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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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EUGENIUSZ IHNATOWICZ and MARIAN TRELA*

Investigations of instability of liquid jets emanating from nozzles into ambient air – Part II†

Institute of Fluid-Flow Machinery PAS, Fiszera 14, 80-952 Gdańsk, Poland

Abstract

The paper presents the results of experimental investigations of instability of liquid jets emanating from sharp-edge orifices into ambient air. The major impact has been paid to the measurements of the jet structure and the distance beyond which the jet loses its continuity and is broken into liquid droplets. Investigations have been conducted at various pressures of water in the orifice and its three diameters. The results have been compared against available data from literature including the own data obtained earlier for the contoured nozzles.

Keywords: Liquid jet; Jet structure

Nomenclature

D	– orifice diameter, mm	V	– volumetric flow rate, l/min
K	– coefficient	w	– velocity, m/s
L, l	– length, distance, m	We	– Weber number, $\text{We} = \rho w^2 D/\sigma$
m	– exponent	Z	– Ohnesorge number, $Z = \sqrt{\text{We}}/\text{Re}$
n	– exponent	δ	– initial disturbance at the jet surface
p	– pressure of water, Pa	μ	– dynamic viscosity, kg/ms
Re	– Reynolds number,	σ	– surface tension, N/m
T	– temperature, ^{o}C	ρ	– density, kg/m^3

*Corresponding author. E-mail address: mtr@imp.gda.pl

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Subscripts

b, B	– breakdown, Bendemann's orifice	g	– gas
bar	– barometric	l	– liquid
c	– contoured orifice	max, min	– maximum, minimum
cr	– critical	s	– droplet, sharp edge orifice
i	– beginning of the region	w	– water
j	– liquid jet	I, II, III	– refers to regions I, II, III

1 Introduction

A phenomenon of liquid jet outflow from the orifice (hole) into the unconfined or confined gaseous environments is present in numerous technical equipments. Such jets have application for example in cooling of hot surfaces, two-phase ejectors (water-steam, water-air), liquid sprays (burners, fuel injectors) and other technical applications. The jet, at some distance from the orifice, breaks up into droplets and a mixture of droplets and gas is being formed. In practical applications of cooling a solid surface by means of jets, we can use two alternatively methods: continuous jet cooling [1-3] or spray cooling [4]. Sufficient liquid atomisation into the form of small droplets as well as their correct mixing with gas decides about the efficiency of technical equipment utilising the latter form of cooling.

An important issue in the investigations of liquid jet stability is a problem of determination of the jet breakdown length L_b. This problem has not attracted so far a sufficient attention, as it has usually be assumed that the loss of stability and the jet breakdown into droplets occurs abruptly and hence contains the physical discontinuity. Such problem has been studied in the previous work [5] by the present authors, where the stability of liquid jet flowing out from the contoured orifice has been investigated. The latter kind of the orifice has been selected for investigations, since it ensures relatively smooth and undisturbed jet outflow. It is known from the literature that initial disturbance of the fluid motion at the orifice outlet influences significantly the process of the jet breakdown. Such disturbances come from the geometry of the feeding orifice as well as the pressure pulsations in the installation. Certainly, the disturbances linked with installation were not eliminated in the case of the contoured orifice. Therefore, the contoured orifice can only serve as a reference geometry for other kinds of orifices used in similar operational conditions.

Due to the implementation of a very accurate measurement method in the former paper [5], it was possible to shown that in the whole domain of the jet flow, in respect to the break-up phenomenon, one can distinguish three characteristic regions: the continuous region (I), the transition region (II) and the discontinuous region (III). In the region I we always deal with the continuous jet (liquid jet core region). In the second region there exist alternatively the periods of jet continuity and discontinuity. In the third region, the liquid exists in the form of stream of droplets. The transition region proved to be relatively long and comparable with the length of the continuous region I. Hence it has been shown in [5], that the breakdown length is determined by the following inequality $L_I \leq L_b \leq L_{iIII}$. Based on the obtained data in [5], it could be estimated, that in the case of disturbances of motion pertinent for the contoured nozzle and the installation under scrutiny, the ratio of a maximum value of L_b to a minimum value was about $L_{b\ max}/L_{b\ min} \cong 2$.

The topic of the present work concerns the investigations of the structure of the liquid jet flowing out of sharp-edge orifices, widely used in practice. The aim of the investigation is to obtain more information about the structure of the jet flowing out from such orifices as well as the relations between the jet breakdown length in the function of the pertinent flow parameters and the orifice geometry. The results of the investigations are presented against the data obtained for contoured orifices used in [5]. The experimental data have been obtained using exactly the same research method and apparatus as described in detail in [5].

2 Experimental results

Investigations of the liquid jet stability have been performed using the sharp-edge orifices. Measurements have been conducted for three different orifice inlet diameters: $D = 3.5$ mm, 6.0 mm and 9.5 mm. The shape and dimensions of the orifices are shown in Fig. 1. Applying the method and the apparatus described in [5] the results have been obtained, which confirmed, similarly as in the case of a contoured orifices, the existence of three different flow regions I, II and III. Figures 2-7 present the distributions of the voltage output recorded on the oscilloscope of the measurement system, schematically presented in Fig. 3 in [5], together with the corresponding photographs of the jet structures. Distributions of the voltage output have been recorded, as before, at the time base of $t = 20$ ms, corresponding to one division and the voltage amplifying of $U = 5$ V for one division. The voltage output distribution images the change of the jet's electric conductivity (or resistance) on the distance between the orifice exit and the location of the mesh wire electrode.

