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

CONDITIONS OF CHANGE OF LIQUID OUTFLOW TYPE THROUGH SHARP INLET EDGED ORIFICE

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Abstract—Liquid can flow through a sharp inlet edged orifice occupying total orifice cross-section area without wetting at all or with partial wetting of inner walls of the aperture. In the present paper an influence of individual parameters on the flow type and possibility of the phenomenon of hysteresis to occur have been discussed. A dimensionless equation was proposed which can be helpful in forecasting a change in the type of outflow in given conditions.

INTRODUCTION

The knowledge of jet hydrodynamics has an essential importance for understanding and designing a series of heat and mass transfer processes which employ liquid jets. This also refers to other processes like, for instance, jet washing of woven fabrics as shown by Iciek & Kiełbasa (1980). In the previous paper the available literature data were reported and analysed together with our own results and opinions on cylindrical liquid jet hydrodynamics and their dependence on the phenomena which take place in the orifice. In the paper it was also stated that for the outflow through short sharp edged inlet orifices a phenomenon of hysteresis is possible to occur (figure 1) which is in connection with the different types of outflow (figures 2a, c, d).

The outflow type has an essential influence on the outflow coefficient and jet properties according to photographs (figures 3a–f) and diagrams (figure 4). Because of this it is of great importance to know the conditions on which the transition from the full cross-section outflow to non-wetting outflow depends. For this reason the present paper is devoted to this problem.

DESCRIPTION AND INTERPRETATION OF THE PHENOMENON OF OUTFLOW HYSTERESIS

The change of flow type has, under given conditions, an irreversible character and therefore the phenomenon of hysteresis occurs. In this case a typical dependence of breakup length on jet velocity has the form shown in figure 1.

For a low velocity region the flow occupies the whole nozzle cross-section, it is laminar, and the breakup length is similar to that obtained for other entry geometry or other length of the nozzle. With further increase of velocity a point is reached when contraction and simultaneous

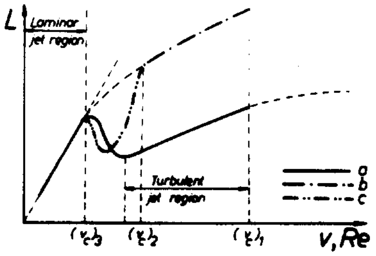


Figure 1. Dependence of breakup length on jet velocity for a short nozzle ($0.4 < l/d < 2$) with sharp inlet edges: (a) full cross-section flow (figures 2a or 2b); (b) flow without wetting of inner nozzle walls (figure 2c); (c) flow with partial wetting of inner nozzle walls (figure 2d).

