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THE INFLUENCE OF SURFACE TENSION ON LIQUID ATOMIZATION

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The function of surface tension during liquid atomization has not been thoroughly investigated and the existing data on this problem are contradictory. The aim of this paper is to present the effect of surface tension on macro- and microscale parameters of an atomized jet. Experiments were carried out using two types of liquid with considerably different surface tension but of the same density and viscosity. To this aim a simple swirl atomizer was used in experiments while the average axial velocity of the liquid outflow was of the order of some scores of metres per second. It has been shown that as surface tension decreases, the radial distribution of density of droplets evidently changes. It has been also proved that surface tension does not effect the atomization spectrum.

NOTATIONS

C	solution concentration,
d	diameter of the drop,
$f_v(d)$	density of probability,
G	mass flow rate,
H	distance from the atomizer outlet,
H_0	non-parametric hypothesis,
Δp	pressure drop,
q	density of droplet distribution,
$\Delta\bar{v}_i$	volume part of droplets,
2α	angle of the swirl cone (spray angle),
Δn_i, Δn_{it}	number of droplets in subset (real and theoretical),
σ	surface tension,
$\varphi_n(d)$, $\varphi_{nt}(d)$	distribution function of number part of droplets (real and theoretical)
$\varphi_v(d)$	distribution function of volume part of droplets,
χ^2	significance test,
χ^2_q	agreement measure.

1. INTRODUCTION

The influence of surface tension on liquid atomization has not been thoroughly investigated. There is no information concerning the effect of surface tension either on the macro- or on the microscale parameters of the atomized jet. Only data exist for the influence of surface tension on mean diameters of droplets; however, those are ambiguous and even contradictory.

The aim of this paper is to present experimental results of studies on the effect of surface tension on the macro- and microscale parameters of the atomized jet in the case of a swirl atomizer. The swirl atomizer was chosen because of its wide application. The results of experiments constitute a new approach to the function of surface tension in the process of liquid atomization.

2. THE CHOICE OF THE LIQUID AND ATOMIZER TYPE

In order to define the function of surface tension, at least two liquids should be chosen. Those liquids should considerably differ in their surface tension but should be of the same density and viscosity. This condition is fulfilled by water and an aqueous solution of Rokafenol N-8. Rokafenol N-8 is a surface — non-active and non-ionic means showing also Newton's liquid characteristics. This is the basic ingredient of liquid detergents. The surface tension of the solution of Rokafenol N-8 in distilled water at temperature 20°C varies from $\sigma=72.9\cdot10^{-3}$ N/m for water to $\sigma=32.7\cdot10^{-3}$ N/m for the solution concentration $C=0.05$ g/l. Above this concentration surface tension does not practically change. Then, the change range of surface tension is from 100% to 45%.

Surface tension has been determined by means of Lecomte du Noüya's ring method (tensiometer, Krüss manufactured, type — K 8600 E/E). The operation of this apparatus consists in measuring the force necessary to deform the liquid surface by means of a metal ring with the tolerance $0.05\cdot10^{-3}$ N/m (0,05 dyn/cm).

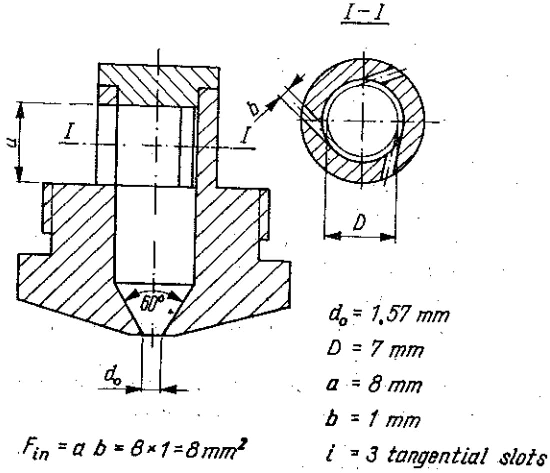

FIG. 1. Basic dimensions of the atomizer [6].

