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Razpad ploščatega tekočega curka**Disintegration of Flat Liquid Jets**

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V prispevku je analitično obravnavan razpad ploščatega curka oziloma ploščatih lamel, ki nastanejo pri razprševanju s ploščatimi tlačnimi šobami. Izstopna odprtina ploščatih šob ima eliptično obliko. V primerjavi s centrifugalnimi tlačnimi šobami so ploščate šobe energijsko ugodnejše, samočistilne, curek pa stabilnejši. Uporabnost šob s ploščatim curkom je lahko vsestranska na različnih področjih procesnega strojništva. Izhodiščna teorija je povzeta po delu [1]. Na podlagi dopolnjene matematične modela smo opravili nekaj tipičnih simulacij za različne hidrodinamične pogoje ter snovne lastnosti razpršene kapljevine in obdajajočega plina.

This paper presents an analysis of disintegration of flat liquid jets or flat liquid sheets, which are produced by atomization of liquid with flat pressure nozzles. The orifice nozzle has an elliptical form. These nozzles are better in terms of energy than centrifugal pressure nozzles. Flat pressure nozzles are self-purifying and produce more stable flat jets. In many applications in the process engineering, flat pressure nozzles can be used. The theoretical basis is taken from literature [1]. On the basis of mathematical model, some typical simulations for different hydrodynamic conditions and different thermophysical properties of atomized liquid in co-flowing gas are made.

0. UVOD

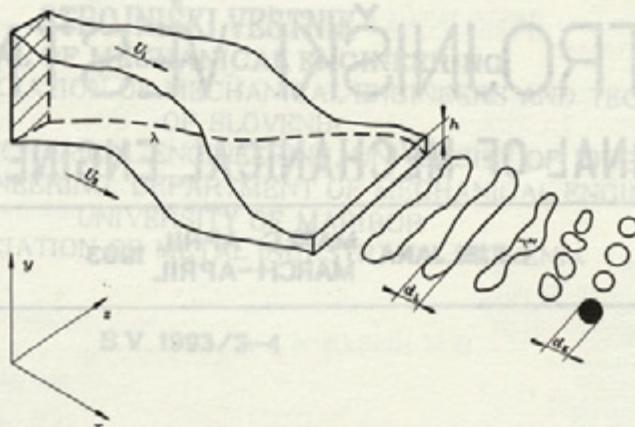
V prispevku bomo podrobneje analizirali razpad ploščatega curka. Teorijo razpada smo delno povzeli po viru [1].

Slika 1 shematično prikazuje razpad ploščatega curka. Na površini gladke lamele se pojavi valovanje zaradi aerodinamičnih vplivov. Vzvalovane lamele nastanejo pri manj viskoznih kapljevinah. Na prostem robu se vzvalovana lamela trga na vezl, katerih širina je pred kontrakcijo enaka polovici valovne dolžine motnje. Vezi zatem razpadajo na kapljice. Pri razpadu nastanejo kapljice različnih velikosti. Spekter kapljic lahko nadomestimo z enotnim srednjim premerom kapljic. Pri razprševanju je to Sauterjev premer kapljic. Pregled razprševanja tekočin najdemo tudi v [2] in [3].

0. INTRODUCTION

In this paper we will analyse in detail the disintegration of flat liquid jet. The theoretical basis is summarized from the paper [1].

The disintegration of a flat liquid jet is shown schematically in Fig. 1. On the surface of the flat sheet waves are induced because of aerodynamical influences. Undulating sheets occur with less viscous liquids. Undulating sheets break-up into ligaments on the edge. Before the contraction, the width of ligaments is equal to one half of the wave length of the disturbance. After disintegration, droplets of different sizes are produced. Droplet size distribution can be replaced with Sauter mean diameter. The review of the literature on this subject can also be found in [2] and [3].



Sl. 1. Poenostavljen prikaz razpada ploščatega curka [1].

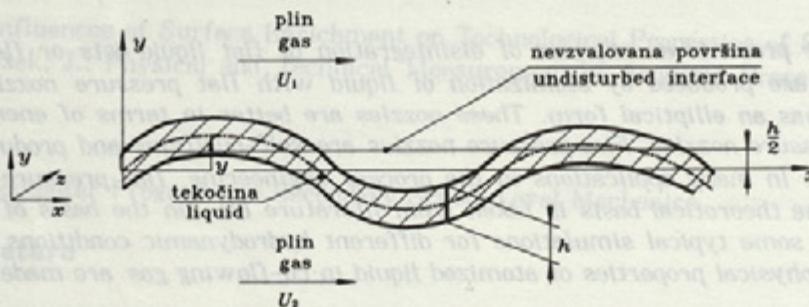
Fig. 1. Schematic representation of disintegration of flat liquid jet. [1].

Features**1. MATEMATIČNI MODEL**

Podrobneje bomo predstavili razpad ploščate lamele, ki se oblikuje pri razprševanju kapljivite faze s ploščatimi tlaknimi šobami v prostor, napolnjen s plinom.

1.1 Razpad ploščate lamele

Fizikalni in matematični model oziroma teoretična izhodišča povzemamo po [1]. Na sliki 2 je prikazan prečni prerez vzvalovane lamele.



Sl. 2. Prečni prerez vzvalovane lamele [1].

Fig. 2. Side view of undulating flat sheet. [1].

Poglavitne predpostavke modela so:

- tekoča lamela se giblje v smeri x skozi plin, ki se nahaja v stacionarnem stanju. Njena srednja hitrost je enaka korenki srednji kvadratični vrednosti: $U = 0,5 \sqrt{U_1^2 + U_2^2}$, kjer sta U_1 hitrost zgornje površine lamele in U_2 hitrost spodnje površine lamele;

- gibalno enačbo neutralne osi, ki je v sredini med dvema plinsko kapljivitima mejnima površinama, dobimo na podlagi ravnotežja sil. Pri tem smo upoštevali sile, ki imajo velik vpliv na razpad lamele: tlakne sile F_p , sile površinske napetosti F_σ , vztrajnostne sile F_{vz} in viskozne sile $F_{\mu K}$;
- za neutralno os dolžine lamele dx velja naslednje ravnotežje sil:

In the continuation, the disintegration of flat liquid sheet, which occurs in the atomization of liquids with flat pressure nozzles in the gas ambient, will be presented in detail.

1.1 Disintegration of liquid sheets

The theoretical and mathematical model and the theoretical basis are taken from [1]. In Fig. 2, the side view of undulating flat sheet is shown.

The basic assumptions of the model are:

- a liquid sheet is moving in direction x through the stationary gas with mean velocity U , which is equal to the square root of the mean value: $U = 0,5 \sqrt{U_1^2 + U_2^2}$, where U_1 is the velocity of the upper and U_2 of lower sheet surface, respectively;

- momentum equation of the neutral axis midway between the two gas liquid interfaces is obtained from the statement of balance forces. We take into account forces, which have significant influences on the disintegration process: pressure forces F_p , surface tension forces F_σ , inertial forces F_{vz} and viscosity forces $F_{\mu K}$;

- the total force on the neutral axis with length dx is:

$$F_p + F_\sigma + F_{vz} + F_{\mu_K} = 2\rho n U^2 y z dx + 2\sigma \frac{\partial^2 y}{\partial x^2} z dx - \rho_K \left(h \frac{\partial^2 y}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial y}{\partial t} \right) z dx + \mu_K h \frac{\partial^3 y}{\partial t \partial x^2} z dx = 0 \quad (1)$$

kjer je h debelina lamele, ρ_K gostota kapljevine, ρ gostota plinaste faze, n valovno število lamele, μ_K dinamična viskoznost kapljevine in σ površinska napetost. Po krajšanju z $yzdx$ lahko enačbo (1) zapišemo:

$$2\rho n U^2 y + 2\sigma \frac{\partial^2 y}{\partial x^2} - \rho_K \left(h \frac{\partial^2 y}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial y}{\partial t} \right) + \mu_K h \frac{\partial^3 y}{\partial t \partial x^2} = 0 \quad (2)$$

Te sile delujejo le prečno na smer toka:

- zaradi delovanja aerodinamičnih sil se na površini lamele pojavi motnja $y = y(t, x)$, ki se spreminja s časom t in krajem x . Funkcija $y = y(t, x)$ je rešitev parcialne diferencialne enačbe (1) in prikazuje prečni odmik lamele od nevtralne osi;
- za motnjo predpostavimo, da se sinusno spreminja:

where h is sheet thickness, ρ_K is liquid density, ρ is gas density, n is wave number of the sheet, μ_K is dynamic liquid viscosity and σ is surface tension, respectively. If eq. (1) is divided by $yzdx$, then:

These forces cause movement only in the y direction:

– because of aerodynamical influences on the sheet surface, disturbance $y = y(t, x)$ emerges, which varies with time t and location x . Function $y = y(t, x)$ is a solution of partial differential equation (1), which shows movement away from neutral axis in the transverse direction;

– a sine wave motion for a disturbance is assumed:

$$y = T(t) \sin(nx + \varepsilon) \quad (3)$$

kjer je $T(t)$ amplituda motnje in ε fazni premik. Če predpostavimo, da se amplituda motnje eksponentno spreminja s časom, lahko (3) zapišemo tudi:

$$y = T_0 \exp[f(t)] \sin(nx + \varepsilon) \quad (4)$$

kjer pomeni funkcija $\exp[f(t)]$ razmerje med amplitudo motnje $T(t)$ in amplitudo začetne motnje T_0 .