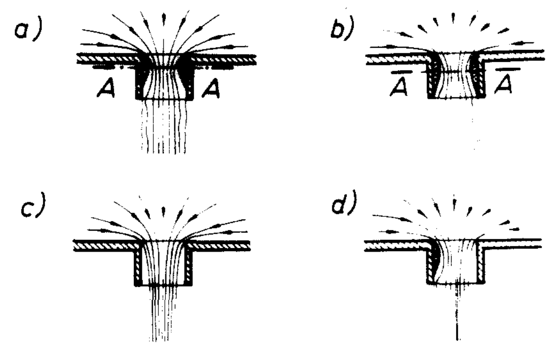
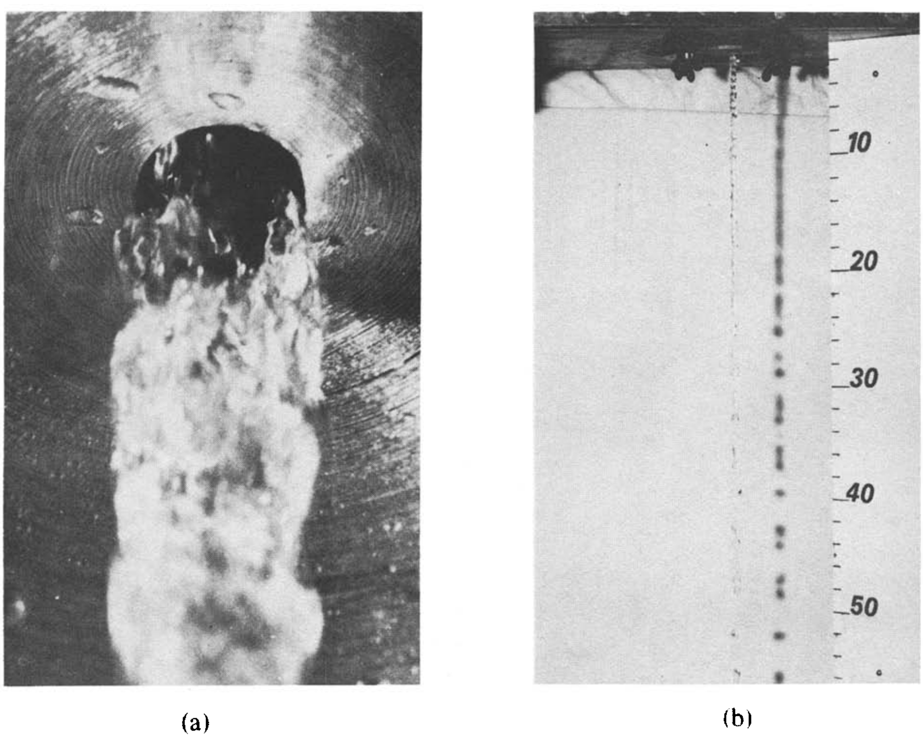
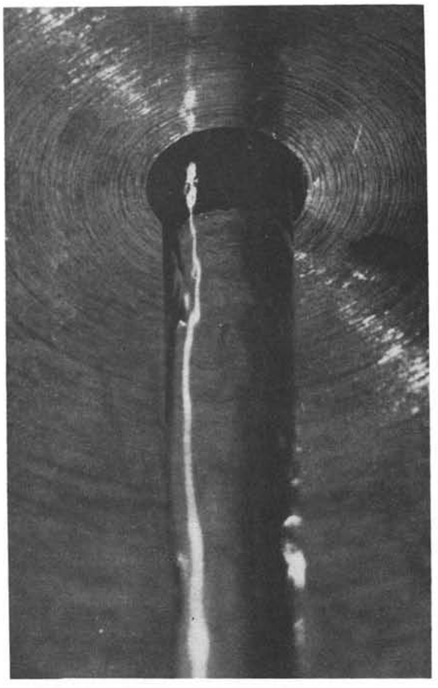


Figure 2. Types of liquid outflow through an orifice when inertial forces predominate over the forces of viscosity: (a) full cross-section flow; (b) full cross-section flow with maximum length of dead zone; (c) flow without wetting of inner walls; (d) flow with partial wetting of inner walls of the nozzle.