In order to carry out the experiment, an ordinary swirl atomizer was chosen (Fig. 1) with the geometrical constant A [7]

$$A=\frac{\pi D d_0}{4iF_{in}}=\frac{\pi\cdot7\cdot1{,}57}{4\cdot3\cdot8}\approx0.36.$$

The experiments were carried out while the pressure drop was $\Delta p<1.5$ bar, e.g. the drop $\Delta p=1{,}47$ bar corresponded to the mass flow rate $G=0.0222$ kg/s. The mean outflow velocity of liquid, in these conditions, was of the order 17 m/s. The spray angle was $2\alpha=58°$ [6].

3. THE EFFECT OF SURFACE TENSION ON MACROSCALE PARAMETERS

The macroscale parameters are connected with the general properties of the atomized jet. The macroscale parameters include: flow rate G, spray angle 2α and density of droplet distribution q. It has been found that surface tension influences only the density of droplet distribution.

The density of droplet distribution is an elementary flow rate of the field element lying in the plane perpendicular to the atomizer axis

$$q = \frac{\Delta G}{\Delta F}\left[\frac{\text{kg/s}}{\text{m}^2}\right].$$

The density of droplet distribution may be discussed in the radial, circular and axial directions. Radial distribution of the density of droplet $q_r = f(r)$ is a parameter characterizing the type of atomizer. Circular distribution $q_\varphi = f(\varphi)$ is a quality measure of the atomizer. A well-made non-polluted atomizer should show $q_\varphi =$

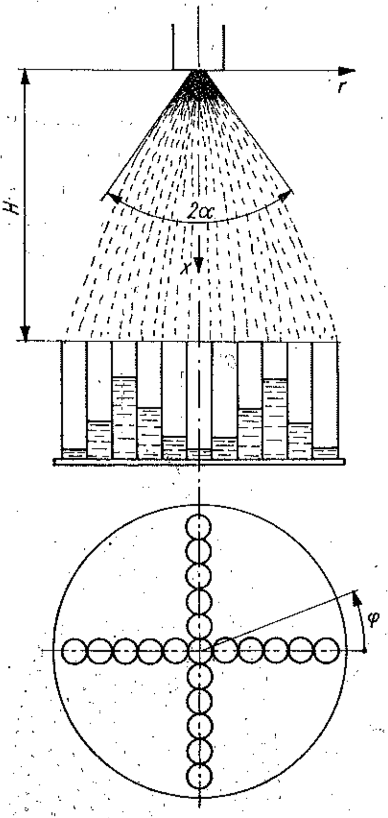

FIG. 2. Measurement of the radial density of droplet distribution, q_r.

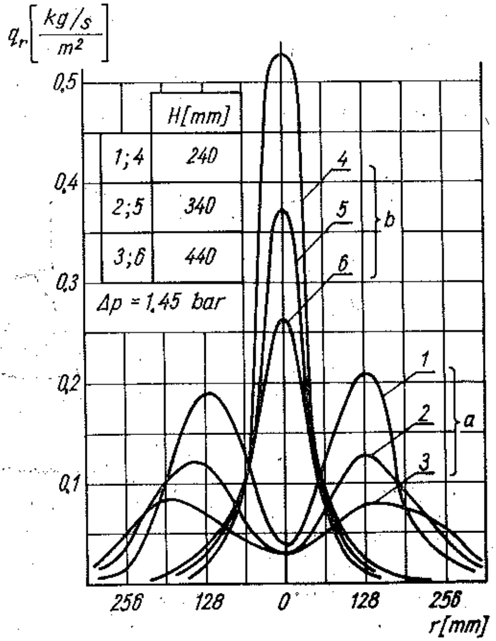

FIG. 3. Radial arrangement of density of droplet distribution, q_r, for different distances H: a) — distilled water ($\sigma = 72.6 \cdot 10^{-3}$ N/m), b) — aqueous solution of Rokafenol N-8 of concentration $C = 0.1$ g/l ($\sigma = 32.6 \cdot 10^{-3}$ N/m) [6].

=const. Axial distribution $q_x=f(x)$ is less important because it may be substituted by the distributions q_r and q_φ.