Enačba (1) je homogena parcialna diferencialna enačba. Njena splošna rešitev je vsota pomikov lamele v prečni smeri, ki jih povzročijo motnje različnih valovnih števil n in začetnih amplitud T_0 :

$$y = \sum T_0 \exp[f(t)] \sin(nx + \varepsilon) \quad (5)$$

Razpad kapljevitih lamele povzroči valovi, ki imajo enako valovno dolžino kakor val z največjo rastjo valov. Valu z maksimalno rastjo pravimo tudi dominantni val. Možno je lahko, da dominantni val nima maksimalne rasti v času njegovega trajanja oziroma obstoja.

Z upoštevanjem (4) zapišemo (2) kot:

$$2\rho n U^2 - 2\sigma n^2 - \rho_K \left[h \left(\frac{\partial f}{\partial t} \right)^2 + h \frac{\partial^2 f}{\partial t^2} + \frac{\partial h}{\partial t} \frac{\partial f}{\partial t} \right] - \mu_K h n^2 \frac{\partial f}{\partial t} = 0 \quad (6)$$

where function $\exp[f(t)]$ is the ratio of amplitude $T(t)$ to initial amplitude T_0 .

Equation (1) is a homogeneous partial differential equation. Its general solution is the sum of the displacements in the transverse direction caused by disturbances with different wave numbers n and initial amplitudes T_0 :

Disintegration of the liquid sheet causes waves, which have the same wave number as the wave with maximum wave growth. This wave is also named »the dominant wave«. It is possible that it does not have maximum growth rate throughout its life.

Combining equations (2) and (4):

Na podlagi velikostne analize členov v (6) sta drugi in tretji člen v oglatem oklepaju zanemarljivi v primerjavi s prvim [1], zato ju lahko zanemarimo. Poenostavljen zapis (6) je sedaj:

$$(1) \quad 0 = \rho n U^2 - 2\sigma n^2 - \rho_K h \left(\frac{\partial f}{\partial t} \right)^2 - \mu_K h n^2 \frac{\partial f}{\partial t} = 0$$

Če v (7) upoštevamo definicijo razmerja rasti valov p :

$$p = \frac{\partial f}{\partial t} \quad (8)$$

je zapis (7) enak:

$$2\rho n U^2 - 2\sigma n^2 - \rho_K h p^2 - \mu_K h n^2 p = 0 \quad (9)$$

NEVISOZNA KAPLJEVINA

Za ta primer ($\mu_K = 0$) izhaja iz (9):

$$p = \frac{\partial f}{\partial t} = \sqrt{\frac{2}{\rho_K} (\rho U^2 n - \sigma n^2)} \frac{1}{h} \quad (10)$$

In po integraciji dobimo:

$$f = \sqrt{\frac{2}{\rho_K} (\rho U^2 n - \sigma n^2)} \int_0^t \frac{1}{\sqrt{h}} dt \quad (11)$$

Valovno število lamele n ima največjo rast valov pri ekstremu funkcije f . Iz pogoja za ekstrem funkcije $\partial f / \partial n = 0$, dobimo:

$$n_{\mu_K=0} = \frac{\rho U^2}{2\sigma} = n_{\text{maks}} \quad (12)$$

Če vstavimo enačbo (12) v (10) in (11), dobimo:

$$f_{\mu_K=0} = \frac{\rho U^2}{\sqrt{2\rho_K \sigma}} \int_0^t \frac{1}{\sqrt{h}} dt \quad (13)$$

In

$$\mu_{\mu_K=0} = \frac{\rho U^2}{\sqrt{2\rho_K \sigma}} \frac{1}{\sqrt{h}} \quad (14)$$

VISOZNA KAPLJEVINA

Valovno število

Valovno število viskozne lamele ($\mu_K > 0$) se za faktor N razlikuje od valovnega števila neviskozne lamele, ($N \leq 1$):

$$n_{\mu_K>0} = N n_{\mu_K=0} = N \frac{\rho U^2}{2\sigma} \quad (15)$$

On the basis of order analysis in (6), the second and third term in square brackets may be neglected compared to the first term [1]. Equation (6) can now be written:

If the definition of the wave growth rates p is considered in (7):

$$p = \frac{\partial f}{\partial t} \quad (8)$$

than (7) is equal to:

$$2\rho n U^2 - 2\sigma n^2 - \rho_K h p^2 - \mu_K h n^2 p = 0 \quad (9)$$

NON-VISCOUS LIQUID

For this case ($\mu_K = 0$), it follows from (9):

$$p = \frac{\partial f}{\partial t} = \sqrt{\frac{2}{\rho_K} (\rho U^2 n - \sigma n^2)} \frac{1}{h} \quad (10)$$

which by integration gives:

The wave number of the sheet n has maximum growth rate at the extreme of function f . Using the condition extreme $\partial f / \partial n = 0$:

Substituting (12) in (10) and (11), it follows:

and

$$f_{\mu_K=0} = \frac{\rho U^2}{\sqrt{2\rho_K \sigma}} \frac{1}{\sqrt{h}} \quad (14)$$

VISCOUS LIQUID

Wave number

Wave number of the viscous liquid sheet ($\mu_K > 0$) differs by factor N from wave number of the inviscid sheet, ($N \leq 1$):

Razmerje rasti valov P

Brezdimenzijsko razmerje rasti valov P je definirano kot razmerje med rastjo valov viskozne lamele p in neviskozne lamele (14):

$$P = p \frac{\sqrt{2h\rho_K\sigma}}{\rho U^2} \quad (16)$$

Celotna rast valov F

Brezdimenzijska celotna rast valov je razmerje med celotno rastjo valov viskozne in neviskozne kapljevine:

$$F = \frac{\int_0^t p_{\mu_K > 0} dt}{\int_0^t p_{\mu_K = 0} dt} = \frac{\int_0^t \frac{P\rho U^2}{\sqrt{2h\rho_K\sigma}} \frac{1}{\sqrt{h}} dt}{\int_0^t \frac{\rho U^2}{\sqrt{2h\rho_K\sigma}} \frac{1}{\sqrt{h}} dt} \quad (17)$$

Z upoštevanjem enačb (15), (16) in (17) lahko (9) zapišemo z brezdimenzijskimi parametri:

$$2N - N^2 - P^2 - VPN^2 = 0 \quad (18)$$

kjer je parameter V določen z (19):

$$V = \frac{\mu_K \rho U^2}{2} \sqrt{\frac{h}{2\sigma^3 \rho_K}} \quad (19)$$

Enačba (18) je veljavna za viskozno in neviskozno kapljivo lamelo.

1.2 Lamela spremenljive debeline h

V resnici se debelina lamele tanjša s časom. Predpostavimo lahko, da je debelina lamele nasprotno sorazmerna r -ti potenci časa in premo sorazmerna konstanti k :

$$h = \frac{k}{t^r} \quad (20)$$

V našem primeru predpostavimo, da je stopnja potence $r = 1$.

$$h = \frac{k}{t} \quad (21)$$

Iz enačbe (17) dobimo za lamelo spremenljive debeline naslednjo povezavo:

$$F = \frac{3}{2} t^{-3/2} \int_0^t Pt^{1/2} dt \quad (22)$$

Non-dimensional wave growth rate P

Non-dimensional wave growth rate P is defined as a ratio of wave growth rate of viscous sheet p to growth rate of inviscid sheet, (14):

Total growth ratio F

The total growth ratio F is the ratio of growth of the viscous liquid to growth of the inviscid liquid:

Combining equations (15), (16) and (17), (9) can be written with non-dimensional parameters:

where parameter V is defined by (19):

Equation (18) is valid for viscous and non-viscous liquid sheet.

1.2 Sheet with variable thickness h

In reality, the sheet attenuates with time. We assume that sheet thickness is in the inverse proportion to the r -power of time and in proportion to the constant k :

We assume in our case that the power r equals 1.

From (17) it follows for attenuating sheet:

Z upoštevanjem enačb (16), (18) in (22) sledi:

$$F = -\frac{3}{4} VN^2 + \frac{1}{2} \frac{1}{8N - 4N^2} \left[(V^2 N^4 + (8N - 4N^2))^{3/2} - V^3 N^6 \right] \quad (23)$$

Z odvajanjem enačbe (23) po N poiščemo ekstrem funkcije F . Takrat dobimo za val z maksimalno rastjo zvezo med parametrom V in N :

$$V = \frac{8}{3N} \frac{N-1}{(8N-4N^2)^2} \left[(V^2 N^4 + 8N - 4N^2)^{3/2} - V^3 N^6 \right] + \frac{1}{3N(8N-4N^2)} \left[\frac{3}{2} (V^2 N^4 + 8N - 4N^2)^{1/2} (4V^2 N^3 + 8 - 8N) - 6V^3 N^5 \right] \quad (24)$$

Za določen N lahko z iterativnim načinom reševanja najprej izračunamo parameter V po (24) in za tem parameter F po (23). Vrednosti izračunanih parametrov, zbrane v preglednici 1, se nekoliko razlikujejo od vrednosti v [1].

From equations (16), (18) and (22):

Differentiating (23) with respect to N and equating to zero, the following relation between parameters V and N is obtained for the wave with maximum growth rate F :

Parameter V (24) can be calculated iteratively for the typical value of the parameter N . Then parameter F can be calculated from (23). Values of the calculated parameters are included in Table 1 and differ slightly from the values in [1].