Figure 2 shows the recorded voltage output on the oscilloscope in the case when the liquid jet was continuous between the orifice and the mesh wire electrode, (see Fig. 4 in [5]) at the border between regions I and II. Some voltage output impulses are seen, which confirm that sometimes the loss of continuity of

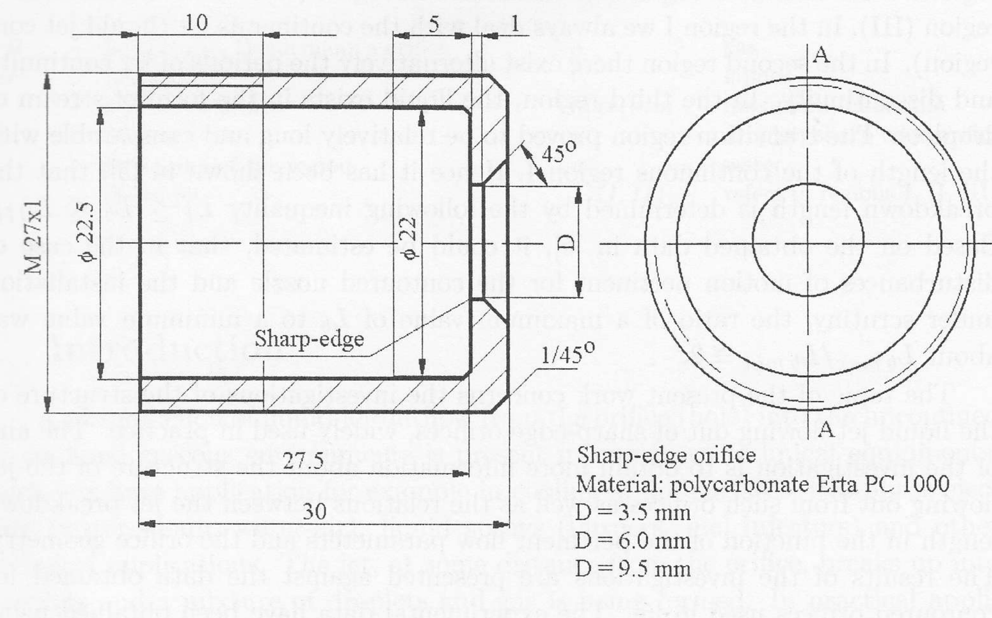

Figure 1. Shape and dimensions of a sharp-edge orifice.

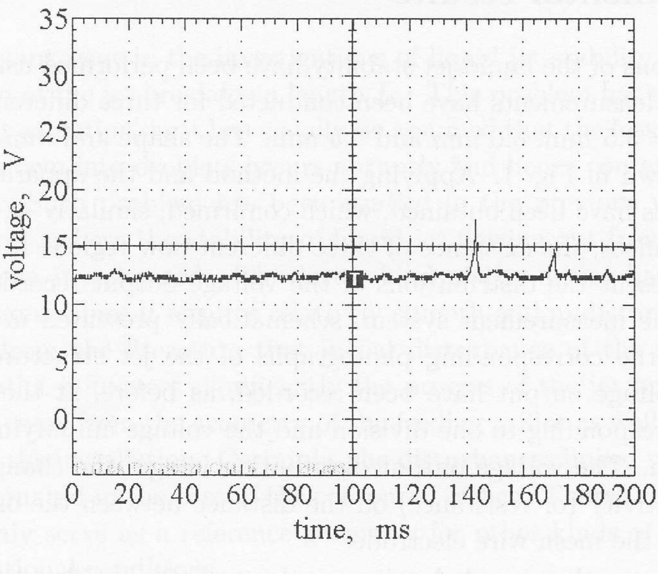

Figure 2. Voltage distribution on the oscilloscope for the mesh wire electrode located at the border between regions I and II.

the jet occurs. The maximum voltage impulse is about 5 V. The corresponding location of the mesh wire electrode in this case determines the beginning of the jet discontinuity. This state of the jet behaviour, when not very often the loss of jet continuity occurs, has been defined (similarly as in [5]) as a border between the regions I and II. Therefore the length for the region I can be determined.

Figure 3 presents the picture of the jet, recorded in the vicinity of the mesh wire electrode for the situation discussed above. The location of the mesh wire electrode in respect to the outlet edge of the orifice, was found to be $L_I = L_{b\,min} = 28$ cm.

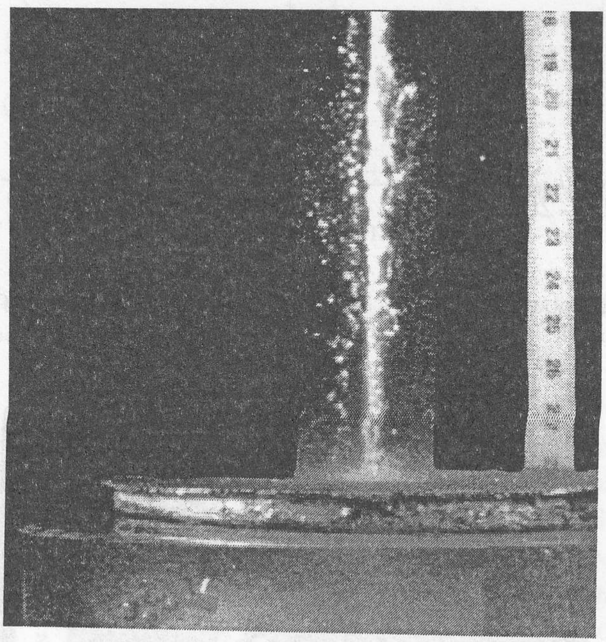

Figure 3. Photograph of the liquid jet in the vicinity of the mesh wire electrode located at the border between regions I and II.