Figure 2 shows the measurement of circular distribution q_r by collecting the atomized liquid into vertical vessels. The liquid level in the vessels presents a typical distribution for swirl atomizers. This distribution lacks similarity in particular sections lying at a different distance H.

While measurements were performed it was found that surface tension had a considerable effect on the radial distribution q_r. This influence is so great that it causes a complete change of the distribution character; this has been shown on Fig. 3.

The distribution, typical of swirl atomizers (curves 1, 2, 3), is transformed into a completely different distribution (curves 4, 5, 6). This process is accompanied by a simultaneous lowering of surface tension. The latter distribution is typical of jet atomizers and shows the highest density in the axis of the atomizer; moreover it is also characterized by mutal similarity.

4. THE EFFECT OF SURFACE TENSION ON MICROSCALE PARAMETERS

4.1. The present state of knowledge

In the case of swirl atomizers there are three typical processes of liquid film disintegration depending on the outflow velocity (Fig. 4). At low outflow velocity of the order of some metres per second, the liquid film undergoes perforation (Fig. 4a), while the liquid forms a network of thin jets which, because of the loss of stability, break into droplets. At higher velocity the film breaks into rings because of the loss stability caused by tangent aerodynamic forces (Fig. 4b), while the rings break

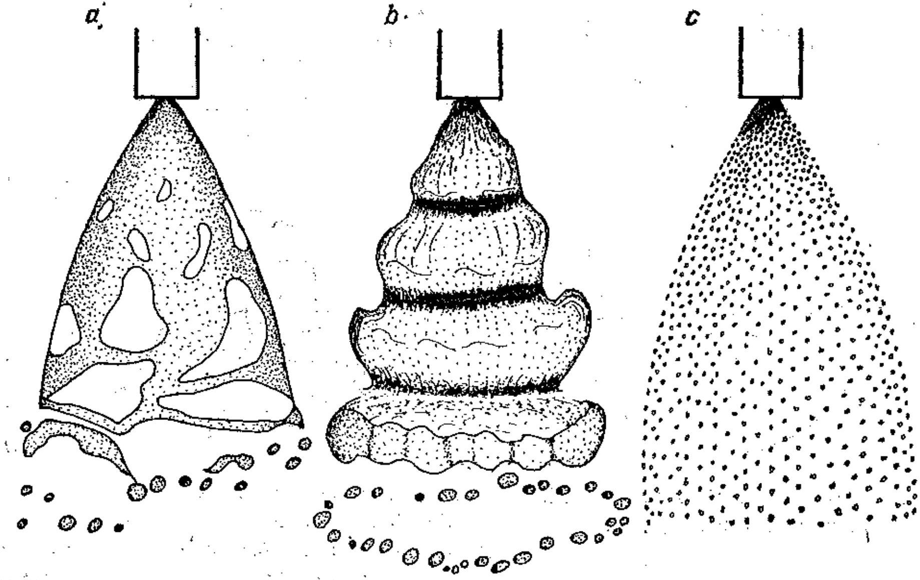

FIG. 4. Typical cases of breakdown at different velocity of outflow from the swirl atomizer.

into droplets under the influence of surface tension. Such is the case since aerodynamic forces have then a direction normal to the ring and do not lead to the loss of its stability [9]. In both cases (Figs. 4a, b) dimensions of droplets, according to Rayleigh's theory, should depend on surface tension. At a velocity of the order of some scores of metres per second the film breakdown occurs directly on the atomizer output; this is caused by high aerodynamic forces (Fig. 4c). Thus the effect of surface tension should decrease or disappear.

In the paper [3] it has been proved in an analytical way that a decrease of surface tension, similarly to an increase of outflow velocity (increase of Δp), broadens the contour of the initial non-atomized part of a jet. Hence the conclusion has been drawn that a decrease of surface tension, similarly to an increase of Δp drop, effects a decrease of droplet dimensions.