Preglednica 1: Vrednosti brezdimenzijskih parametrov N , V , F , $VF^{-1/3}$ in $F^{1/3}N^{-1/2}$.
Table 1: Calculated values of non-dimensional parameters: N , V , F , $VF^{-1/3}$ and $F^{1/3}N^{-1/2}$.

N	V	F	$VF^{-1/3}$	$F^{1/3}N^{-1/2}$
1.00	0.0000	1.0000	0.0000	1.0000
0.95	0.0363	0.9746	0.0366	1.0172
0.90	0.0793	0.9453	0.0507	1.0356
0.85	0.1305	0.9213	0.1341	1.0554
0.80	0.1917	0.8933	0.1991	1.0765
0.75	0.2656	0.8644	0.2785	1.1000
0.70	0.3554	0.8345	0.3775	1.1253
0.65	0.4658	0.8036	0.5010	1.1532
0.60	0.6032	0.7715	0.6577	1.1840
0.55	0.7767	0.7381	0.8595	1.2186
0.50	1.0000	0.7031	1.1246	1.2546
0.45	1.2935	0.6665	1.4509	1.3021
0.40	1.6903	0.6278	1.9740	1.3539
0.35	2.2453	0.5868	2.6820	1.4151
0.30	3.0576	0.5428	3.7483	1.4893
0.25	4.3205	0.4951	5.4615	1.5522
0.20	6.4606	0.4424	8.4787	1.7035
0.15	10.5995	0.3828	14.5950	1.8748
0.10	20.6760	0.3123	30.4751	2.1455
0.05	61.5952	0.2206	102.4306	2.7024

Z upoštevanjem enačb (16), (21) in (22) dobimo:

From equations (16), (21) and (22):

$$f = \frac{2}{3} F \rho U^2 \sqrt{\frac{t^3}{2\rho_k \sigma k}} \quad (25)$$

(19) Če vstavimo enačbo (21) v (19) in izrazimo čas iz (19) ter (23), dobimo funkcionalno zvezo parametrov:

(18)

$$VF^{-1/3} = \mu_K \sqrt{\frac{k\rho^4 U^8}{48f\rho_K \sigma^5}} \quad (26).$$

Povezavo med eksperimenti in teorijo določimo s pomočjo enačbe (26).

Določitev velikosti vezi

Na določeni razdalji od šobe razpade lamela širine $\lambda/2$ in debeline h na vezi, ki imajo valjasto obliko. To je tudi temeljna predpostavka Webrove teorije oziroma prilagojene Rayleighove teorije [4]. Premer nastalih vezi je enak:

$$d_L = \sqrt{\frac{4h}{n}} \quad (27).$$

Iz enačb (27) in (25) izrazimo debelinu lamele h :

(25)

$$h = kF^{2/3} \left[\frac{9f^2 \sigma \rho_K k}{2\rho^2 U^4} \right]^{-1/3} \quad (28).$$

Iz enačb (27) in (28) dobimo premer vezi:

$$d_L = 2F^{1/3} N^{-1/2} \left[\frac{16k^2 \sigma^2}{9f^2 \rho \rho_K U^2} \right]^{-1/6} \quad (29).$$

S poznavanjem parametrov F in N izračunamo $F^{1/3} N^{-1/2}$, premer vezi pa določimo po enačbi (29). Za funkcionalno odvisnost med $F^{1/3} N^{-1/2}$ in $VF^{-1/3}$ sta Dombrowski in Johns predlagala naslednjo aproksimacijsko enačbo:

$$F^{1/3} N^{-1/2} = (c + aVF^{-1/3})^b \quad (30).$$

Enačba (30) ima tudi fizikalno razlogo: vrednost izraza (30) mora biti za neviskozno kapljevinino enaka 1. V tem primeru je vrednost parametra V enaka nič, zato mora biti vrednost parametra c enaka 1. Vrednosti parametrov smo določili z ne-linearno aproksimacijo po metodi najmanjših kvadratov [6], [7], [8]:

$$a = 2,09029$$

$$b = 0,18322$$

$$c = 1,00000$$

(20) If (21) is substituted into (19) and time is expressed from (19) and (23), the following dependence between parameters:

Determination of ligament size

At the same distance from the nozzle, a sheet with thickness h is separated into ligaments which are initially $\lambda/2$ in width and then contract into cylinders. This is the basic assumption of the Weber's modification of Rayleigh's jet-breakup theory [4]. The diameter of these ligaments equals:

In this case, the sheet thickness h does not change with time t . In literature [4], a model of the sheet with constant thickness is used.

From equations (27) and (25) the sheet thickness h is calculated:

Combining (27) and (28) gives:

If the values of parameter F and N are known, then the product $F^{1/3} N^{-1/2}$ is calculated and diameter of ligaments is given by (29). For the dependence between products $F^{1/3} N^{-1/2}$ and $VF^{-1/3}$, Dombrowski and Johns propose this approximation equation:

Equation (30) also has a physical meaning: the value of (30) must equal 1 for non-viscous liquid. In this case the value of parameter V must vanish, so the parameter c must equal 1. The values of the parameters a , b , c can be determined numerically by the least squares method [6], [7], [8]:

$$(a = 2,6)$$

$$(b = 0,2)$$

$$(c = 1,0)$$

The values in brackets are taken from [1].

Better agreement with values in Table 1 can be obtained if the parameter c is also determined numerically by the least squares method. The values of the parameters are:

$$a = 2,09793 \quad b = 0,18301 \quad c = 1,06615$$

Če vstavimo enačbo (30) v (29) in upoštevamo (26), dobimo končni izraz za izračun premera vezi:

$$d_L = 2 \left(\frac{4}{3f} \right)^{1/3} \left(\frac{k^2 \sigma^2}{U^4 \rho \rho_K} \right)^{1/6} \left[c + a \mu_K \sqrt[3]{\frac{\rho^4 U^8 k}{48 f \rho_K^2 \sigma^5}} \right]^b \quad (31).$$

S preizkusi je bilo ugotovljeno, da ima pri razpadu lamele funkcija f ne glede na vstopne pogoje stalno vrednost $f(t_r) = 12$ [1], [5], kjer po meni t_r čas razpada lamele. To je posledica stalnega razmerja med amplitudo motnje pri razpadu lamele in amplitudo začetne motnje.

V članku [5] je zapisana definicija parametra debeline lamele K . Debeline lamele v poljubni točki izrazimo kot:

$$h = K/x \quad (32),$$

kjer ima krajevni polmer x izhodišče v notranjosti ustja šobe. Krajevni polmer izračunamo:

$$Ut = x \quad (33).$$

Parameter debeline K lahko določimo tudi s preizkusi [1], [5], [3].

Z upoštevanjem enačb (32), (33) in (21) izračunamo konstanto k :

$$k = K/U \quad (34).$$

Premet vezi zapisemo z upoštevanjem enačbe (34):

$$d_L = 2 \left(\frac{4}{3f} \right)^{1/3} \left(\frac{K^2 \sigma^2}{U^4 \rho \rho_K} \right)^{1/6} \left[c + a \mu_K \sqrt[3]{\frac{\rho^4 U^8 K}{48 f \rho_K^2 \sigma^5}} \right]^b \quad (35).$$

Določitev velikosti računskega in Sauterjevega premera kapljic

Vezi se gibljejo vzdolžno skozi obdajajoči plin in razpadajo po Webrovi teoriji v večje in nato manjše kapljice zaradi simetričnih valov.

Računski srednji premer kapljic je z upoštevanjem zakona o ohranitvi snovi [4]:

$$d_K^3 = \frac{3}{2} d_L^2 \lambda_L = \frac{3 \pi d_L^2}{n_L} \quad (36).$$

Velikost kapljic, ki nastanejo po Webrovi teoriji, izračunamo po enačbi:

$$\frac{1}{n_L d_L} = \frac{1}{\sqrt{2}} \left[1 + \frac{3 \mu_K}{\sqrt{\rho_K \sigma d_L}} \right]^{1/2} \quad (37).$$

If we substitute (30) into (29) and use (26), we get the final formula for the size of ligaments:

Experimental observations show that at the break-up of liquid sheets, function f has a constant value independent of operating conditions $f(t_r) = 12$ [1], [5], where t_r is the time of break-up of the liquid sheets. This implies a constant ratio of amplitude of the waves at break-up to the initial disturbance.

Definition of the thickness parameter K is written in the paper [5]. The sheet thickness is at any point equal to:

$$h = K/x \quad (32),$$

where x is the radial distance from the nozzle orifice, calculated from:

$$Ut = x \quad (33).$$

The thickness parameter K can also be determined experimentally [1], [5], [3].

Combining (32), (33) and (21), the constant k can be calculated:

$$k = K/U \quad (34).$$

The diameter of ligaments can be written by (34):

$$d_L = 2 \left(\frac{4}{3f} \right)^{1/3} \left(\frac{K^2 \sigma^2}{U^4 \rho \rho_K} \right)^{1/6} \left[c + a \mu_K \sqrt[3]{\frac{\rho^4 U^8 K}{48 f \rho_K^2 \sigma^5}} \right]^b \quad (35).$$

Determination of the size of calculated and the Sauter drop size diameters

The ligaments move transversely through the gas environment and then breakup according to the Weber's theory into droplets of different sizes.