Figure 4 presents the recorded voltage output on the oscilloscope for the mesh wire electrode embedded in the flow domain pertinent for the region II, that is the transition region, where two flow structures occur alternatively i.e.: the continuous liquid jet and the droplet flow regimes. The photograph of the jet in the vicinity of the wire electrode is shown in Fig. 5 for the corresponding voltage output given in Fig. 4. The discussed case corresponds to the location of the electrode at the distance of $L_{II} = 54$ cm from the orifice.

The next Fig. 6 shows the voltage output on the oscilloscope recorded in the case of location of the electrode at the beginning of the region III. The voltage base level is equal to about 25 V. A perceptible voltage impulse represents the

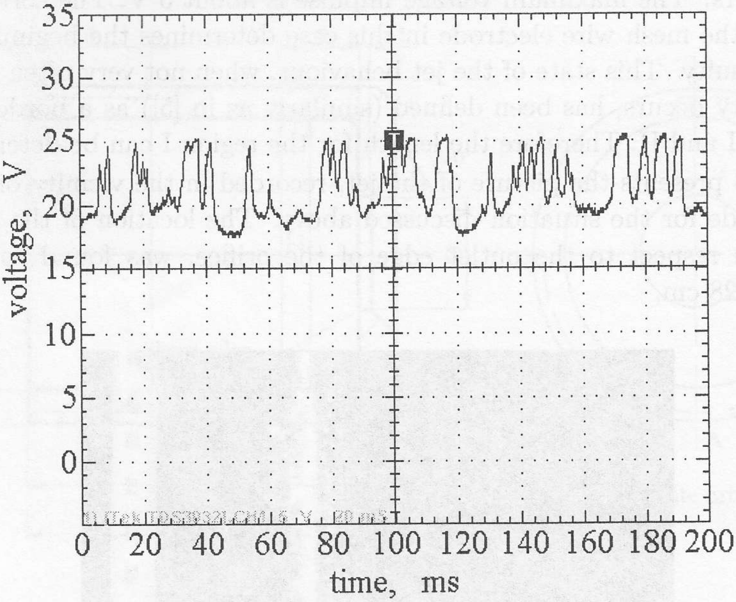

Figure 4. Voltage distribution on the oscilloscope for the mesh wire electrode embedded in the flow region II.

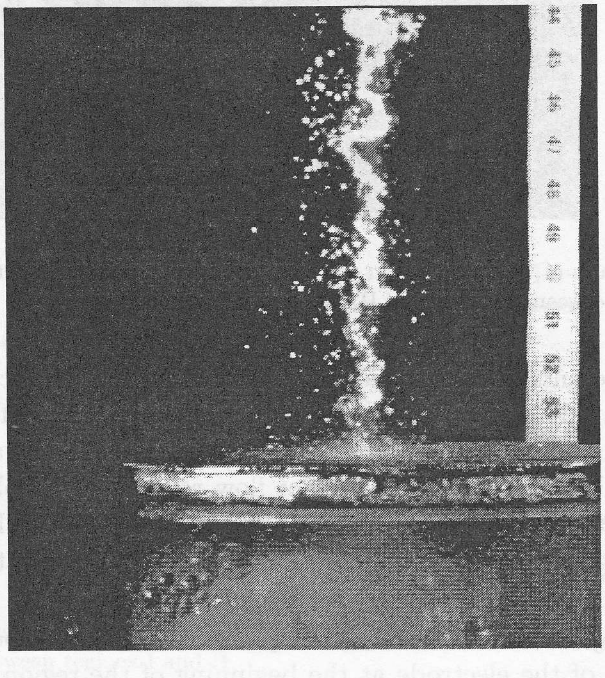

Figure 5. Photograph of the liquid jet in the vicinity of the electrode embedded in the flow region II.

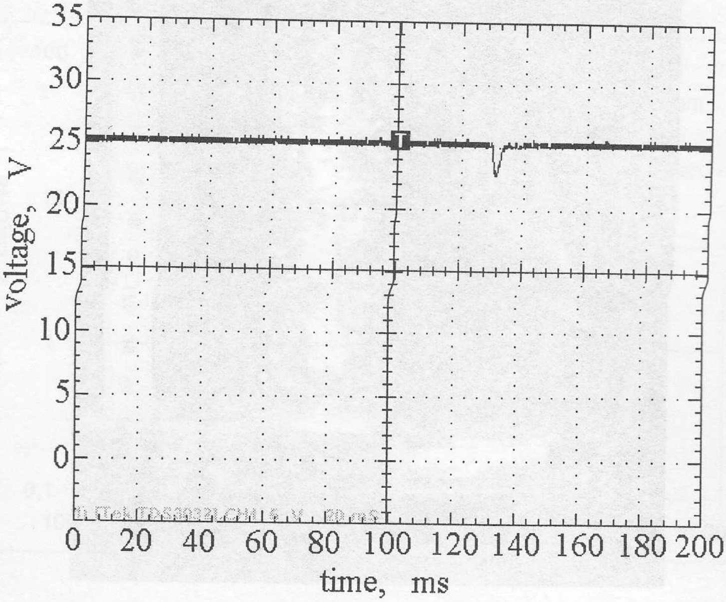

Figure 6. Voltage distribution on the oscilloscope in the case of the electrode located at the border between regions II and III.

moment of time, where the coalescence of the liquid "lumps" takes place, which results in voltage drop. A value of the impulse amplitude is about 2.5 V, whereas the voltage level during the short electric short-circuit, (which corresponds to the jet continuity), reaches 22.5 V. Such location of the measurement mesh wire electrode determines the end of the region II (transition region), where the jet is periodically continuous. Figure 7 presents a respective photograph of the jet recorded in the vicinity of the electrode for the discussed case. The location of the electrode corresponding to the discussed situation was equal to $L = 80.7$ cm. Since the periods of the electric short-circuits (coalescence) in the measurement system were sporadic, hence it was decided that such kind of the voltage output determines the beginning of the region III, where the liquid jet exists in the form of a droplet spray. Hence it can be assumed that $L_{i\ III} = L_{b\ max} = 80.7$ cm.