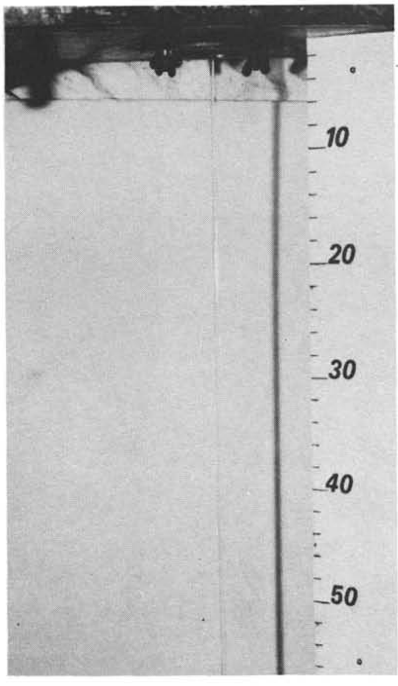
loss of laminarity occur. This results in a reduction of the breakup length. Further reduction in the breakup length with increase in velocity takes place until a fully turbulent jet flow is developed. Any further velocity increase results in breakup length growth. This behaviour is continued up to a certain critical velocity value (v_{c1}). It separates the region where the jet occupies the whole nozzle cross-section (figures 2a, 3a, 3b) from the region where the jet is not wetting the inner nozzle walls (figures 2c, 3c, 3d). Increasing the velocity beyond this point results in a rapid and irreversible change of the outflow character and considerable increase of the breakup length. A possible explanation is as follows: for the case when the length of the "dead"zone is less than that of the nozzle (figure 2a) the flow occupies the whole nozzle cross-section. At the moment when the "dead" zone length becomes longer than that of the nozzle, as a result of a lowered pressure in the converged jet area (cross-section *A–A*, figure 2b), the air is sucked in and liquid flows without wetting the nozzle inner walls at all (figure 2c). For this case the breakup length is the same as in the case of the sharp-edged orifice provided the inertial forces strongly overwhelm those of viscosity. Nozzle walls can be wetted again when the jet velocity is reduced down to a certain critical value (v_{c2}). At the same time the case most often met is that when the wetting of inner nozzle walls is partial (local) (figures 2d and 3e)



(a) (b)



(c)



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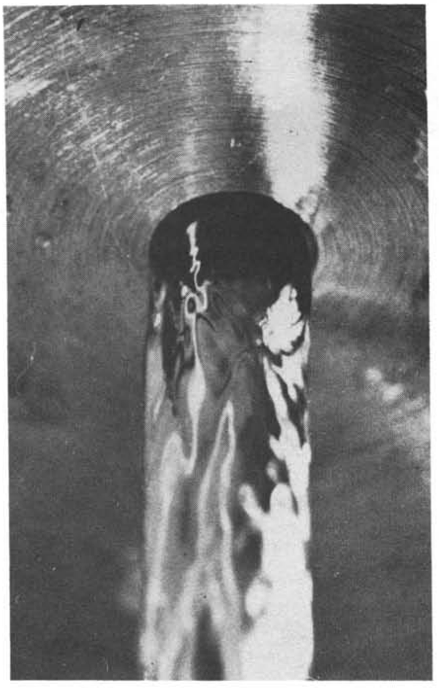

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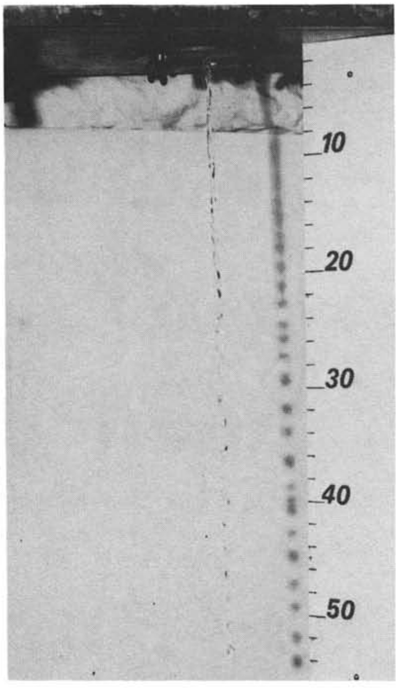


(f)

Figure 3. Photograph of a water jet (8°C) outflowing from a sharp-edged brass orifice ($d = 5.03$ mm, $l = 4.00$ mm): (a, b) full cross-section flow; $H = 0.400$ m; Re = 8230; (c, d) flow without wetting of inner walls; $H = 0.400$ m; Re = 6300; (e, f) flow with partial wetting of inner walls; $H = 0.103$ m; Re = 3300.

thus deforming the jet surface and reducing its breakup length. Greater reduction of velocity results in the declination of the jet axis from that of the nozzle (figure 3f). Finally, further reduction of velocity below a critical value (v_{c3}) restores the total wetting of the nozzle inner walls, full cross-section outflow, thus increasing the jet breakup length.