Calculated mean diameters of droplets are obtained according to the mass conservation law [4]:

The size of droplets according to Weber's theory is:

Računski premer kapljic dobimo iz enačb (36) in (37):

$$d_K = \left(\frac{3\pi}{\sqrt{2}} \right)^{1/3} d_L \left[1 + \frac{3\mu_K}{\rho_K \sigma d_L} \right]^{1/6} \quad (38)$$

Povezavo med eksperimentalno določenim Sauterjevim premerom kapljic d_{32} in računskim premerom kapljic d_K podaja naslednja enačba [1],

$$d_{32} = C_1 d_K \quad (39),$$

kjer je C_1 korekcijski koeficient.

The correlation between the measured Sauter diameter and the calculated diameter d_K is given by the following formula [1], [3]:

$$d_{32} = C_1 d_K \quad (39),$$

where C_1 is the correction factor.

1.3 Lamela konstantne debeline h

V tem primeru se debelina lamele h s časom ne spreminja. V literaturi [4] je prikazan model razpada ploščate lamele, kjer se debelina lamele ne tanja. Izhodiščna enačba je še vedno enačba (9). Pri konstantni debelini lamele med njenim razpadom ($h = \text{konst}$), funkcijo rasti valov zapišemo kot linearno funkcijo časa:

$$f(t) = \beta t \quad (40),$$

kjer je β faktor amplitudne rasti valov. Za lamelo konstantne debeline h , je po enačbi (8) $p = \beta$. V tem primeru zapišemo (9):

$$2\rho n U^2 - 2\sigma n^2 - \rho_K h \beta^2 - \mu_K h n^2 \beta = 0 \quad (41).$$

Lamela bo razpadla, ko bo imel faktor β največjo vrednost, zato polščemo ekstrem funkcije β , ($\partial\beta/\partial n = 0$):

$$\rho U^2 - 2\sigma n - \mu_K h n \beta = 0 \quad (42).$$

Če vstavimo enačbo (42) v (41), dobimo valovno število, pri katerem lamela razpade na vezi:

$$n = \frac{\rho_K}{\rho} \frac{\beta^2}{U^2} h \quad (43).$$

Sedaj uporabimo Webrovo teorijo razpada curka. Enačbo (43) vstavimo v (27) in dobimo:

$$d_L = 2 \frac{U^2}{\beta} \sqrt{\frac{\rho}{\rho_K}} \quad (44).$$

Če upoštevamo enačbo (33) in eksperimentalno ugotovitev [1], [3], da ima funkcija $f(t)$ v času razpada lamele t_r konstantno vrednost 12, enačbo (44) zapišemo kot:

$$d_L = \frac{1}{6} \sqrt{\frac{\rho}{\rho_K}} x \quad (45).$$

In this case, the sheet thickness h does not vary with time t . In literature [4], a model of disintegration of the sheet with constant sheet thickness is shown. The basic equation is also (9). The function of growth rate f can be written as a linear function of time for the sheet with constant thickness ($h = \text{const}$):

where β is the amplitude growth factor. From equation (8) it follows for $h = \text{const}$ that $p = \beta$.

In this case, equation (9) can be written:

The sheet will breakup when the parameter β has a maximum value. Since ($\partial\beta/\partial n = 0$) for the maximum:

Substituting (42) in (41), the wave number of the sheet is obtained, at which the sheet breakup into ligaments:

According to the Weber's theory, (43) is substituted into (27):

If we consider (33) and experimental finding [1], [3] that function $f(t)$, for liquid sheet, has a constant value of 12 in the break-up time of sheet t_r , (44) can be written:

Upoštevajmo še funkcionalno zvezo med K , h in x (32). Premer vezl d_L je enak:

$$(42) \quad d_L = \frac{1}{6} \frac{K}{h} \sqrt{\frac{\rho}{\rho_K}} \quad (46)$$

V enačbi (46) se pojavljata dve neznani veličini h in d_L , ki sta med seboj prav tako povezani. Poleg tega se v enačbi pojavi tudi parameter debeline lamele K , ki ga moramo določiti s preizkusi. Zato sta v literaturi [4] ločeno obravnavana dva primera:

a) neviskozen fluid ($\mu_K \rightarrow 0$):

$$d_L^3 = \frac{4}{3} \left(\frac{K\sigma}{U^2} - \frac{1}{\sqrt{\rho\rho_K}} \right) \quad (47)$$

b) zanemarjen vpliv površinske napetosti ($\sigma \rightarrow 0$):

$$d_L^3 = \frac{2}{9} \sqrt{\frac{\rho}{\rho_K^3}} \frac{K^3}{U} \mu_K \quad (48)$$

Z namenom, da bi hkrati upoštevali vpliv viskoznosti in površinske napetosti, smo enačbo (43) vstavili v (42) in dobili kvadratno odvisnost debeline lamele h :

$$16\mu_K \beta h^2 + 32\sigma h - \rho_K \beta^2 d_L^4 = 0 \quad (49)$$

V enačbi (49) ni parametra debeline lamele K . Od dveh korenov (49) bomo upoštevali samo pozitivnega, ki ima dejanski pomen:

$$h = \frac{-32\sigma + \sqrt{(32\sigma)^2 + 64\mu_K \beta^2 \rho_K d_L^4}}{32\mu_K \beta} \quad (50)$$

Za nastanek kapljic smo prevzeli Webrovo teorijo z upoštevanjem enačb (36), (37) in (38).

2. RAČUNALNIŠKI ALGORITEM IN ANALIZA IZRAČUNANIH VREDNOSTI

2.1 Opis algoritmov

S sodobnimi optičnimi brezdotikalnimi metodami, kot sta npr. PDA ali PDP [9], je mogoče meriti hitrost in velikost kapljic. Zato smo računalniški algoritem priredili po matematičnem modelu tako, da je vstopni podatek »izmerjen« Sauterjev premer kapljic. V matematičnem modelu se

(46) Considering also the dependence between K , h and x , (32). The diameter of ligaments d_L is:

In (46) there are two unknown variables h in d_L , which are dependent on each other. In the equation, there is also the thickness parameter K , which must be determined experimentally. In literature [4], two cases are separately treated:

a) inviscid fluid ($\mu_K \rightarrow 0$):

b) surface tension is neglected ($\sigma \rightarrow 0$):

To obtain a solution which considers the influence of viscosity and surface tension, (43) is substituted into (42) and the quadratic equation for sheet thickness h obtained:

In (49) the thickness parameter K is not found. Only positive solution of the quadratic equation has a meaning:

For evaluation of the drop diameter, the Weber's theory is used. (36), (37) and (38).

2. COMPUTER ALGORITHMS AND ANALYSIS OF CALCULATED VALUES

2.1 Description of algorithms

The new optical measurement methods, such as the PDA or PDP systems [9], offer measurement of velocity and droplet size distributions. For this reason, a computer algorithm was adapted on the basis of the mathematical model, so that an input value is the measured Sauter diameter of

tokrat kot neznanka pojavlja parameter debeline lamele K . Najprej iterativno rešujemo enačbe (36), (39) in (50), dokler ne dosežemo predpisane točnosti za parameter debeline K . Računalniška algoritma smo izoblikovali za lamele spremenljive debeline $h = k/t$ in lamele stalne debeline h_{const} .

Računalniški algoritem smo priredili tudi tako, da je poudarjeno eksperimentalno določanje parametra debeline K . V literaturi [5] je opisana možnost merjenja parametra K z laserskim interferometrom in hitro kamero, s katerima lahko merimo valovne dolžine vzvalovane lamele. Druga možnost merjenja je opisana v [3], kjer uporabljamo posebno lovilno komoro. V literaturi [3] je podana formula, po kateri lahko izračunamo vrednost parametra debeline lamele K :

$$K = h_x \approx \frac{A_{\text{eq}}}{2\gamma} \quad (51),$$

kjer pomeni 2γ kot pri razpadu ploščatega curka. Prav tako lahko izračunamo ekvivalentni premer šob d_{eq} :

$$d_{\text{eq}} = \sqrt{\frac{4A_{\text{eq}}}{\pi}}$$

Opisan algoritem smo izoblikovali za lamele spremenljive debeline $h = k/t$.

Po računalniških algoritmih smo izdelali tudi računalniške programe, s katerimi imamo možnost simuliranja različnih vstopnih podatkov. Izstopne veličine so debelina lamele h , čas razpada lamele t_r , premer vezil d_L , računski premer kapljic d_K in parameter debeline lamele K ali Sauterjev premer kapljic d_{32} .

2.2 Analiza izračunanih vrednosti

Z računalniškimi programi smo simulirali izotermni razpad vodne lamele in lamele plinskega olja v zraku, gostote $\rho_z = 1,16 \text{ kg/m}^3$. Temperatura fluidov je bila 20°C , snovne lastnosti vode in plinskega olja so:

- gostota vode: 998 kg/m^3 ,
- gostota plinskega olja: 750 kg/m^3 ,
- površinska napetost vode: $0,072 \text{ N/m}$,
- površinska napetost plinskega olja: $0,0258 \text{ N/m}$,
- dinamična viskoznost vode: $\mu_K = 0,001 \text{ Pas}$,
- dinamična viskoznost plinskega olja: $\mu_K = 0,05 \text{ Pas}$.

droplets. Thickness parameter of the sheet K is the unknown in the mathematical model. The equations (36), (39) and (50) are solved by iteration until the prescribed accuracy for parameter K is achieved. The computer algorithm was made for attenuating sheet $h = k/t$ and for with constant sheet thickness h_{const} .