Detailed results of the investigations of pressure, temperature, volumetric flow rate of water and the jet lengths L_I and $L_{i\ III}$ have been given in the Appendix. However, the main results in respect to the distributions of the jet lengths L_I and $L_{i\ III}$ in comparison with the results of the other authors are presented below.

The results of the present investigation concerning the jet length L_I for the region I as well as $L_{i\ III}$ for the region III, are plotted respectively in Fig. 8 and Fig. 9 in adequately selected co-ordinates. Such coordinate system has been

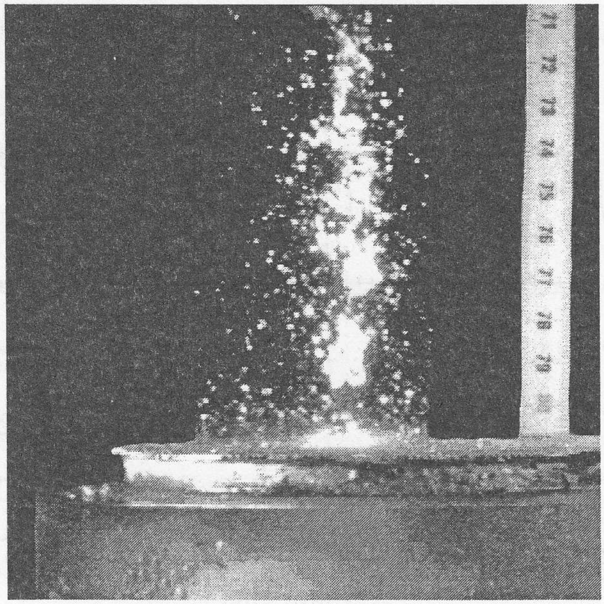

Figure 7. Photograph of the liquid jet in the vicinity of the electrode embedded in the flow at the border between II and III regions.

suggested by Lienhard and Day [7]. These authors conducted experimental investigations of the breakdown of liquid jets flowing out from sharp-edge orifices with diameters D varying in the range $D = 0.8 \div 3.17$ mm, where the value of a corresponding cylindrical part of orifice (see Fig. 1) was equal to $l = 0.5$ mm. Hence the ratio l/D varied in their experiments in the range $l/D = 0.157 \div 0.635$. Their results have been described by them by means of two correlations [7]:

$$\frac{L_b}{D\sqrt{\mathrm{We}}} = 2.75 \cdot 10^{10}\ \mathrm{Re}^{-2} \tag{1}$$

for $\mathrm{Re} \geq 48000$ and

$$\frac{L_b}{D\sqrt{\mathrm{We}}} = 11.5 \tag{2}$$

for $\mathrm{Re} < 48000$.

These correlations approximate the results of experimental investigations obtained in [7] with the accuracy of $\pm 22\%$. The above investigations have not showed the influence of the geometry of the orifice on the jet breakup length L_b, due to the fact that the ratio l/D did not appear in the above correlations. This can probably be attributed to the applied simple experimental technique, which was the only available in those days (a stroboscopic lamp with the visual assessment of the jet quality).

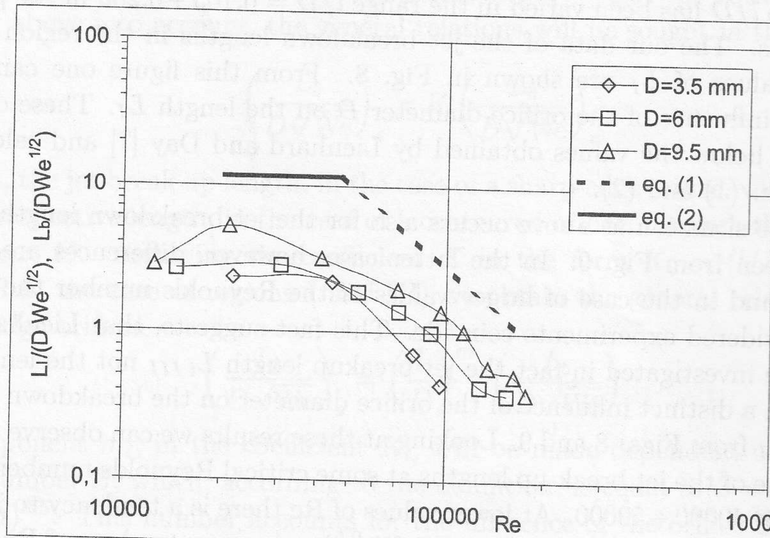

Figure 8. The jet breakup lengths L_I, L_b versus the Reynolds number according to the authors own investigations and the paper [7] (Eqs. (1) and (2)).

