jet breakup and his approach is commonly followed in the literature (e.g. Grant & Middleman (1966) and Orzechowski (1976)). According to him the jet breakup can take place owing to: (i) axisymmetrical disturbances - "varicose breakup"; (ii) asymmetrical (transverse) disturbances - "sinuous breakup"; (iii) aerodynamic loading.

For varicose breakup aerodynamic loading can be neglected. With greater disturbances or velocities aerodynamic forces increase and evoke waves. Finally the breakup is caused by asymmetrical waves. For high velocities and appropriately great drag forces spray atomization takes place. According to Ohnesorge the mode of breakup can be forecasted on the basis of Laplace and Reynolds numbers. According to Orzechowski (1976) the breakup mode is additionally dependent on the nozzle geometry, which can influence the scale of disturbances in the jet. Apart from that the available literature is lacking in a quantitative treatment of the influence of nozzle geometry on the breakup mode.

Fenn & Middleman (1969) proposed an ambient Weber number We_a as a criterion of the disintegration mode. According to them for $We_a < 5.3$ varicose breakup is observed, while for $We_a > 5.3$ the jet breaks up due to asymmetrical waves. This critical value of We_a was corroborated by Phinney (1972) and (1973).

Jet character

Jets can be laminar or turbulent according to the type of flow which they have before leaving the nozzle. In addition the character of the jet depends on the aerodynamic loading evoked by the ambient medium (drag forces). For the cases when drag can be neglected, according to Helmholtz theorem jet turbulence cannot be generated or perish. In other words in the varicose breakup the jet character remains constant along the jet length. For the case when drag is significant, disturbances grow along the jet length resulting in a sinuous breakup or atomization.

In most of the papers, jet type is characterized by means of a Reynolds number which is defined in a similar way to the definition used for fully developed flow in pipes. It is obvious that such simplification is valid only in certain cases. To characterize quantitatively the jet turbulence a prior knowledge of stream turbulence in the nozzle is necessary. Unfortunately, despite vast literature, the reason for the turbulence generation and development in the initial segment of a duct length still remains obscure as mentioned by Eckert & Drake (1972), Ito *et al.* (1977) and others. In addition, jet hydrodynamics are influenced by other parameters such as vibrations of the nozzle, method of liquid supply, the accuracy of the nozzle machining etc.

In this situation a divergence of opinions on the jet turbulence criteria is understandable. Grant & Middleman (1966) cited a series of papers whose authors proposed many different values of critical Reynolds number (from 240 to 10 000). Concluding, they maintained that knowledge of the Reynolds number is not sufficient to characterize the jet character. Additionally the nozzle geometry and physical properties of both jet and ambient medium must be taken into account. Grant & Middleman (1966) on the basis of their own experiments concluded that the transition from a laminar to a turbulent jet is dependent on the Ohnesorge number. For the investigated nozzle types ($L/d > 95$) they obtained a relationship of the form

$$\mathrm{Re}_c = 325 Z^{-0.28} \qquad [1]$$

where Re_c is the critical Reynolds number and $Z = \eta/\sqrt{\rho d \sigma}$ is the Ohnesorge number; η is the dynamic viscosity, ρ is the density and σ is the surface tension. Similar results, but with coefficients somewhat different, were obtained by Fenn & Middleman (1969) and Phinney (1972). Later Phinney (1975) completed the conclusions given in his earlier paper (1973) and proposed to treat the jet as "truly turbulent" if $\sqrt{\mathrm{We}_j} > 25$ and "pseudolaminar" if $\sqrt{\mathrm{We}_j} < 25$.

It seems that both We_a and We_j can serve only as criteria for the breakup mode, while the character of the jet is controlled by the nozzle geometry and the Reynolds number. Van de Sande (1974) and Van de Sande & Smith (1976) investigated the effect of nozzle geometry on the jet character and found that the effect of the shape of the nozzle outlet is negligible. In contrast the inlet shape and nozzle length have an effect on jet character. For the investigated apertures (Ø 2,3 and 5 mm with conically tapered edges) and for water into air a correlation for the transiton point was given in the form

$$\mathrm{Re}_c = 12\,000 (l/d)^{-0.3} \qquad [2]$$

where l is the nozzle length and d is the nozzle diameter. It seems that for other liquids and nozzle types this equation can have other forms.