A computer algorithm was also adapted to emphasise the experimental determination of thickness parameter K . In literature [5], a possibility of using an Interferometric method for measurement of the thickness parameter K is described. The second possibility is described in [3], where a special interception chamber is used. The thickness parameter K can be calculated from an equation found in [3]:

where 2γ is the disintegration spray angle of flat jet. The equivalent diameters of nozzle d_{eq} can be calculated:

The described algorithm is made for the attenuating liquid sheet $h = k/t$.

On the basis of computer algorithms, computer programs were made which give a possibility to perform simulation for different inlet conditions. The outlet variables are: the sheet thickness h , the time of sheet break-up t_r , the diameter of ligaments d_L , the calculated diameters of droplets d_K , the thickness parameter K and the Sauter diameter d_{32} .

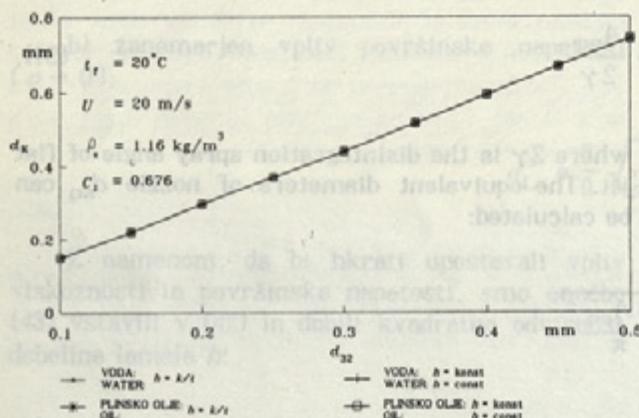
2.2 Analysis of calculated values

Isothermal disintegration of liquid sheets was simulated on the basis of computer programs. Simulations were made for water and oil sheets in air at a density of $\rho_z = 1,16 \text{ kg/m}^3$. The temperatures of fluids are 20°C and the thermophysical properties are:

- density of water: 998 kg/m^3 ,
- density of oil: 750 kg/m^3 ,
- surface tension of water: $0,072 \text{ N/m}$,
- surface tension of oil: $0,0258 \text{ N/m}$,
- dynamic viscosity of water: $\mu_K = 0,001 \text{ Pas}$,
- dynamic viscosity of oil $\mu_K = 0,05 \text{ Pas}$.

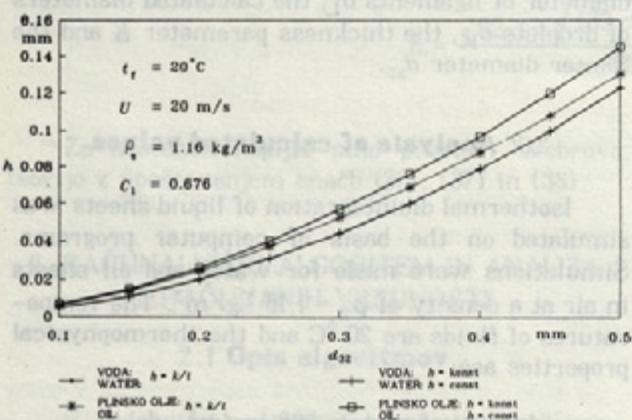
Za izbrane vstopne podatke smo proučevali odvisnost med d_K , d_L , h , x , t_r , N in d_{eq} od izmerjenega Sauterjevega premera kapljic pri razprševanju vode in plinskega olja. Pri tem smo upoštevali vrednost faktorja korekcije $C_1 = 0.676$ (39), [1], hitrost lamele $U = 20 \text{ m/s}$ in vrednost funkcije f v času razpada lamele $f(t_r) = 12$ [1], [5]. Rezultati simuliranj so zbrani v preglednicah 2 do 5 in prikazani na slikah 3 do 10. S tem simuliranjem smo primerjali tudi oba matematična modela za $h = k/t$ in $h = \text{const}$. Iz izračunanih vrednosti ugotavljamo:

— Dolžina razpada lamele raste z naraščanjem d_{32} . Podobna ugotovitev velja za parameter debeline K , premer vezi d_L in računski premer kapljic d_{32} .



Sl. 3. Odvisnost med računskim premerom kapljic d_K in Sauterjevim premerom kapljic d_{32} .

Fig. 3. Dependence between the calculated d_K and Sauter drop sizes d_{32} .

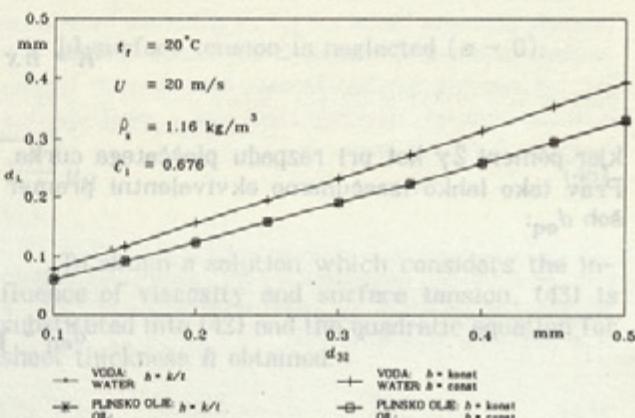


Sl. 5. Odvisnost med debelino lamele h in Sauterjevim premerom kapljic d_{32} .

Fig. 5. Dependence between sheet thickness h and Sauter drop sizes d_{32} .

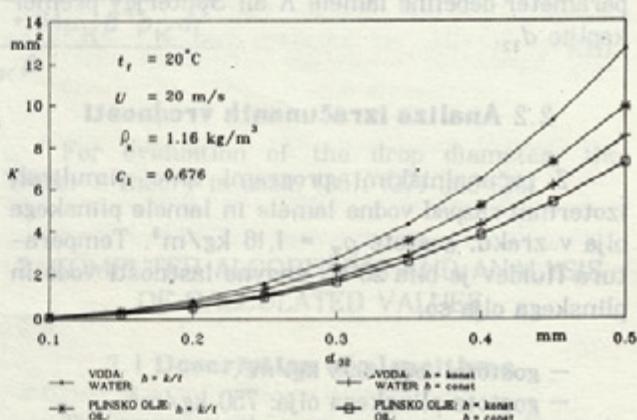
For these inlet conditions, dependences of d_K , d_L , h , x , t_r , N and d_{eq} on the measured Sauter diameters of droplets in atomization of water and oil were examined. In these simulations the value of 0.676 is taken for correction factor C_1 , (39), [1]. The velocity of sheets was $U = 20 \text{ m/s}$ and the value of function $f(t_r) = 12$, [1], [5]. The calculated values are contained in table 2 to 5 and shown in figures 3 to 10. The comparison between two mathematical models for $h = k/t$ and $h = \text{const}$ was also made. On the basis of calculated values, we came to the following conclusions:

— The break-up length of liquid sheet increases with the increase in d_{32} . A similar conclusion is valid for the thickness parameter K , the diameters of ligaments d_L and the calculated droplet diameters d_{32} ;



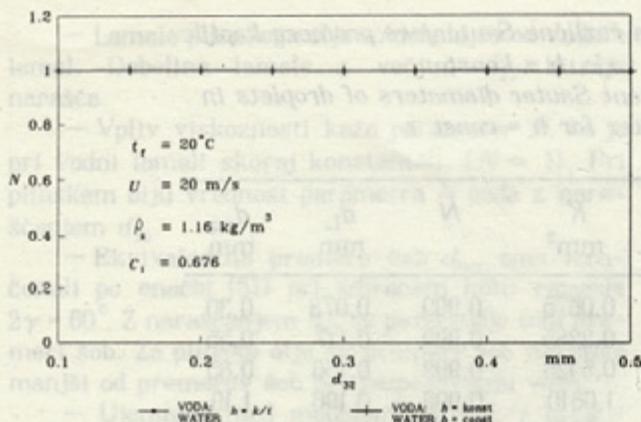
Sl. 4. Odvisnost med premerom ligamenta d_L in Sauterjevim premerom kapljic d_{32} .

Fig. 4. Dependence between the diameters of the ligaments d_L Sauter drop sizes d_{32} .



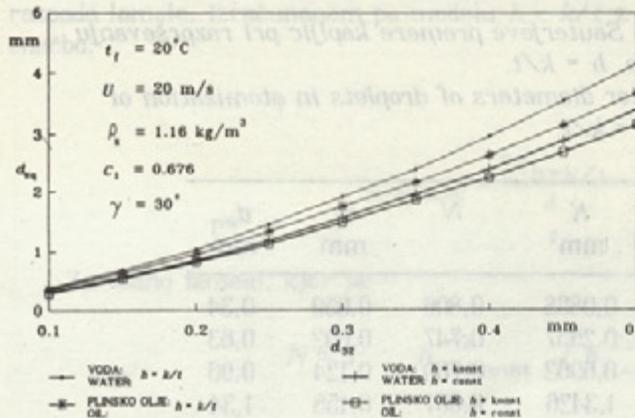
Sl. 6. Odvisnost med parametrom debeline K in Sauterjevim premerom kapljic d_{32} .

Fig. 6. Dependence between thickness parameter K and Sauter drop sizes d_{32} .