There are criterion and dimension equations to calculate the mean diameter of droplets. In the paper [1] the dependence $d \sim \sigma^{0,1}$ was given which had been established for water and an aqueous solution of glycerol, recommending to use it also for liquid fuels where d is the virtually undefined mean diameter of droplets. In the paper [8] the dependence for liquid fuels was given; it thus follows that $d_s \sim \sigma^{0,6}$ where d_s is the mean Sauter's diameter. In the paper [2] after experimental results of many authors had been analysed, the dependence for water and aqueous solutions of glycerol was obtained, $d_m \sim \sigma^{-0,11}$, and for kerosene, $d_m \sim \sigma^{-0.07}$, where d_m is a diameter of droplets, the so-called median. There are also some other dependences reflecting the effect of surface tension [4] etc. All these dependences are incomparable and largely divergent.

4.2. Types of microscale parameters

The effect of surface tension on the structure of atomization may be evaluated in a proper way by means of appropriate parameters of the spray spectrum because only the spray spectrum contains full statisitc information concerning the behaviour of a variable which, in this case, is the diameter of droplets, d. The spray spectrum is an experimental step diagram presenting quantity, surface of volume (mass) part of droplets in the diameter range $\langle d_i - \frac{\Delta d_i}{2}, d_i + \frac{\Delta d_i}{2} \rangle$. Probability density and the distribution function are typical values of the spectrum, e.g. probability density of the volume part of the variable d is a function in which the volume part of the droplets $\Delta \bar{v}_i$ refers to the interval value Δd_i

$$f_v(d) = \frac{\Delta \bar{v}_i}{\Delta d_i}.$$

The distribution function of the volume part is a function which presents the volume part of droplets with diameters smaller than d in the summarical volume of all the droplets

$$\varphi_v(d) = 100 \sum \Delta \bar{v}_i \ [\%].$$

Step curves are approximated by means of theoretical equations. One of the most frequently used is the Rosin-Rammler equation

$$1-v=e^{-\left(\frac{d}{\bar{d}}\right)^{\delta}},$$

where $(1-v)$ — volume part of droplets with a diameter larger than d, $\bar{d}$ — dimension parameter which means that 63.2% of droplets have a diameter smaller than $\bar{d}$, δ — distribution parameter.

From the point of view of practice we often use not the whole spectrum but only some of its parameters such as concentration size (conventional diameters of droplets), dispersion size and skewness size of distribution. All these parameters, as individual values, do not characterize, however, the atomization spectrum in a proper way.

4.3. Measurement results and their estimation

In order to determine the quantity and diameters of droplets in the atomized jet a microphotographic method was used, the so-called method of optical separation of droplets [5]. This method enables one to make a selective recording of droplets in a known volume (Fig. 5) since all droplets in this volume have characteristic reflections from the side light.

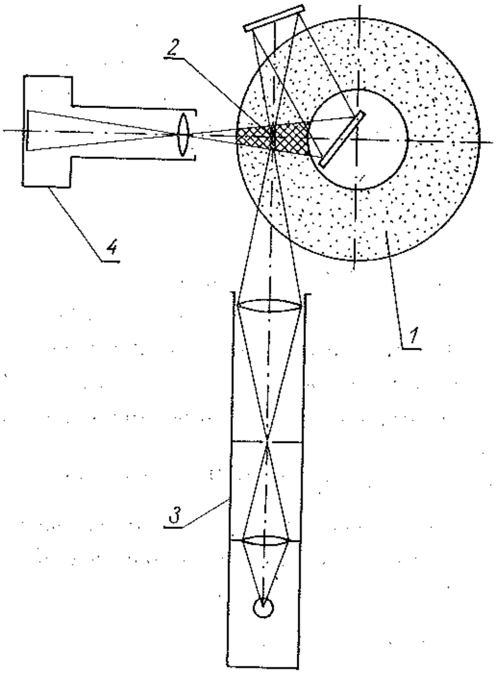

FIG. 5. Scheme of measurement system: 1 — cross section of atomized jet, 2 — volume separated, 3 — spark-gap generator, 4 — camera.

Pictures of droplets were taken in a selected measurement section at the distance $H=70$ mm. Droplet diameters magnified 50-times were measured with a gauge on a screen. As a result, atomization spectra were made. The range of the measured diameters of droplets was $10 \div 400$ μm.