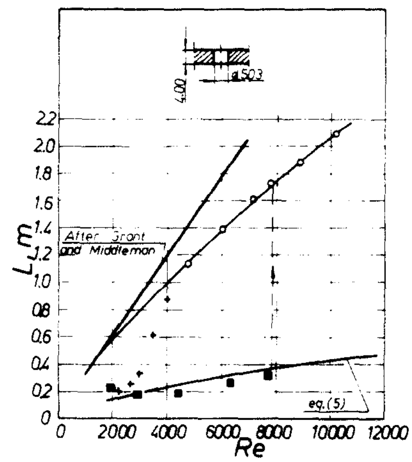
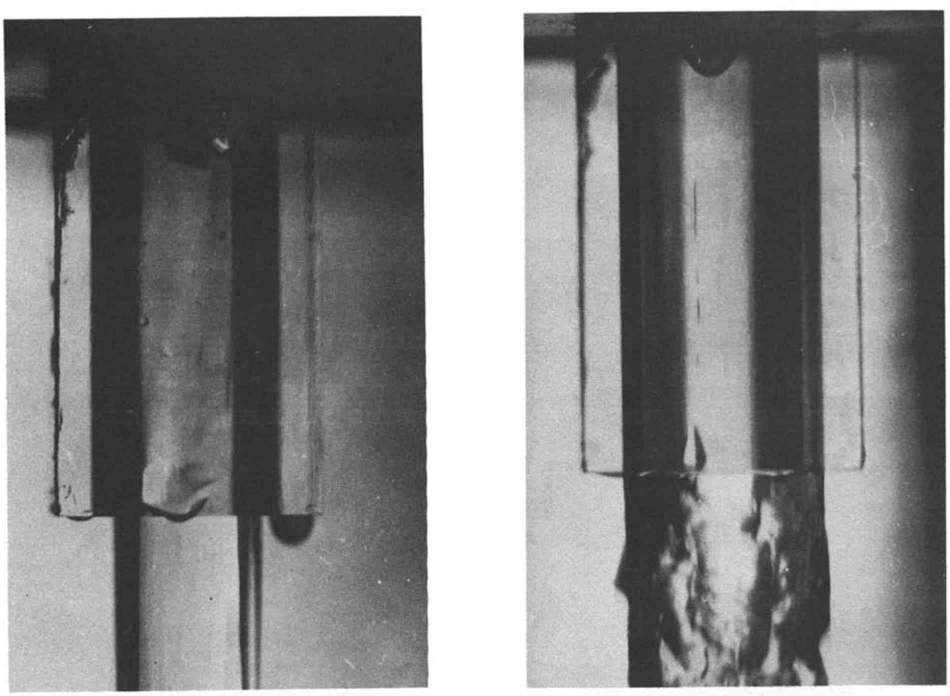


Figure 4. Dependence of breakup length of water jet (8°C) on its outflow type for brass orifice: ■, full cross-section flow (figures 3a or 3b); ⊙, flow without wetting of inner walls (figures 3c or 3d); +, flow with partial wetting of inner walls (figures 3e or 3f).

The phenomenon of hysteresis has not been discussed previously in the literature, except for a discussion of mouthpiece properties (e.g. Pazhi & Galustov (1979)). It was found that for short nozzles (most often mentioned aspect ratios <2) the flow is not accompanied by wetting of the inner walls. For longer nozzles ($l/d > 2$) the literature (e.g. Prosnak (1970)) describes an effect of cavitation which takes place for great issuing velocities in the "dead" zone in its narrowest place. This can also result in a flow without wetting. However, this has not so far been related to the phenomenon of hysteresis. One can suspect that for longer nozzles ($l/d > 2$) the critical velocity (v_{c1}, figure 1) is identical to the cavitation velocity.