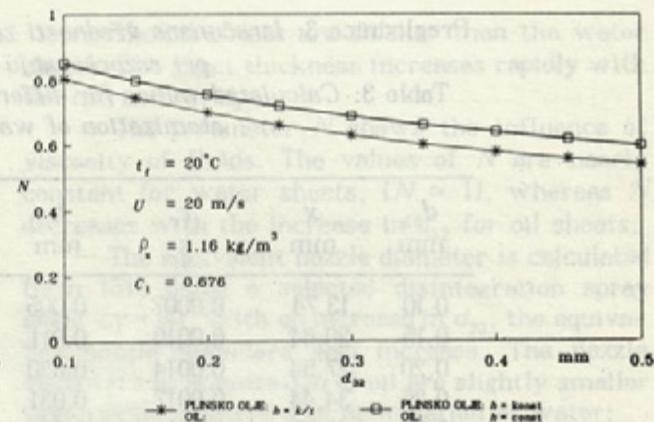
Sl. 7. Odvisnost med parametrom N in Sauterjevim premerom kapljic d_{32} pri razprševanju vode.

Fig. 7. Dependence between the parameter N and Sauter drop sizes d_{32} in atomization of water.



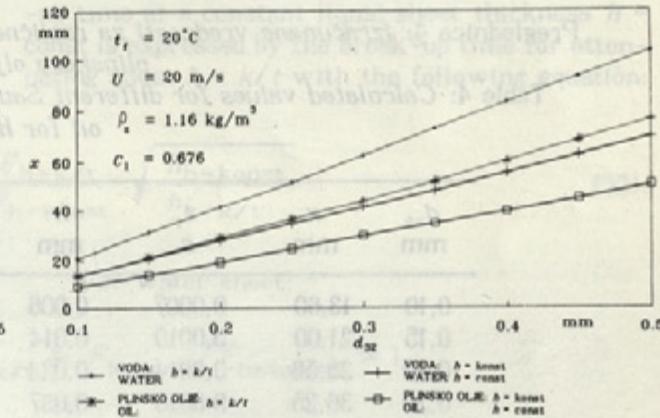
Sl. 9. Odvisnost med ekvivalentnim premerom šobe d_{eq} in Sauterjevim premerom kapljic d_{32} .

Fig. 9. Dependence between equivalent nozzle diameters d_{eq} and Sauter drop sizes d_{32} .



Sl. 8. Odvisnost med parametrom N in Sauterjevim premerom kapljic d_{32} pri razprševanju plinsko olje.

Fig. 8. Dependence between the parameter N and Sauter drop sizes d_{32} in atomization of oil.



Sl. 10. Odvisnost med dolžino razpada lamele x in Sauterjevim premerom kapljic d_{32} .

Fig. 10. Dependence between the break-up length of sheet x and Sauter drop sizes d_{32} .

Preglednica 2: Izračunane vrednosti za različne Sauterjeve premere kapljic pri razprševanju vode, $h = k/t$.

Table 2: Calculated values for different Sauter diameters of droplets in atomization of water for $h = k/t$.

Parameter d_{32} mm	x mm	t_f s	h mm	K mm^2	N	d_L mm	d_{eq} mm
0,10	20,62	0,0010	0,005	0,1012	0,999	0,078	0,38
0,15	30,96	0,0015	0,011	0,3426	0,998	0,117	0,67
0,20	41,31	0,0021	0,020	0,8134	0,995	0,156	1,04
0,25	51,67	0,0026	0,031	1,59	0,998	0,196	1,46
0,30	62,02	0,0031	0,044	2,75	0,997	0,235	1,91
0,35	72,38	0,0036	0,060	4,368	0,997	0,274	2,41
0,40	82,74	0,0041	0,078	6,522	0,996	0,313	2,95
0,45	93,09	0,0046	0,100	9,288	0,996	0,353	3,52
0,50	103,45	0,0052	0,123	12,74	0,995	0,392	4,12

Preglednica 3: Izračunane vrednosti za različne Sauterjeve premere kapljic pri razprševanju vode, $h = \text{konst.}$

Table 3: Calculated values for different Sauter diameters of droplets in atomization of water for $h = \text{const.}$

d_{32} mm	x mm	t_r s	h mm	K mm^2	N	d_L mm	d_{eq} mm
0,10	13,74	0,0007	0,005	0,0675	0,999	0,078	0,30
0,15	20,64	0,0010	0,011	0,2265	0,999	0,117	0,55
0,20	27,54	0,0014	0,020	0,5426	0,999	0,156	0,85
0,25	34,44	0,0017	0,031	1,0610	0,999	0,196	1,19
0,30	41,35	0,0021	0,044	1,8349	0,998	0,235	1,56
0,35	48,25	0,0024	0,060	2,9144	0,998	0,274	1,97
0,40	55,15	0,0028	0,079	4,3535	0,998	0,313	2,41
0,45	62,06	0,0031	0,100	6,2002	0,997	0,353	2,87
0,50	68,97	0,0034	0,123	8,5066	0,997	0,392	3,37

Preglednica 4: Izračunane vrednosti za različne Sauterjeve premere kapljic pri razprševanju plinskega olja, $h = k/t$.

Table 4: Calculated values for different Sauter diameters of droplets in atomization of oil for $h = k/t$.

d_{32} mm	x mm	t_r s	h mm	K mm^2	N	d_L mm	d_{eq} mm
0,10	13,60	0,0007	0,006	0,0568	0,806	0,059	0,34
0,15	21,00	0,0010	0,014	0,2957	0,747	0,092	0,63
0,20	28,56	0,0014	0,024	0,6962	0,700	0,124	0,96
0,25	36,25	0,0018	0,037	1,3426	0,661	0,155	1,34
0,30	44,03	0,0022	0,052	2,2550	0,628	0,192	1,75
0,35	51,87	0,0026	0,069	3,5709	0,601	0,226	2,18
0,40	59,78	0,0030	0,088	5,2449	0,577	0,260	2,64
0,45	67,73	0,0034	0,108	7,3497	0,556	0,295	3,13
0,50	75,74	0,0038	0,131	9,9264	0,538	0,329	3,64

Preglednica 5: Izračunane vrednosti za različne Sauterjeve premere kapljic pri razprševanju plinskega olja, $h = \text{konst.}$

Table 5: Calculated values for different Sauter diameters of droplets in atomization of oil for $h = \text{const.}$.

d_{32} mm	x mm	t_r s	h mm	K mm^2	N	d_L mm	d_{eq} mm
0,10	9,05	0,0005	0,007	0,0609	0,852	0,059	0,29
0,15	13,97	0,0007	0,015	0,2104	0,799	0,092	0,53
0,20	18,99	0,0009	0,026	0,5004	0,756	0,124	0,82
0,25	24,09	0,0012	0,040	0,9722	0,720	0,158	1,14
0,30	29,25	0,0015	0,057	1,6643	0,689	0,192	1,49
0,35	34,45	0,0017	0,076	2,6130	0,661	0,226	1,87
0,40	39,70	0,0020	0,097	3,5522	0,638	0,260	2,27
0,45	44,97	0,0022	0,120	5,1141	0,616	0,295	2,69
0,50	50,28	0,0025	0,146	7,3305	0,597	0,330	3,13

— Lamele plinskega olja so debelejše od vodnih lamele. Debelina lamele z večjim d_{32} hitreje narašča.

— Vpliv viskoznosti kaže parameter N , ki je pri vodni lamelei skoraj konstanten, ($N \approx 1$). Pri plinskem olju vrednost parametra N pada z naraščanjem d_{32} .

— Ekvivalentne premere šob d_{eq} smo izračunali po enačbi (51) pri izbranem kotu razpada $2\gamma = 60^\circ$. Z naraščanjem d_{32} se povečujejo tudi premeri šob. Za plinsko olje so premeri šob nekoliko manjši od premerov šob pri razprševanju vode.

— Ujemanje med modeloma $h = k/t$ in $h = \text{konst}$, opazimo pri izračunu premerov vezl, računskega premerov kapljic in debelin lamele. Pri plinskem olju, kjer je večji vpliv viskoznosti, ($N < 1$), modela odstopata pri izračunu dolžin in časov razpada lamele. Čas razpada lamele pri konstantni debelini h lahko izrazimo s časom razpada lamele, izračunanem po modelu $h = k/t$ z enačbo:

— The oil sheets are thicker than the water sheets. The sheet thickness increases rapidly with the increase in d_{32} .