Breakup length

One of the essential parameters in the field of liquid jets is the breakup length. This is defined as the length of the continuous segment of the jet, from the nozzle outlet to the breakup point. Research on this variable was originated by Savart in 1833 and continued by Rayleigh in 1878, Weber in 1931 and many others as reviewed by McCarthy & Molloy (1974). Unfortunately, despite many papers on this topic the analysis is still incomplete. At the same time many divergences and uncertainties are observed in the literature.

The breakup length depends on many parameters such as the issuing velocity, the nozzle geometry, the jet character and breakup mode, the physical properties of the liquid and the ambient medium. The relationship is complicated because of interaction between these parameters. That is why most of the investigations have a strictly experimental form and only a few successful analytical treatments deal with the laminar region.

The influence of jet diameter on breakup length was analysed by many investigators. Their investigations lead to the conclusion that breakup length increases as the jet diameter is increased (for other variables being unchanged) – Orzechowski (1976).

The influence of the issuing velocity is much more complex (figure 1). The segment BC corresponds with the varicose breakup of the laminar jet. To describe the breakup length for this area Weber (1931) proposed the following equation

$$\frac{L}{d} = \ln \frac{d}{2\delta} \sqrt{\mathrm{We}_j}(1 + 3Z) \qquad [3]$$

where δ is the initial jet disturbance level and $\mathrm{We} = \rho v^2 d/\sigma$ is the Weber number, v is the jet exit velocity. The value of ($\ln d/2\delta$) must be found experimentally. On the basis of Haenlein's data Weber found that $\ln d/2\delta \cong 12$. Similar values were found by other authors as cited by McCarthy & Molloy (1974). However, somewhat different values of this logarithm were also found by Grant & Middleman (1966), Fenn & Middleman (1969) and Phinney (1972). Finally

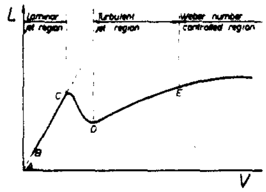

Figure 1.

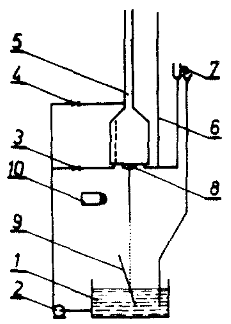

Figure 2.

Figure 1. The dependence of breakup length on jet velocity for the outflow with a developed velocity profile.

Figure 2. Experimental equipment: (1) circulation tank; (2) pump; (3, 4) valves; (5) thrust tank; (6) water glass; (7) overflow; (8) nozzle attachment; (9) plate for dumping jet impact; (10) stroboscope.

Tyler and Watkin, as cited by McCarthy & Molloy (1974), Grant and Middleman (1966) and others, proposed other forms of the correlation [3].

The data of Grant & Middleman (1966) is novel. They found the parameter $\ln d/2\delta$ to be dependent on Ohnesorge number and presented the following relationship

$$\ln d/2\delta = -2.66 \ln Z + 7.68 \qquad [4]$$

Fenn and Middleman (1969) and Phinney (1972) confirmed this type of dependence although their coefficients in [4] are somewhat different. Matching together [1], [3] and [4] provides a basis for a better description of the breakup point of a cylindrical liquid jet.

In addition it is necessary to mention that for the cylindrical laminar jet, the breakup length is independent of the nozzle geometry as stated by McCarthy & Molloy (1974) and Phinney (1972).

At point C (figure 1) the jet loses its laminar character and beyond point D it becomes fully turbulent. There is a series of correlations of the breakup length of a turbulent jet which were obtained by Chen & Davis (1964), Grant & Middleman (1966), Phinney (1975), Van de Sande & Smith (1976) and others. Unfortunately the results calculated from those relationships are divergent which proves that further study will be worthwhile. Point E (figure 1) is a transition from the varicose to the transverse breakup mode.

The results for sharp-edged nozzles with an aspect ratio of about zero are worth mentioning. It has been found by Phinney (1972) and Van de Sande (1974) that jets issuing from this type of the nozzle remain laminar in spite of high Reynolds numbers which result in relatively long breakup lengths.