(a) (b)

Figure 5. Photograph of a water jet (18°C) outflowing from a sharpedged perspex nozzle ($d = 17.0$ mm, $l = 43.0$ mm): (a) flow without wetting of inner walls, $H = 0.21$ m, Re = 19700; (b) full cross-section flow, $H = 0.21$ m, Re = 25700.

As a result of our own investigations it was found that the change of outflow type can also take place for interrupted flow (by temporary closing of the opening inlet) and conditions when inertial forces predominate over the forces of viscosity. It has to be stressed that the interrupted outflow can produce this effect despite relatively low outflow velocity and high l/d ratio—c.f. figure 5(a). For comparison figure 5(b) shows full cross-section outflow. It was also found that any disturbances can facilitate the change of outflow type, Our own investigations were devoted mainly to the transition caused by air suction into the "dead" zone and conditions for which an influence of any disturbances can be neglected.

LENGTH OF THE "DEAD ZONE"

According to the above presented interpretation of hysteresis it would be much easier to forecast the range of its presence if the "dead zone" length was known. Unfortunately in the literature (e.g. Prosnak (1970)) only the conditions in which the "dead zone" occurs are discussed and its shape is outlined in general. At the same time more precise information on the length of this zone and its dependence on any parameters is still lacking.

It is obvious that the "dead zone" is created as a result of contraction, the contraction coefficient being dependent on Reynolds number (figure 6) according to, e.g. Prosnak (1970). It follows from above that the length of the "dead zone" should be also dependent on Reynolds number, i.e. on the flow velocity, liquid viscosity, density and orifice diameter. In addition, in our own interpretation of the "dead zone" it was presumed that alike the droplet shape on the wall is dependent on wetting ability of liquid; also the "dead zone" length should depend on this wetting ability. Consequently, according to the remarks given above, the length of the "dead zone" l_m should depend on the following parameters

$$l_m = f(v, d, \rho, \eta, \theta). \qquad [1]$$

where v is the mean outflow velocity, d is the orifice diameter, ρ is the jet density, η is the dynamic viscosity and θ is the angle of wetting.

As a matter of fact, the main aim of the research described in the present paper was not an analysis of the "dead zone" shape and length, but only the influence of the increase of this zone length on the transition point from short nozzles.

DISCUSSION OF THE TRANSITION CONDITIONS

On the basis of the interpretation presented here of the change of the outflow type and on

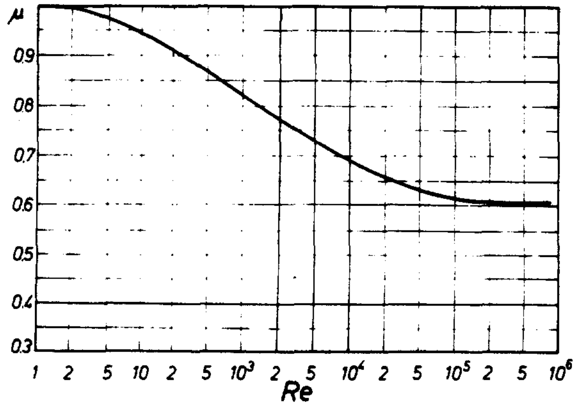


Figure 6. Dependence of contraction coefficient on Reynolds number.

the basis of [1] it could be supposed that the critical velocity v_{c1} depends on the following parameters

$$v_{c1} = f(d, l, \rho, \eta, \theta, \sigma) \qquad [2]$$

where σ is the surface tension and l is the orifice length.

To prove this hypothesis and to find quantitative correlations a series of 59 experiments was performed in the equipment already described by Iciek (1981). Ranges of change of the investigated parameters are given in tables 1–3. The effect of transition took place in 35 of the mentioned experimental runs.