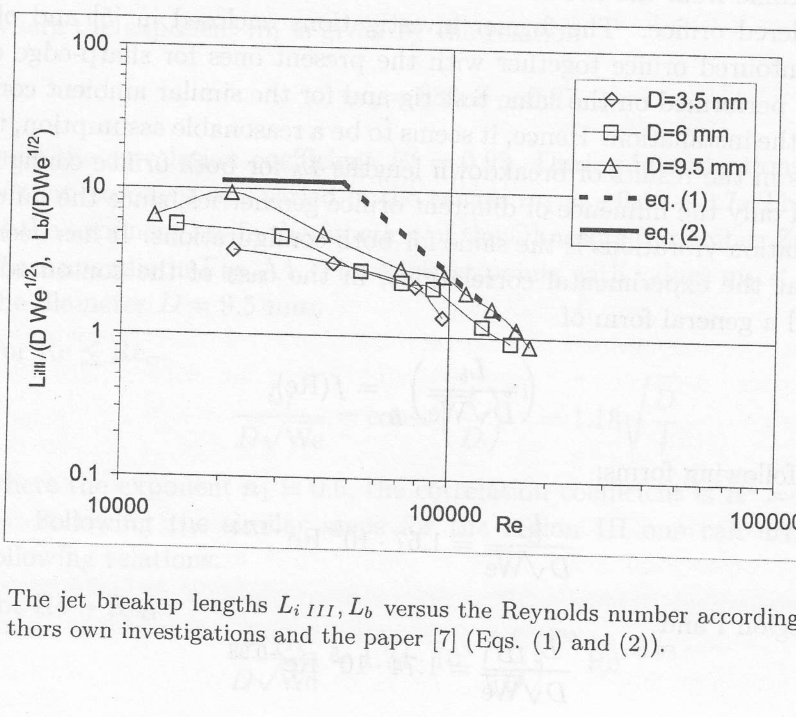

Figure 9. The jet breakup lengths $L_{i\ III}, L_b$ versus the Reynolds number according to the authors own investigations and the paper [7] (Eqs. (1) and (2)).

The ratio l/D has been varied in the range $l/D = 0.105 \div 0.285$ in the present investigations. The our data of the jet breakdown lengths in the region I, and hence the values of L_I are shown in Fig. 8. From this figure one can see a pronounced influence of the orifice diameter D on the length L_I. These data lie significantly below the values obtained by Lienhard and Day [7] and calculated from the Eqs. (1) and (2).

The same situation as above occurs also for the jet breakdown length $L_{i\,III}$, as can be seen from Fig. 9. In the latter case, however, differences are not so significant, and in the case of larger values of the Reynolds number the results of both considered experiments coincide. This fact suggests, that Lienhard and Day [7] have investigated in fact the jet breakup length $L_{i\,III}$ not the length L_I.

It is seen a distinct influence of the orifice diameter on the breakdown lengths L_I and $L_{i\,III}$ from Figs. 8 and 9. Looking at these results we can observe a qualitative change of the jet break-up lengths at some critical Reynolds numbers in the range $\mathrm{Re}_{cr} \cong 40000 \div 50000$. At lower values of Re there is a tendency to increase and then to decrease of the term $L_b/(D\ \mathrm{We}^{0.5})$, whereas at values of Re greater than Re_{cr} there is clear and monotonic decrease of the term $L_b/(D\ \mathrm{We}^{0.5})$. Such variation of the term $L_b/(D\ \mathrm{We}^{0.5})$ versus the Reynolds number is qualitatively consistent with the results of Lienhard and Day [7].

It has been indicated at the beginning of the present paper on the role of the initial motion perturbances on the jet breakup length. These disturbances generally come from the two sources i.e.: from the feeding installation and from the considered orifice. The former investigations enclosed in [5] and obtained for the contoured orifice together with the present ones for sharp-edge orifices, have been performed on the same test rig and for the similar ambient conditions including the installation. Hence, it seems to be a reasonable assumption, that the differences in the results of breakdown lengths L_b for both orifice configurations will reveal only the influence of different orifice geometries, since the influence of the installation vibrations is the same for both configurations. It has been shown in [5], that the experimental correlations, in the case of the contoured orifice, which had a general form of

$$\left(\frac{L_b}{D\sqrt{\mathrm{We}}}\right)_B = f(\mathrm{Re}) \tag{3}$$

took the following forms:

$$\frac{L_I}{D\sqrt{\mathrm{We}}} = 1.67 \cdot 10^6\ \mathrm{Re}^{-1.24} \tag{3a}$$

for the region I and

$$\frac{L_{i\,III}}{D\sqrt{\mathrm{We}}} = 1.74 \cdot 10^5\ \mathrm{Re}^{-0.98} \tag{3b}$$

for the region III, with the correlation coefficient $R^2 = 0.97$ for both expressions. Taking above into account, the general relations will be sought in the form

$$\left(\frac{L_b}{D\sqrt{\mathrm{We}}}\right)_s = K\left(\frac{L_b}{D\sqrt{\mathrm{We}}}\right)_c$$

That is, the jet break up length, in the case of a sharp-edge orifice, will be referred to the respective length, in the case of a contoured orifice, through the correction coefficient K. Assuming the coefficient K in the form $K_i = (l/D)^{m_i}$ (where $i = 1, 3$ in the case of regions I and III) we obtain the general relation for the sharp-edge orifices

$$\left(\frac{L_b}{D\sqrt{\mathrm{We}}}\right)_s = \left(\frac{l}{D}\right)^{m_i}\left(\frac{L_b}{D\sqrt{\mathrm{We}}}\right)_c \tag{4a}$$

The exponent m_i, in the coefficient K_i, will be made dependent on the Ohnesorge number Z, which, according to the definition, is equal to $Z = \mathrm{We}^{0.5}/\mathrm{Re} = \mu/(\rho D\sigma)^{0.5}$. This number accounts for the influence of the orifice diameter and the jet physical properties. Having in mind the above considerations one can arrive at the pertinent relations for the first region I:

- For $\mathrm{Re} > \mathrm{Re}_{cr} = 40000$

$$\frac{L_I}{D\sqrt{\mathrm{We}}} = 1.67 \cdot 10^6 \left(\frac{l}{D}\right)^{m_1} \mathrm{Re}^{-1.24} \tag{5}$$

where the exponent m_l is given by the relation

$$m_1 = 886\ Z - 0.87 \tag{5a}$$

with the correlation coefficient $R^2 = 0.93$. During investigations the value of that exponent was varied in the range: $m_1 = -0.10 \div 0.7$. The variation of the exponent m_1 in the function of the Ohnesorge's number Z is given in the Appendix in Fig. A4. Three lowest points with values $m_1 < 0$ concerns the diameter $D = 9.5$ mm.