Conclusions

It follows from the above literature review that there are divergent opinions both on quantitative and qualitative findings for the jet character, its breakup mode and breakup length. An evaluation of the influence of the nozzle geometry is especially lacking. For the above mentioned reasons it was decided, first, to investigate qualitatively the influence of the nozzle geometry (inlet and outlet shape and nozzle length) on jet hydrodynamics, and then, to check the quantitative relationships describing the breakup length of laminar and turbulent jets for the axisymmetrical mode of disintegration.

EXPERIMENTAL EQUIPMENT

The equipment in which jet hydrodynamics and direct contact heat transfer is being investigated, has already been presented in the paper by Iciek (1977). As it was found necessary for this more detailed study to extend the area of investigation (especially a bigger range of velocities), a new experimental apparatus was constructed (figure 2). It has the following features:

The free, vertical flow of liquid through the investigated nozzle is induced by a hydrostatic pressure which can be controlled within the range 0–4.5 m of water gauge.

The jets issue into the open air.

The breakup length can be measured by means of a strobe lamp and an adjustable indicator sliding along a vertical mm scale within the range 0–2.2 m with an accuracy 1.0 mm.

The jet velocity can be measured by flow rate measurements.

Thanks to a very big discharge tank (precisely, its bottom part), appropriate water supply (two possible levels of water supply) and the use of a discharge net in the bottom part of the tank, disturbances caused by the water supply, tank side walls etc., were successfully eliminated.

In the investigations the jet issuing velocity, nozzle geometry and physical properties of the liquid (table 1) were used as the variables. The scheme of the apparatus is given in figure 2. From the thermostatic circulation tank (1) water was delivered by a pump (2) via one of the valves (3) or (4) to the discharge tank (5). The lower valve (3) was used for low hydrostatic pressure experiments and the upper one (4) for higher pressure runs. The bottom part of the discharge tank (5) is a $0.35 \times 0.5 \times 0.45$ m cubicoid with an upper tube of 0.1 m in diameter and 4.2 m long. In the bottom plate of the tank a connection (8) for the exchangeable nozzles is installed. The height of water gauge in the tank was read from a water gauge glass (6). The level of the water in this water gauge was changed by adjusting the overflow (7) to a desired height and appropriate regulation of the water supply rate. To eliminate vibrations caused by the jet splashing against the water surface in the circulation tank a rigid plate (9) slightly inclined to the jet axis was installed in the circulation tank just under the jet.

EXPERIMENTAL RESULTS

Laminar jet stability

It was found that laminar jets are very unstable and even small disturbances, such as disturbances in the supply tank, in the nozzle and vibrations of the equipment can cause a serious (more than 50%) reduction of the continuous segment of the jet. Turbulent jets are less affected by the disturbances.

In agreement with the conclusions from the literature, it was found that for laminar jets the

Table 1. Physical properties of the experimental liquids

	T °C	$\eta \cdot 10^3$ Pa·s	$\sigma \cdot 10^3$ N/m	ρ kg/m^3
water	18	1.06	73.1	999
44% per weight water solution of ethylene glycol	17	3.09	61.6	1046
ethylene glycol	18	22.1	51.8	1112
0.01% per weight water solution of Rokafenol N8 (polyoxyethylene nonylphenol)	18	1.26	39.7	1000

Note: water in all experiments comes from town water supply; other liquids are of technical purity.

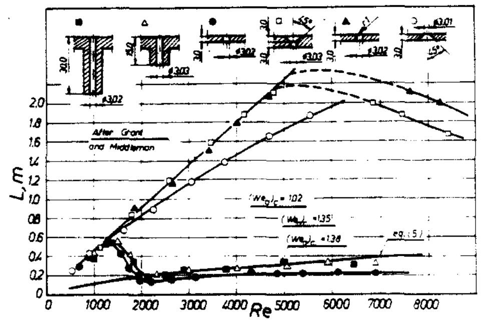

Figure 3.

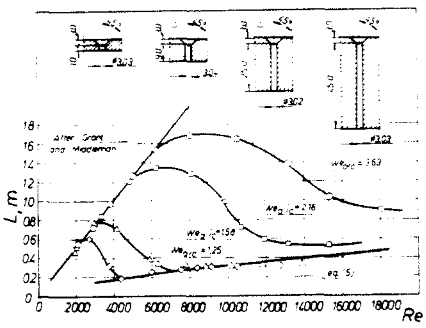

Figure 4.