— The parameter N shows the influence of viscosity of fluids. The values of N are nearly constant for water sheets, ($N \approx 1$), whereas N decreases with the increase in d_{32} for oil sheets;

— The equivalent nozzle diameter is calculated from (51) using a selected disintegration spray angle $2\gamma = 60^\circ$. With an increase in d_{32} , the equivalent nozzle diameters also increase. The nozzle diameters in atomization of oil are slightly smaller than nozzle diameters in atomization of water;

— Agreement between the two models $h = k/t$ and $h = \text{konst}$ is found for diameters of ligaments, calculated diameters of droplets and sheet thickness. With oil, where the influence of viscosity is greater, ($N < 1$), the models differ in the calculated break-up length and time of liquid sheets. The break-up time at a constant liquid sheet thickness $h = \text{konst}$ is expressed by the break-up time for attenuating sheet $h = k/t$ with the following equation:

$$t_{h=\text{konst}} = \frac{2t_{h=k/t}}{3} \frac{F_{h=k/t}}{F_{h=\text{konst}}} \sqrt{\frac{h_{h=\text{konst}}}{h_{h=k/t}}} \quad (52).$$

Za vodno lamelo, kjer je:

$$N \approx 1; \quad h_{h=\text{konst}}^{1/2} / h_{h=k/t}^{1/2} \approx F_{h=k/t} / F_{h=\text{konst}} \approx 1$$

enačbo (52) lahko poenostavimo:

For water sheet:

$$t_{h=\text{konst}} \approx \frac{2}{3} t_{h=k/t} \quad (53).$$

Podobna ugotovitev velja tudi za dolžino razpada lamele:

the equation (52) can be simplified:

As similar statement is also valid for the break-up length of liquid sheets:

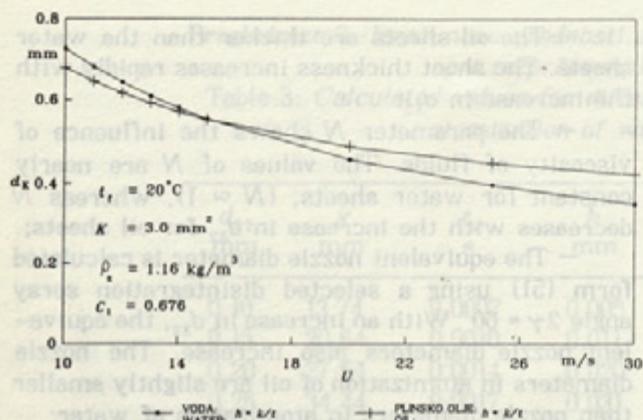
$$x_{h=\text{konst}} \approx \frac{2}{3} x_{h=k/t} \quad (54).$$

Na slikah 11 do 16 in preglednicah 6 in 7 so prikazane in zbrane izračunane vrednosti za primer razpada vodne lamele in lamele plinskega olja pri različnih izstopnih hitrostih tekočine iz šobe. Parameter debeline lamele K je v tem primeru 3 mm^2 . Na podlagi simuliranj za model $h = k/t$ lahko sklepamo:

The calculated values are contained in tables 6 to 7 and shown in figures 11 to 16. These values were obtained for water and oil sheets at different outlet nozzle velocity. The thickness parameter K was equal to 3 mm^2 . On the basis of simulation for the model $h = k/t$, the conclusions are as follows:

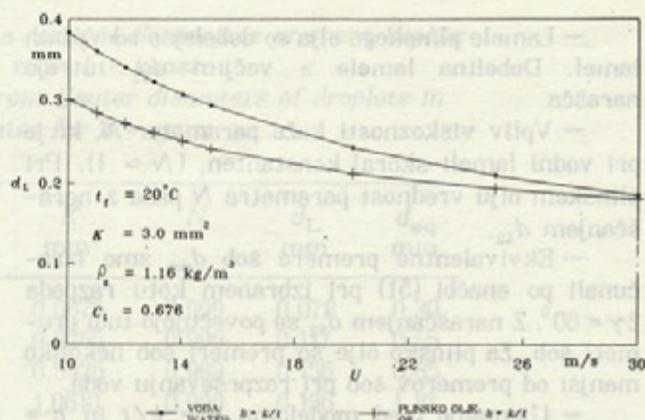
— S povečevanjem hitrosti U se zmanjšuje dolžina razpada lamele: Pri manjših hitrostih je dolžina razpada lamele večja od lamele plinskega olja. Velikosti Sauterjevih premerov in računskega premerova vodnih kapljic so pri večjih hitrostih lamele manjše od kapljic plinskega olja. Pri manjših hitrostih so nekoliko večje vodne kapljice.

— With the increase in velocity U the break-up length of sheet decreases. The break-up length is greater at smaller velocities for water sheet as compared to oil sheet. The Sauter diameters and the calculated diameters of droplets are smaller at higher velocities for water sheets and slightly greater at lower velocities as compared to oil sheets.



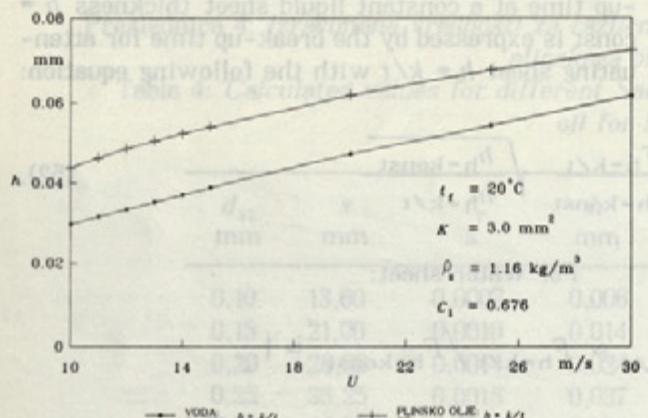
Sl. 11. Vpliv hitrosti lamele U na računski premer kapljic d_K .

Fig. 11. Effect of the sheet velocity U on the calculated diameters of droplets d_K .



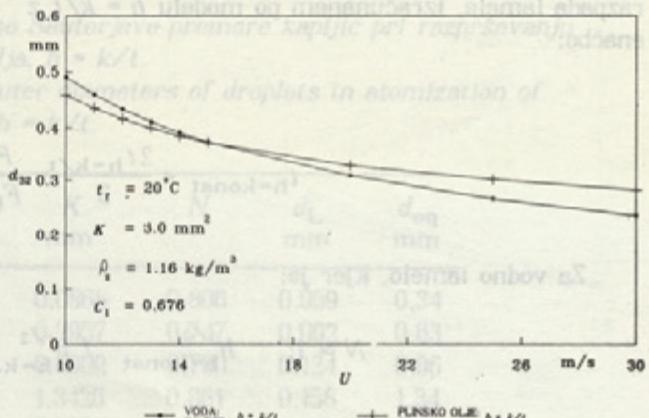
Sl. 12. Vpliv hitrosti lamele U na premer ligamentov d_L .

Fig. 12. Effect of the sheet velocity U on the diameters of ligaments d_L .



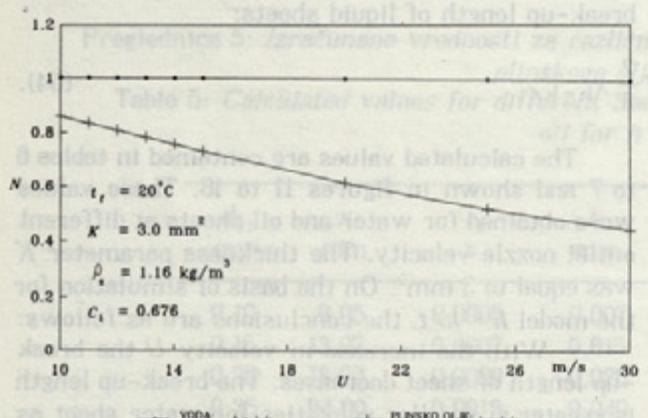
Sl. 13. Vpliv hitrosti lamele U na debelino lamele h .

Fig. 13. Effect of the sheet velocity U on the thickness of sheet h .



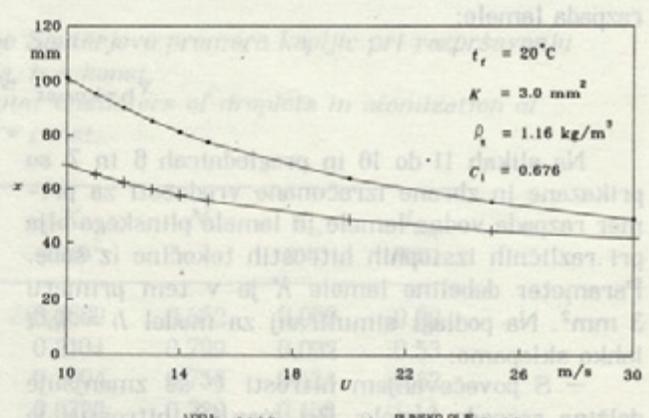
Sl. 14. Vpliv hitrosti lamele U na Sauterjev premer kapljic d_{32} .

Fig. 14. Effect of the sheet velocity U on Sauter diameter of droplets d_{32} .



Sl. 15. Vpliv hitrosti lamele U na parameter N .

Fig. 15. Effect of the sheet velocity U on the parameter N .



Sl. 16. Vpliv hitrosti lamele U na dolžino razpada lamele x .

Fig. 16. Effect of sheet velocity U on the break-up length of the sheet x .

Preglednica 6: Vpliv izstopne hitrosti vode iz šobe pri razprševanju kapljic, $h = k/t$.
 Table 6: Effect of sheet velocity in atomization of water droplets for $h = k/t$.

U m/s	x mm	t_r s	h mm	N	d_L mm	d_K mm	d_{32} mm
10	101,28	0,0101	0,030	0,999	0,384	0,724	0,489
11	95,05	0,0086	0,032	0,999	0,360	0,680	0,460
12	89,70	0,0075	0,033	0,999	0,340	0,641	0,433
13	85,40	0,0065	0,035	0,999	0,322	0,608	0,411
14	80,95	0,0058	0,037	0,999	0,307	0,579	0,391
15	77,31	0,0051	0,039	0,998	0,293	0,553	0,374
20	63,85	0,0032	0,047	0,997	0,242	0,457	0,309
25	55,06	0,0022	0,055	0,995	0,209	0,394	0,266
30	48,79	0,0016	0,061	0,993	0,165	0,349	0,236

Preglednica 7: Vpliv izstopne hitrosti plinskega olja iz šobe pri razprševanju kapljic, $h = k/t$.