- For $\mathrm{Re} \leq \mathrm{Re}_{cr}$

$$\frac{L_I}{D\sqrt{\mathrm{We}}} = \mathrm{const}\left(\frac{l}{D}\right)^{n_1} = 1.18\sqrt{\frac{D}{l}} \tag{6}$$

where the exponent $n_1 \cong 0.5$, the correlation coefficient is $R^2 = 0.97$.

Following the similar steps for the region III one can arrive at the following relations:

- For $\mathrm{Re} > \mathrm{Re}_{cr}$

$$\frac{L_{i\ III}}{D\sqrt{\mathrm{We}}} = 1.74 \cdot 10^5 \left(\frac{l}{D}\right)^{m_3} \mathrm{Re}^{-0.98} \tag{7}$$

where the exponent m_3 is given by the relation

$$m_3 = 421\ Z - 0.36 \tag{7a}$$

with the correlation coefficient $R^2 = 0.75$. During the investigations the value of that exponent varied in the range: $m_3 = -0.6 \div 0.4$. The variation of the exponent m_3 in the function of the Ohnesorge's number Z is shown in the Appendix in Fig. A5. Two lowest points with the values $m_3 < 0$ concerns the diameter $D = 9.5$ mm.

- For $\mathrm{Re} \leq \mathrm{Re}_{cr}$

$$\frac{L_{i\ III}}{D\sqrt{\mathrm{We}}} = \mathrm{const}\left(\frac{l}{D}\right)^{n_3} = 1.47\left(\frac{D}{l}\right)^{0.69} \tag{8}$$

where the correlation coefficient in the case of the exponent n_3 is equal to $R^2 = 0.99$.

Relations (5) $\div$ (8) are valid in the following range of the pertinent parameters: $12000 < \mathrm{Re} < 180000$, $0.0008 < Z < 0.0018$, $l/D = 0.1 \div 0.285$, $50 < \mathrm{We} < 47000$.

For comparison reason the experimental data of the jet break-up lengths L_I and $L_{i\ III}$ together with their calculated values according to the Eqs. (5), (6), (7) and (8) for the orifice diameter $D = 9.5$ mm are plotted in Fig. 10 and Fig. 11. This is the largest orifice diameter used in the present investigation. In the case of this diameter the experimental values of exponents m_1 and m_3, in Eqs. (5) and (7), vary respectively in the ranges: $m_1 = -0.10 \div 0.1$ and $m_3 = -0.03 \div 0.14$. If the values of m_1 and m_3 reach zero $m_1 = m_3 = 0$ then the correction coefficient is equal $K_i = 1$. In other words, the results for the sharp-edge orifice are the same as for the contoured one. For the case of $m_i < 0$ then the coefficient $K_i > 1$ which, according to Eq. (4a), would mean that in the case of the sharp-edge orifice the jet break-up length is larger than for the contoured one. This is rather not a plausible result and it shall be attributed rather to the measurement errors and different motion perturbations in the installation during the experiments for both considered cases i.e. for contoured and sharp-edge orifices. Negative values of exponents m_1 and m_3 appeared only at three measurement points with orifice diameter $D = 9.5$ mm (see Fig. A4 and A5). In the case of smaller diameters the values of m_1 and m_3 were always positive. It is worth to note, that with the increase of the diameter D, and hence the decrease of the ratio (l/D) the sharp-edge orifice approaches the contoured orifice, as far as the flow situation is concerned. This finding is also confirmed by the work of Iciek [8], (Fig. 3). Then, small changes in external conditions (installation vibrations) can render a situation described above.

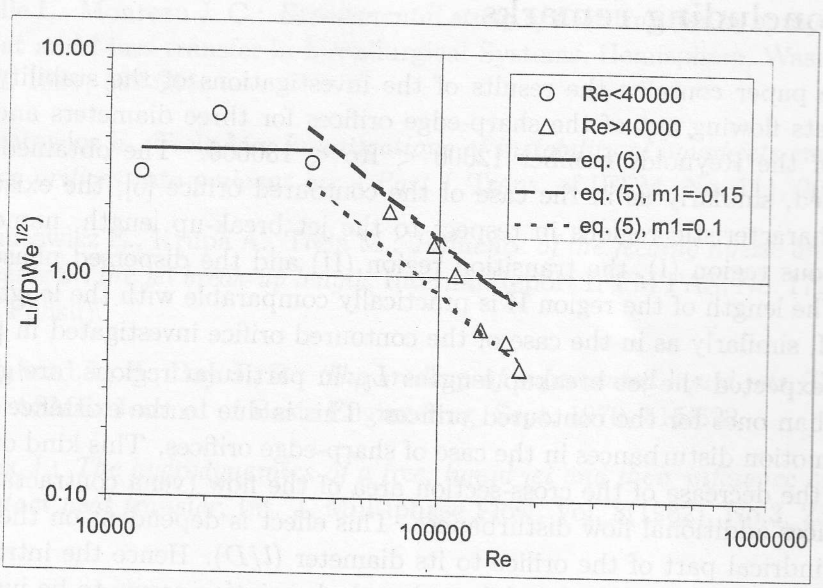

Figure 10. Experimental and calculated values of the jet length L_I for $D = 9.5$ mm.