Those experiments allowed to state that the critical velocity depends:

To a great extent on the nozzle length, i.e. it increases rapidly with the nozzle length increase. This rule holds for nozzles shorter than their diameter. For longer orifices the transition (as an effect of air suction) does not take place. On the nozzle diameter, it decreases when the diameter increases. On the liquid viscosity, it increases when viscosity increases.

In the reported experiments the influence of wetting ability of the fluid was also studied. It was changed by the change of orifice material or the change of liquid surface tension. It was found that the effect of wetting ability is of minor importance.

Table 1. Physical properties of the experimental liquids

	T °C	η 10³ Pa·s	σ 10³ N/m	ρ kg/m³
Water (liquid A)	8	1.39	74.7	1000
	18	1.06	73.1	999
	40	0.656	69.8	992
44% per weight water solution of ethylene glycol (liquid B)	17	3.09	61.6	1046
0.01% per weight water solution of Rokafenol N8 (polyoxyethylene nonylphenol) (liquid C)	18	1.26	39.7	1000
Petroleum (liquid D)	16	4.29	29.6	847

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

Table 2. Angles of wetting for the used systems

Nozzle material / Liquid	Brass	Duralumin	Perspex
A	77	75	51
B	75	-	50
C	52	46	38
D	25	24	-

Note: angles of wetting were measured in the equipment described by Doniec and Kącki (1973).

Table 3. Ranges of investigation of other parameters

d, mm	2.00 to 3.06
l/d	0.40 to 1.05
H, m	0.03 to 4.5

Table 4. An exemplary set of experimental results

No	Nozzle material	d mm	*l/d*	Liquid	T °C	v_{c1} m/s	v m/s	Remarks
1	Brass	5.04	0.794	A	8	2.16		
2	Brass	2.00	0.900	A	40	5.26		
3	Brass	5.04	1.02	A	8	-	6.97	no transition
4	Duralumin	5.00	0.800	A	8	2.31		
5	Perspex	7.22	0.873	A	8	2.17		
6	Brass	2.00	0.900	C	18	7.03		
7	Brass	4.50	0.888	C	18	3.47		
8	Brass	5.04	0.794	C	18	1.79		
9	Brass	7.10	1.05	C	18	-	7.04	no transition
10	Brass	4.00	0.455	D	16	3.55		
11	Brass	5.04	0.794	B	17	4.48		
12	Brass	4.01	0.823	B	17	-	6.85	no transition
13	Perspex	7.22	0.873	B	17	4.20		

Although the experiments show no influence of liquid density on the critical velocity v_{c1}, this observation cannot be reliable because in those experiments liquid density was changed in a narrow range (from 992 to 1046 kg/m^3). To illustrate the conclusions table 4 presents exemplary results of the experiments.

In addition the experiments allowed to draw the conclusion that transition:

Can occur only in the range of a pronounced predominance of the inertial forces over the forces of viscosity (according to our own data for Re > 2800).

Is clearly visible in experimental conditions (figures 3a–3d or 5a and 5b).

Takes place with a very good reproducibility if only all disturbances (e.g. vibrations of the installation, uneven liquid supply etc.) are eliminated.

Our own essential experiments were carried out for conditions when the influence of disturbances was negligible and only those results were used for the mathematical analysis. In addition, on the basis of those experiments it could be also stated that:

Critical velocity v_{c3} corresponds to the conditions in which the Reynolds number is approximately equal to 2300.

Critical velocity v_{c2} depends on the precision of the inlet nozzle machining and various types of disturbances, and corresponds to the conditions in which the Reynolds number ranges from 2500 to 5000.

Critical velocity v_{c1} depends on a series of parameters. The evaluation of quantitative relationships requires a statistical analysis.