Figure 3. Influence of nozzle inlet shape and nozzle length on jet character (44% per weight water-solution of ethylene glycol, $d \cong 3.0$ mm).

Figure 4. Influence of nozzle length on jet character (0.01% per weight water solution of Rokafenol N8, $d \cong 3$ mm conically shaped inlet).

breakup length is linearly dependent on Reynolds number and that for cylindrical nozzles it is independent of the inlet or outlet shape, nozzle length etc. (figures 3 and 4). At the same time the inlet shape and nozzle length have an effect on the transition point during flow in the nozzle thus changing the jet character.

The effect of nozzle inlet shape on the jet character

Figure 3 shows an example of the experimental data on the influence of the nozzle inlet shape on the jet laminarity loss. The jet laminarity is lost first at sharp inlet edges, then at conically tapered edges, and next at rounded edges. It was stressed by Van de Sande (1974) that this "rounding" has not been defined by the authors of many papers. In the present experiments, following Perry (1963), nozzles are treated as "rounded" if $2r/d > 0.30$.

It is well known from hydrodynamics that a rapid change of flow cross-section causes a stream contraction if the entry edge is sharp. For a laminar flow around an edge this phenomenon does not occur (figure 5a). This is also so in the case of a trubulent flow around the rounded edge (figure 5b). In contrast with turbulent flow around a sharp edge this phenomenon does take place (figure 5c,d) producing disturbances which result in the jet losing its laminar character.

The aforementioned remarks allow us to explain the results shown in figure 3. Both rounding and conical tapering of the nozzle inlet edges prevent jet contraction. A reduction in the jet length is caused by the change of jet character resulting from disturbances due to friction against the nozzle walls. Having in mind these explanations the influence of the nozzle length on the breakup length can be easily deduced.

The influence of nozzle length on jet hydrodynamics

It was found for a conically tapered inlet edge that the bigger the aspect ratio the earlier the transition appears. In figure 4 the results for water solution of Rokafenol are given as an example. Van de Sande (1974) found similar conclusions for water. According to him for relatively high aspect ratios ($l/d > 50$) the influence of the nozzle length on the transition vanishes.

For sharp inlet edges the transition from laminar to turbulent flow takes place for relatively lower Reynolds numbers. This Reynolds number value is not dependent on the nozzle length (figure 3). For the conditions when inertial forces overwhelm the viscous forces, the effect of the nozzle length is pronounced and of a more complicated nature.

For the case of a sharp-edged orifice ($l/d \cong 0$) when the inertial forces prevail over the

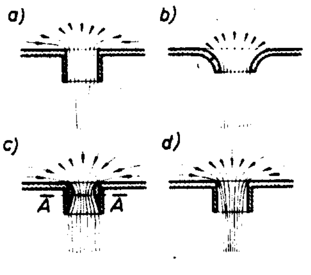

Figure 5.

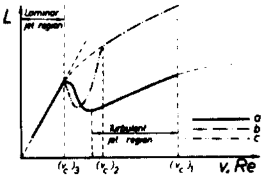

Figure 6.

Figure 5. Streamlines in nozzle for different inlet shapes, ratios of inertial to viscous forces and nozzle lengths.

Figure 6. Dependence of breakup length on jet velocity for a short nozzle ($0.4 < l/d < 2$) with sharp inlet edges: (a) full cross-section (figure 5a or 5c); (b) flow without wetting of inner nozzle walls (figure 5d); (c) flow with partial wetting of inner nozzle walls.

viscous forces, the jet loses its laminar character because of the contraction. On the other hand the lack of the presence of a wall and negligible aerodynamic loading do not allow a fully turbulent flow to be developed. Visually, this type of jet resembles a laminar one but its breakup length is shorter (figures 3, 6 and 7). In the papers by Gavis and Modan (1967) and Van de Sande (1974) it was stated that for orifices, greater breakup lengths could be reached, but no explanation in terms of jet contraction was provided.

For longer orifices ($l/d > 5$) having sharp inlet edges jet turbulence is generated much earlier ($\mathrm{Re} \cong 3000$) and the effect of nozzle length on jet hydrodynamics disappears (figures 3 and 7). It was also found that for short sharp-edged nozzles the phenomenon of hysteresis is possible. In such a case a typical relation between the breakup length vs velocity is shown in figure 6. To explain and describe this phenomenon more extensive studies were carried out. They will be presented in detail in a future paper.