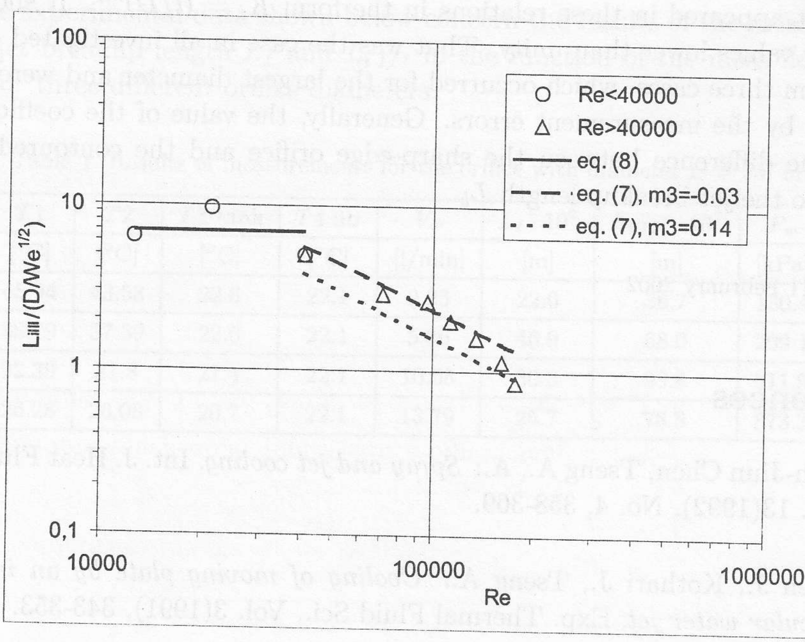

Figure 11. Experimental and calculated values of the jet length $L_{i\ III}$ for $D = 9.5$ mm.

3 Concluding remarks

The paper contains the results of the investigations of the stability of the liquid jets flowing out of the sharp-edge orifices for three diameters and in the range of the Reynolds number $12000 < \mathrm{Re} < 180000$. The obtained results confirmed, similarly as in the case of the contoured orifice [5], the existence of three characteristic regions in respect to the jet break-up length, namely: the continuous region (I), the transition region (II) and the dispersed phase region (III). The length of the region II is practically comparable with the length of the region I, similarly as in the case of the contoured orifice investigated in [5].

As expected the jet breakup lengths L_b, in particular regions, are generally lower than ones for the contoured orifices. This is due to the existence of additional motion disturbances in the case of sharp-edge orifices. This kind of orifices causes the decrease of the cross-section area of the flow (vena contracta), which introduces additional flow disturbances. This effect is dependent on the ratio of the cylindrical part of the orifice to its diameter (l/D). Hence the introduction of the ratio (l/D) into the breakdown length description seems to be justified.

Based on the obtained results, the Eqs. (5), (6), (7) and (8) have been proposed, which describe the jet break-up length for regions I and III. The correction coefficient appeared in these relations in the form $K_i = (l/D)^{m_i}$. It should assume the values lower than unity. That was the case in all investigated orifices, apart from three cases, which occurred for the largest diameter and were caused probably by the measurement errors. Generally, the value of the coefficient K_i reflect the difference between the sharp-edge orifice and the contoured one in respect to the jet breakup length L_b.

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Appendix

The experimental data shown below concern the results of the measurements of the jet breakup length L_I and $L_{i\ III}$ in the function of the mass flow rate of water for three different orifice diameters.

Table 1. Results of measurements for the orifice with diameter $D = 3.5$ mm

Lp.	$T1$ [°C]	$T2$ [°C]	$T3$ tank [°C]	$T4$ air [°C]	V_w [l/min]	$L_I \cdot 10^2$ [m]	$L_{i\ III} \cdot 10^2$ [m]	P_w [kPa]	P_{bar} [kPa]
1	45.94	43.58	22.8	22.1	2.23	22.6	36.7	130.4	101
2	38.79	37.39	22.6	22.1	5.06	46.9	68.0	209.1	101
3	32.39	31.8	21.4	22.1	10.05	30.3	93.8	511.9	101
4	26.28	26.08	20.7	22.1	13.79	25.7	78.8	873.3	101

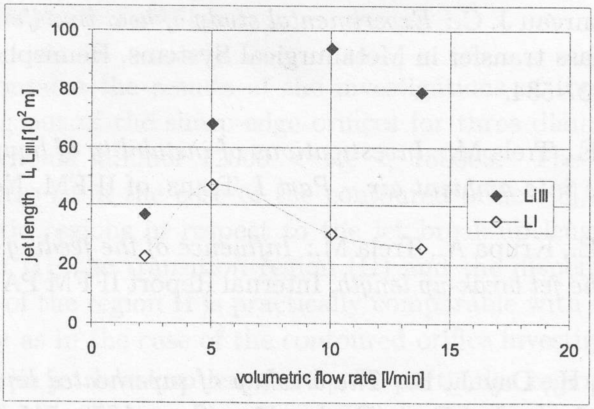

Figure A1. Variation of the jet beak-up lengths L_I and $L_{i\ III}$ versus the flow rate for $D = 3.5$ mm nozzle.