A MATHEMATICAL EVALUATION OF THE RESULTS

To previously motivated relationship[2] an acceleration due to gravity was added which allowed a possible influence of the gravity force (directly immeasurable) to be taken into account. Finally the following variables form the relationship

$$v_{c1} = f(d, l, \rho, \eta, \vartheta, \sigma, g) \quad [3]$$

where g is the acceleration due to gravity from which by means of a dimensional analysis the following dimensionless equation was obtained

$$l/d = A \cdot (\mathrm{Re})^{n_1}(\mathrm{We})^{n_3}(\mathrm{Fr})^{n_4}. \quad [4]$$

Where $\mathrm{Re} = vd\rho/\eta$ is the Reynolds number; $\mathrm{We} = \rho v^2 d/\sigma$ is the Weber number and $\mathrm{Fr} = v^2/dg$ is the Froude number.

It was also decided to check the influence of wetting ability on the transition point by introducing to [4] factor tg θ which resulted in [5]

$$l/d = A \cdot (\mathrm{Re})^{n_1}(\mathrm{tg}\theta)^{n_2}(\mathrm{We})^{n_3}(\mathrm{Fr})^{n_4}, \quad [5]$$

Coefficients A, n_1, n_2, n_3, n_4 were searched for by a statistical method (cf. Volk (1973)) solving a set of 35 experimental equations by means of Gaussian multiplier methods. In all these 35 experiments transition occurred. The other 24 experiments without transition were used in the further part of the analysis.

All calculations were performed by ODRA 1204 digital computer by means of the software prepared in the Institute of Chemical Engineering, Łódź Technical University. For the assumed 5% range of confidence interval the following values of coefficients were computed

$$A = 0.0353,\ n_1 = 0.317,\ n_2 = -0.0081,\ n_3 = 0.0249,\ n_4 = 0.00179$$

with the corresponding standard deviations

$$(n_1) = 0.0308,\ (n_2) = 0.0266,\ (n_3) = 0.0260,\ (n_4) = 0.0227.$$

Correlation coefficient c at 26 degrees of freedom is equal to 0.916 and the value of F test to 39.3. Values of test t for zero order hypothesis and significance of the obtained regression coefficients were checked by calculating partial correlation coefficient (r_{yx}). The computed values are given in table 5. The results presented in table 5 prove that only the coefficient n_1 is significant. For it the partial correlation coefficient is greater than 0.6 and the value of test t is greater than the tabulated one (2.056). On the basis of those results correlation computations in the form $l/d = f(\mathrm{Re})$ were performed. They resulted in the following equation

$$l/d = 0.0354\ \mathrm{Re}^{0.34} \quad [6]$$

with correlation coefficient $r = 0.91$. Standard deviation for the exponent was equal to $\sigma = 0.027$. Function $l/d = f(\mathrm{Re})$ was plotted on a log–log plot in figure 7. It is clearly seen from

Table 5. Values of partial correlation coefficient (r_{yx}) and test t for the investigated independent variables

Regression coefficient	Number of independent variable	Independent variable	r_{yx}	t
n_1	1	Re	0.910	10.281
n_2	2	tg ~	0.038	0.304
n_3	3	We	0.496	0.957
n_4	4	Fr	0.466	0.079

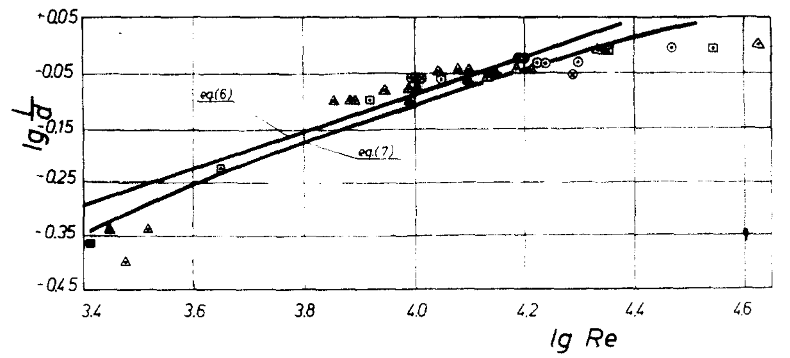


Figure 7. Dependence of critical values of parameter l/d on Reynolds number: Material of the orifice: ○, perspex; △, brass; □, duralumin; Liquid: ●, water; +, water solution of glycol; ×, water solution of Rokafenol; ▲, petroleum.