Table 7: Effect of sheet velocity in atomization of oil droplets for $h = k/t$.

U m/s	x mm	t_r s	h mm	N	d_L mm	d_K mm	d_{32} mm
10,00	68,79	0,0069	0,0436	0,860	0,3002	0,677	0,457
11,00	65,22	0,0059	0,0460	0,834	0,2845	0,644	0,435
12,00	62,21	0,0052	0,0482	0,808	0,2713	0,615	0,416
13,00	59,64	0,0046	0,0503	0,782	0,2601	0,591	0,399
14,00	57,42	0,0041	0,0522	0,756	0,2503	0,570	0,385
15,00	55,48	0,0037	0,0541	0,731	0,2419	0,552	0,373
20,00	48,65	0,0024	0,0617	0,611	0,2118	0,487	0,329
25,00	44,45	0,0018	0,0675	0,515	0,1933	0,447	0,302
30,00	41,60	0,0014	0,0721	0,437	0,1804	0,419	0,283

— Medtem ko so vodne lamele debelejše od lamele plinskega olja, se premeri vezl d_L zmanjšujejo z naraščanjem hitrosti U . Absolutna vrednost gradienata $|\partial d_L / \partial U|$ je pri vodni lameli precej večja.

— Vpliv viskoznosti tekočine najbolje prikazuje vrednost parametra N , ki je pri vodni lameli skoraj konstanten, ($N \approx 1$), pri plinskem olju pa se s povečevanjem hitrosti U parameter N zmanjšuje.

Do podobnih ugotovitev smo prišli tudi pri simuliraju drugih vstopnih pogojev [10].

Proučevali smo tudi vpliv korekcijskega količnika C_1 in vrednost funkcije $f(t_r)$ modelov $h = k/t$ in $h = \text{konst}$. Pri tem smo simulirali vstopne podatke, kakršni so bili pri eksperimentu [6]. Za nastajanje dvofaznega curka je Bajšič uporabil tlačno razpršilno šobo, ki jo je izdelala tovarna Lechler iz Fellbacha v Nemčiji. Poglavitni geometrijski podatki za šobo so bili:

- manjša polos eliptične odprtine: 0,77 mm
- večja polos eliptične odprtine: 1,3 mm
- iztočni prerez razpršilne šobe: 3,14 mm²
- kot razpada: ≈ 40°

— Water sheets are thicker than oil sheets, whereas the diameters of ligaments d_L decrease with the increase in velocity. The absolute value of gradient $|\partial d_L / \partial U|$ is much greater for water sheets.

— An influence of viscosity is best shown by the value of parameter N , which is almost constant for water sheets, ($N \approx 1$). The parameter N decreases with the increase in velocity U .

Similar conclusions are obtained from simulations at different inlet conditions [10].

An influences of the correction factor C_1 and values of function $f(t_r)$ for two models $h = k/t$ and $h = \text{const}$ were also examined. We simulated the same inlet conditions as in the experiment by Bajšič [6]. For generation of a two-phase jet, the author used pressure atomization nozzle manufactured by Lechler Company from Fellbach in Germany. Its main characteristics were:

- smaller half-axis of the elliptical outlet: 0,77 mm,
- longer half-axis of the elliptical outlet: 1,3 mm,
- outlet section area of the nozzle: 3,14 mm²,
- angle of disintegration: ≈ 40°

Izstopna hitrost vode iz šobe je znašala 17,24 m/s, Sauterjev premer kapljic pa 0,267 mm, parameter debeline K , ki smo ga izračunali po (51), je enak $4,5 \text{ mm}^2$. Rezultati simuliranj obeh modelov $h = k/t$ in $h = \text{konst}$ za vrednosti $f(t_r) = 12$ in 20, so zbrani v preglednicah 8 in 9. Pri tem smo upoštevali korekcijo $C_1 = 0,4627$. V preglednicah so izračunane tudi vrednosti, pri katerih smo upoštevali korekcijo $C_1 = 0,4267$, ki smo jo določili po (39).

Iz računskih rezultatov lahko ugotovimo, da smo dobili ujemanje računskega premora kapljic in Sauterjevega premora kapljic ob upoštevanju korekcije $C_1 = 0,4627$ obeh modelov. Pri obeh simuliranjih se dobro ujemata tudi ekvivalentna premora šob.

Prav tako lahko ugotovimo, da se pri povečanju funkcije f_{tr} v času razpada lamele za 67 % sorazmerno poveča tudi dolžina razpada lamele.

3. SKLEP

Iz dobljenih vrednosti, ki so zbrane v preglednicah 2 do 8 in prikazane na slikah 3 do 16, ugotavljamo:

– računalniški algoritmi omogočajo pomoč pri eksperimentalnem preverjanju matematičnega modela razpada tanke lamele;

The outlet nozzle velocity was 17.24 m/s and the measured Sauter diameter was 0.267 mm, the thickness parameter K was calculated by equation (51) and equaled 4.5 mm^2 . The calculated values for both models $h = k/t$ and $h = \text{const}$ and for $f(t_r) = 12$ and 20 are contained in tables 8 and 9. The value of parameter C_1 was 0.4627. The calculated values for correction factor $C_1 = 0,4267$, determined from (39), are also in tables 8 and 9.

From the calculated values it can be concluded: agreement between the calculated diameters of droplets and the measured Sauter diameter is good for both models at $C_1 = 0,4627$. In these simulations the calculated and measured equivalent diameters of nozzles also agree well.

We also conclude that with the increase in the value of f_{tr} for 67 %, the break-up length of sheets increases proportionally.

3. CONCLUSION

From the obtained values, which are collected in tables 2 to 8 and shown in figures 3 to 16, we conclude:

– The computer algorithms enable experimental verification of the mathematical models of disintegration of liquid sheets;

Preglednica 8: Vpliv funkcije $f(t_r)$ in korekcijskega koeficienta C_1 pri razprševanju vodnih kapljic, $h = k/t$.

Table 8: Effect of function $f(t_r)$ and correction factor C_1 in atomization of water droplets for $h = k/t$.

d_{32} mm	x mm	t_r s	h mm	K mm^2	N	d_L mm	d_K mm	d_{eq} mm	$f(t_r)$	C_1
0,267	55,19	0,0032	0,0261	1,441	0,998	0,209	0,395	1,39	12	0,67600
0,267	91,98	0,0053	0,0261	2,402	0,998	0,209	0,395	1,79	20	0,67600
0,267	80,68	0,0047	0,0560	4,500	0,998	0,306	0,577	2,00	12	0,46270
0,267	117,46	0,0068	0,0560	7,500	0,998	0,306	0,577	2,58	20	0,46270

Preglednica 9: Vpliv funkcije $f(t_r)$ in korekcijskega koeficienta C_1 pri razprševanju vodnih kapljic, $h = \text{konst}$.

Table 9: Effect of function $f(t_r)$ and correction factor C_1 in atomization of water droplets for $h = \text{const}$.

d_{32} mm	x mm	t_r s	h mm	K mm^2	N	d_L mm	d_K mm	d_{eq} mm	$f(t_r)$	C_1
0,267	36,79	0,0021	0,026	1,9613	0,999	0,209	0,395	1,132	12	0,6760
0,267	61,31	0,0036	0,026	1,6021	0,999	0,209	0,395	1,462	20	0,6760
0,267	53,79	0,0031	0,056	3,0025	0,999	0,306	0,577	1,634	12	0,4627
0,267	89,64	0,0052	0,056	5,0041	0,999	0,306	0,577	2,109	20	0,4627

— po lastnih eksperimentalnih podatkih [6], [7] za porazdelitev velikosti kapljic ($d_{32} = 0,267$ mm), smo določili debelino, razdaljo in čas razpada lamele ter določili premer nastalih vezi;

— računalniški algoritem omogoča simuliranje različnih hidrodinamičnih pogojev in snovnih lastnosti kapljevitve in plinaste faze, od katerih je odvisen proces razprševanja;

— opisane računalniške algoritme lahko vgradimo v že znane modele toka kapljic in plina, npr. [6], [11];

— v prihodnje bomo eksperimentalno spremljali in proučevali razpad kapljevitve lamele s sodočnimi optičnimi metodami brez dotika. Izmerke bomo primerjali z rezultati, ki so dobljeni iz računalniških algoritmov;

— pri konstruiranju razpršilnih naprav moramo pravilno izbrati tlačno šobo. Opisan matematični model bo olajšal delo pri pravilni izbiri, saj poznavanje d_{32} ni zadosten podatek za optimalno delovanje razpršilnih procesov.

— On the basis of own experimental data [6], [7] for droplet size distribution ($d_{32} = 0.267$ mm), the thickness of sheet, break-up length, break-up time and diameters of ligaments were determined;

— The computer algorithms enable simulations for different hydrodynamical conditions and thermophysical properties of liquid and gas phase;

— The computer algorithms can be incorporated into own models and models of other authors for two-phase droplets/gas flow, like as in [6], [11];

— In the continuation of our research we will investigate experimentally the disintegration of liquid sheets with new optical measurement methods and systems. Experimental data will be compared with the values obtained from the computer algorithms;

— the pressure nozzle for the construction of the atomization devices must be selected correctly. The described algorithms can help us with the selection, because d_{32} is not a sufficient data for the optimal execution of atomization processes.

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