Table 2. Results of measurements for the orifice with diameter $D = 6.0$ mm

Lp.	$T1$	$T2$	$T3$ tank	$T4$ air	V_w	$L_I \cdot 10^2$	$L_{i\ III} \cdot 10^2$	P_w	P_{bar}
	[°C]	[°C]	[°C]	[°C]	[l/min]	[m]	[m]	[kPa]	[kPa]
1	48.7	46.26	24.9	21.5	2.43	21.1	45.1	110.5	101.1
2	42.91	42.19	24.5	21.5	5.5	51.7	86.7	120.2	101.1
3	37.21	37.19	24.3	21.5	10.5	64.2	96.9	151.9	101.1
4	33.22	33.26	24.1	21.5	15.12	67.9	116	199.9	101.1
5	30.31	30.26	24	21.5	20.22	65.6	140.4	272.8	101.1
6	27.09	27.03	21.9	21.5	30.62	43.4	118.3	489.7	101.1
7	23.76	23.73	21.2	21.5	40.28	49.3	118.4	769.8	101.1

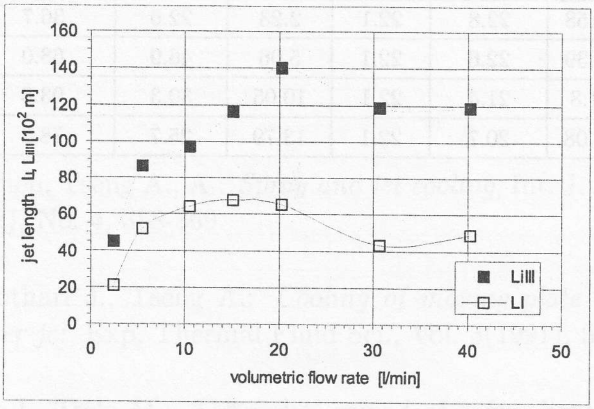

Figure A2. Variation of the jet beak-up lengths L_I and $L_{i\ III}$ versus the flow rate for $D = 6.0$ mm nozzle.

Table 3. Results of measurements for the orifice with diameter $D = 9.5$ mm

Lp.	$T1$ [°C]	$T2$ [°C]	$T3$ tank [°C]	$T4$ air [°C]	V_w [l/min]	$L_I \cdot 10^2$ [m]	$L_{i\,III} \cdot 10^2$ [m]	P_w [kPa]	P_{bar} [kPa]
1	62.09	60.25	29	22.1	2.64	20	44.9	108.6	99.12
2	50.7	49.83	31.2	22.1	5.31	73	132.5	109.5	99.12
3	44.42	44.37	33	22.1	11.16	92.2	145.3	115.5	99.12
4	40.19	40.73	34.2	22.1	20.57	104.3	156.1	134.2	99.12
5	36.24	36.44	30	22.1	30.37	108.8	207.3	164.6	99.12
6	29.61	29.79	28	22.1	40.67	108.3	209.3	213.8	99.12
7	27.88	27.77	25	22.1	50.85	76.7	207.3	273	99.12
8	27.3	27.24	22	22.1	61.44	81.3	180.3	356.3	99.12
9	22.35	22.04	20.5	22.1	75.84	75	166.8	481.9	99.12

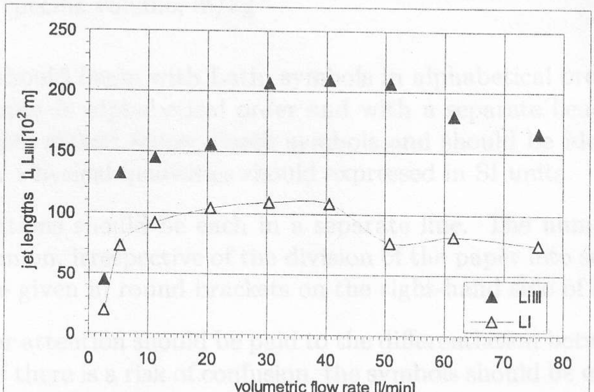

Figure A3. Variation of the jet beak-up lengths L_I and $L_{i\,III}$ versus the flow rate for $D = 9.5$ mm nozzle.

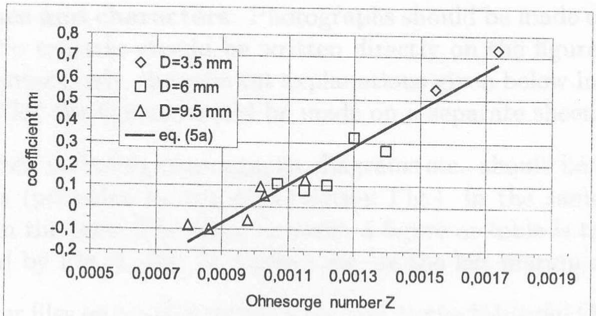

Figure A4. Dependence of the exponent m_1 on the Ohnesorge number for three considered diameters.

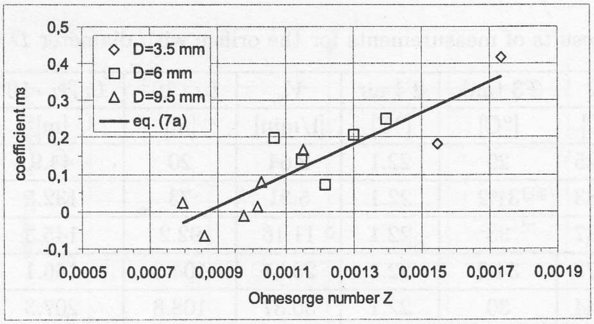

Figure A5. Dependence of the exponent m_3 on the Ohnesorge number for three considered diameters.