Below we shall present the cases where the phenomenon of hysteresis does not occur.

The influence of the nozzle outlet geometry

According to Van de Sande (1974) the nozzle outlet geometry is of secondary importance. Our experiments, which were carried out for nozzles similar to those investigated by Van de Sande, corroborated his conclusions (figure 7). However, it is known from the literature on divergent mouthpieces (Prosnak 1970) that full cross-section flow takes place only for relatively small divergence angles ($\alpha < 15°$). In our experiments angles $\alpha = 5°$, $10°$ and $90°$ were used.

When $\alpha > 0$ the influence of outlet geometry appeared to be negligible for laminar jets as no wetting of the inner walls of the cone occurred. This behaviour changes neither the jet diameter nor the breakup length (figure 7).

With turbulent flow conditions the influence of the outlet geometry depends both on the value of α and the jet turbulence intensity in the nozzle. For large values of α this influence is negligible. However, in the case of small values of α ($\alpha = 5°$ and $10°$) the flow occupies the whole nozzle cross-section and this results in an increase in the jet diameter and earlier asymmetrical breakup (figure 7).

These experiments were carried out for low issuing velocities and therefore for most of the cases, an asymmetrical breakup occurred. Additional experiments allow us to claim that there is an influence of the jet character and of the numerous disturbances on the mode of breakup. In the case of sharp-edged orifices or for outflow without wetting of the nozzle inner walls (figure 5d) the axisymmetrical breakup takes place at greater velocities as shown in figures 3 and 7. The mode of breakup is changed for relatively smaller Reynolds numbers for a turbulent jet issuing

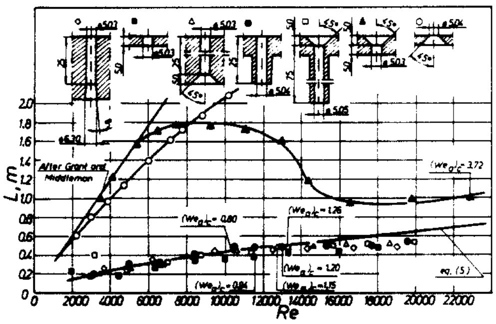

Figure 7.

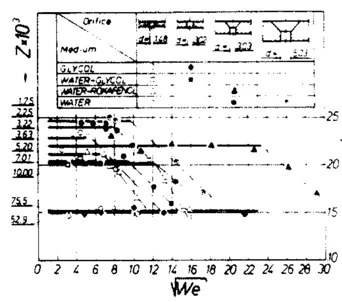

Figure 8.

Figure 7. Influence of nozzle geometry on jet character ($d \cong 5.0$ mm, water).

Figure 8. Dependence of $\ln d/2\delta$ in the Weber equation on jet character and Ohnesorge number.

through a short nozzle with conically tapered or rounded entry edges (figure 7). The presence of any disturbances in the nozzle or at the inlet can result in further reduction of critical Reynolds number at which the mode of breakup is changed.

Breakup length of laminar jets which are breaking by axisymmetrical waves

To predict the breakup length for laminar jets the Weber equation is used most frequently. At the same time there are divergent opinions on the value $\ln d/2\delta$ in [3]. The values of $\ln d/2\delta$ found experimentally and those calculated from [3] are shown plotted vs $\sqrt{\mathrm{We}_j}$ in figure 8. The graph shows that for a given nozzle and a given liquid the value of $\ln d/2\delta$ is constant throughout the whole laminar flow range and is dependent on the Ohnesorge number. For each run, which was at a constant Ohnesorge number, a mean value of $\ln d/2\delta$ was found by means of the least squares method. This value was plotted in figure 9 to compare it with the line described by [4].

The results do not differ significantly from the values calculated from the Grant and Middleman equation, which was corroborated by a statistical analysis. The t value for the deviation of our results from the value calculated from [4] is less than the tabulated value for the applied significance level ($\beta = 0.05$, $t = 2.13$, $t_{8,0.05} = 2.306$). Figure 9 also shows the results obtained by recalculation of the data given by Kitamura & Takahashi (1976). The analysis of these results confirms the effect of Ohnesorge number on the value of $\ln d/2\delta$ although Kitamura's results for the breakup length, and therefore also $\ln d/2\delta$, seem small. This was probably caused by unsatisfactory elimination of outside disturbances.