Figure 6 presents exemplary complete results in the form of probability density and the distribution function of the volume part of the atomization spectra of water and aqueous solutions of Rokafenol N-8. Step diagrams were approximated by means of fair curves according to the Rosin-Rammler distribution where $\bar{d}=275.6 \div 312$ μm, $\delta=2.74$.. Results for water and aqueous solutions of Rokafenol N-8 are arranged along the same curves while the results concerning the curve 1 show normal, in such conditions, scatter; however, this scatter does not follow from the influence of surface tension. As it has been proved, surface tension does not effect the atomization spectrum of droplets produced by means of the swirl atomizer.

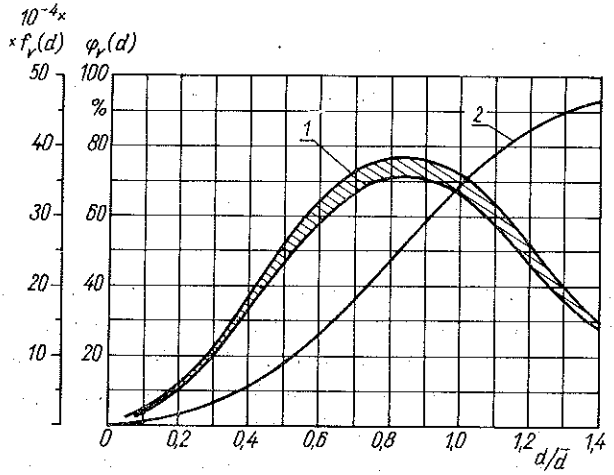

FIG. 6. Volume distribution (mass): 1 — probability density $f_v(d)$, 2 — dsitribution function $\varphi_v(d)$

4.4. *Estimation of results by means of a statistical method*

The results of jet spectrum investigations have been achieved from measurements of droplet parts called "sample" occurring in the assumed jet section. The minimum sample size has been calculated assuming a group, unlimited and dependent method of sampling, and assuming that the value of estimation error (difference between the estimation and the real value) equals to the triple standard deviation of the sample mean. In order to carry out sampling, random numbers have been used.

On this basis, dispersion spectrum estimation in the whole jet section was made using estimation of the distribution function and verification of the statistical hypothesis; this deals with the rightness of choice of theoretical distribution to the empirical one.

The function estimation of distribution of the variable d (d-droplet diameter) in population (in the whole section) was made by means of an interval method [10]. In this method the interval (interval limits a_1 and a_2) of the empirical distribution function $\varphi_n(d)$ in which, with probability $1-\alpha$, the distribution function of general population $\varphi_{nt}(d)$ is contained:

$$P(a_1 < \varphi_{nt}(d) < a_2) = 1-\alpha. \tag{4.1}$$

The biggest difference $|\varphi_n(d) - \varphi_{nt}(d)|$ for all values d, forms a new random variable D_n:

$$D_n = \max |\varphi_n(d) - \varphi_{nt}(d)|. \tag{4.2}$$

This is the random variable which has a distribution independent of $\varphi_{nt}(d)$. Therefore such a critical value may be determined at which the following equality is satisfied:

$$P(D_n \leqslant \lambda_\alpha) = 1 - \alpha . \tag{4.3}$$

Using Eq. (4.2) we obtain

$$P\{\max_d |\varphi_n(d) - \varphi_{nt}(d)| \leqslant \lambda_\alpha\} = 1 - \alpha \tag{4.4}$$

hence,

$$P\{\varphi_n(d) - \lambda_\alpha < \varphi_{nt}(d) < \varphi_n(d) + \lambda_\alpha\} = 1 - \alpha \tag{4.5}$$

for each d.

Equation (4.5) is defined by the confidence interval which, with probability $1-\alpha = 0.95$ (for $\alpha = 0.05$ from tables [11] $\lambda_\alpha = 0.134$ has been obtained), covers the distribution function $\varphi_{nt}(d)$ of general population. In other words, with probability 0.95, the function $\varphi_{nt}(d)$, i.e. the distribution function of general population is contained in the achieved confidence interval.