figure 7 that the log–log transformation cannot straighten the curve $1/d = f(\mathrm{Re})$, although the computation results suggest that the hypothesis about linearity of this relationship is not fulfilled only by two points outside the confidence interval. It is possible to find a function which better describes the data but it is of a more complicated form. For instance such a function is

$$\lg d/1 = 5.42\left(\frac{1}{\lg \mathrm{Re}}\right) - 1.25. \qquad [7]$$

The curve described by [7] is also shown in figure 7.

Relationships [6] or [7] allow to forecast for given conditions a moment of transition. Thus, if $(l/d)_{calc} < l/d$, the outflow should take place through the full cross-section, and if $(l/d)_{calc} > l/d$ the flow without wetting the inner walls of the orifice can be expected ($(l/d)_{calc}$ was calculated from [6] or [7].

For corroboration of these inequalities the results of the remaining 24 "no transition" experiments were used. In 23 cases the results were in accordance with the above presented conclusions. Apart from the above mentioned conclusions the results suggest that in the range of decreasing μ caused by increasing Reynolds number the length of the "dead zone" increases and for large values of the Reynolds number (Re > 50,000) it is nearly equal to the orifice diameter.

CONCLUDING REMARKS

On the basis of the presented experiments it is possible to draw the following conclusions.

1. For sharp inlet edged orifices and turbulent flow around them the outflow can occupy full orifice cross-section without wetting or with partial wetting of the orifice inner walls.

2. Transition from the full cross-section flow to the flow without wetting inner walls can be caused by air suction into the "dead zone", cavitation, different types of disturbances and interrupted outflow.

3. Parameters on which the moment of air suction into the "dead zone" is dependent, are described by relationship [3].

4. For forecasting of the conditions of transition due to air suction into the "dead zone" relationship [7] is proposed.

5. It can be supposed that for large values of the Reynolds number (Re > 50,000) the length of the "dead zone" is approximately equal to the nozzle diameter.

NOMENCLATURE

A, n_1, n_2, n_3, n_4	constants in dimensionless equations
d	orifice diameter, m
g	acceleration due to gravity, m/s^2
H	height of hydrostatic head, m
l	orifice length, m
l_m	dead zone length, m
L	jet breakup length, m
v	mean outflow velocity, m/s
$v_{c1}, v_{c2}, vc3$	critical outflow velocities, m/s
η	dynamic viscosity, Pa s
θ	angle of wetting, °
μ	contraction coefficient
ρ	jet density, kg/m^3
σ	surface tension, N/m

Dimensionless numbers

Fr Froude number, v^2/dg

Re Reynolds number, $vd\rho/\eta$

We Weber number, $\rho v^2 d/\sigma$

REFERENCES

DONIEC, A. & KACKI, E. 1973 Shape of a droplet on a plane—III. Experimental Part. Reports of Łódź Technical University, *Chemistry*, **27**, 21–29.

ICIEK, J. & KIEŁBASA, J. 1980 Design of nozzles for jet washing of woven fabrics. Unpublished paper. Łódź.

ICIEK, J., Hydrodynamics of a free cylindrical lindrical liquid jet—I. *Int. J. Multiphase Flow.*

PAZHI, D. G. & GALUSTOV, V. S. 1979 *Liquid Atomizers.* Khimia, Moskva (in Russian).

PROSNAK, W. J. 1970 *Fluid Mechanics.* **1**, PWN, Warsaw (in Polish).

VOLK, W. 1973 *Applied Statistics for Engineers*, WNT, Warsaw.