Axisymmetrical breakup length of turbulent jets

It has been found (figures 3, 4 and 7) that the nozzle geometry has an important influence on jet character, its breakup mode and thus its breakup length. The results show that if the jet turbulence is sufficiently developed the effect of the nozzle length disappears with nozzles which have sharp inlet edges when $l/d > 5$ and $\mathrm{Re} > 3000$, and with nozzles which have rounded inlet edges when $l/d > 15$ and $\mathrm{Re} > 4000$. For such conditions axisymmetrical breakup occurs when $\mathrm{We}_a < 1.2$ (figures 3, 4 and 7). Figure 10 shows the results for fully developed turbulent jets disintegrating by axisymmetrical waves. For comparison some correlations proposed by other authors are shown as dotted lines.

On the basis of 56 data points the following equation was obtained

$$\frac{L}{d} = 11.5\,\mathrm{We}_j^{0.31}. \qquad [5]$$

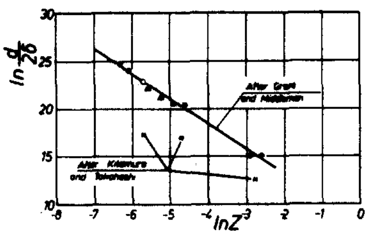

Figure 9.

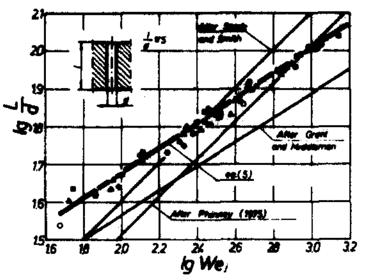

Figure 10.

Figure 9. Influence of Ohnesorge number on ln $d/2\delta$ for laminar jet.

Figure 10. Breakup length of a turbulent jet broken by axisymmetrical waves. Diameters: ◇, $d = 7.06$ mm; □, $d = 5.04$ mm; △, $d = 3.03$ mm; ○, $d = 1.48$ mm. Medium: ·, water; +, water solution of ethylene glycol; ×, water solution of Rokafenol N8.

The correlation coefficient equals 0.957 and the t test indicates that the obtained relationship is significant.

CONCLUDING REMARKS

The following conclusions were drawn from the above experiments.

(1) Laminar jets are very unstable. To get reproducible results all sources of disturbances (e.g. vibrations, inlet or outlet disturbances) have to be eliminated.

(2) For laminar flow in a nozzle the influence of nozzle geometry on jet hydrodynamics is negligible.

(3) In the case when inertial forces predominate over viscous forces, the influence of nozzle geometry is of importance and affects the moment of transition from laminar to turbulent flow, jet turbulence and the mode of breakup, jet diameter and its breakup length. More studies are required for quantitative analysis.

(4) For the outflow through short nozzles having sharp inlet edges a phenomenon of hysteresis may appear.

(5) Breakup length of the laminar jet is well described by the Grant and Middleman relationship.

(6) For turbulent jets the effect of nozzle length becomes negligible – turbulence becomes fully developed for sharp inlet edges when $l/d > 5$ and $\mathrm{Re} > 3000$ and for conically tapered edges when $l/d > 15$ and $\mathrm{Re} > 4000$.

(7) Disintegration of fully developed turbulent jets is caused by axisymmetrical waves if $\mathrm{We}_a < 1.2$.

(8) The correlation $L/d = 11.5\,\mathrm{We}_j^{0.31}$ is proposed to describe the breakup length of fully developed turbulent jets which are breaking with axisymmetrical breakup mode.

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NOMENCLATURE

d	nozzle diameter, m
l	nozzle length, m
L	breakup length of jet, m
r	nozzle inlet curvature radius, m
Re	Reynolds number, $vd\rho_j/\eta$
v	jet exit velocity, m/s
We	Weber number, $\rho v^2 d/\sigma$
Z	Ohnesorge number, $\eta/\sqrt{\rho_j d\sigma}$
α	cone divergence angle of nozzle outlet,
δ	initial jet disturbance level, m

η dynamic viscosity of jet, $Pa \cdot s$
ρ density, kg/m^3
σ surface tension, N/m

Indices
a ambient medium
c critical
j jet