Then the estimation of the dispersion spectrum in the whole jet section was carried out using non-parametric hypothesis H_0 verification by means of the significance test χ^2. The hypothesis H_0 assumes that the unknown distribution hypothetical function $\varphi_{nt}(d)$ of the quantitative distribution of the variable d in general population has the form of the Rosin-Rammler distribution function and agrees with the empirical distribution function $\varphi_n(d)$ obtained from the sample, i.e.

$$H_0\colon \varphi_{nt}(d) = \varphi_n(d) . \tag{4.6}$$

Therefore, the droplet set obtained from the sample was divided into r disjunctive subsets defined by diameter intervals $\langle d_i, d_{i+1} \rangle$ and for each subset Δn_i of droplets was fixed. Treating the hypothetical distribution in a similar way, Δn_{it} of droplets was defined. The agreement measure χ_q^2 of empirical distribution with the theoretical one is determined by the formula

$$\chi_q^2 = \sum_{i=1}^{i=r} \frac{(\Delta n_i - \Delta n_{it})^2}{\Delta n_{it}} . \tag{4.7}$$

This is the statistics which has such a property that at $n \to \infty$ the expression (4.7) tends to the distribution χ^2 with the number of freedom degrees $v = r - m - i$ (r-number of subsets, m-number of parameters).

Verification of the hypothesis is reduced to the comparison of values χ_q^2 calculated from the formula (4.7) and the values χ^2 read out from the tables for v degrees of freedom on the assumed significance level α.

It has been found, for the measurement results, that on the significance level $\alpha = 0.01$ there is $\chi_q^2 < \chi^2$, which indicates that the hypothesis, under verification, on the assumed significance level need not be rejected. On this basis a conclusion may be drawn that the Rosin-Rammler distribution approximates well the empirical distribution.

5. CONCLUSIONS

Experiments carried out on one swirl atomizer at one average axial velocity of the liquid outflow about 17 m/s. The results of the experiments have shown the considerable effect of surface tension on the radial distribution of density of droplets as well as on the shape of jet contour and have proved a complete lack of influence on the atomization spectrum. Liquid breakdown during experiments was just in between the breakdowns shown on Figs. 4b, c. Hence a conclusion may be drawn that in an important, from the technical point of view, atomization process (Fig. 4c), forces of surface tension do not effect completely droplet dimensions.

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STRESZCZENIE

ROLA NAPIĘCIA POWIERZCHNIOWEGO W PROCESIE ROZPYLANIA CIECZY

Rola napięcia powierzchniowego podczas rozpylania cieczy jest mało zbadana, a istniejące informacje na ten temat są na ogół sprzeczne. Celem artykułu jest przedstawienie wpływu napięcia powierzchniowego na parametry makro- i mikroskopowe rozpylonej strugi. W tym celu wykonano badania przy użyciu dwóch cieczy o bardzo różniącym się napięciu powierzchniowym, lecz o tej samej gęstości i lepkości. Do badań użyto prostego rozpylacza wirowego przy średniej osiowej prędkości wypływu cieczy rzędu kilkunastu metrów na sekundę. Wykazano, że wraz ze zmniejszeniem napięcia powierzchniowego zmienia się znacznie promieniowy rozkład gęstości zraszania. Wykazano również, że napięcie powierzchniowe nie ma wpływu na widmo rozpylenia.

Резюме

РОЛЬ ПОВЕРХНОСТНОГО НАТЯЖЕНИЯ В ПРОЦЕССЕ РАСПЫЛЕНИЯ ЖИДКОСТИ

Роль поверхностного натяжения во время распыления жидкости мало исследована; существующие информации на эту тему в общем противоречивы. Целью статьи является представление влияния поверхностного натяжения на макро- и микроскопические параметры распыленной струи. С этой целью проведены исследования при использовании двух жидкостей с очень отличающимися поверхностными натяжениями, но с теми же самыми плотностью и вязкостью. Для исследований использован простой центробежный распылитель при средней осевой скорости истечения жидкости порядка от 10 до 20 м/с. Показано что совместно с уменьшением поверхностного натяжения значительно изменяется радиальное распределение плотности орошения. Показано тоже, что поверхностные натяжение не имеет влияния на спектр распыления.

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