HYDRODYNAMICS OF INTERACTION OF A GAS JET AND A LIQUID

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The author investigates regimes of interaction between a liquid and jets of gas discharging from immersed nozzles, and the dimensions of the gas volumes generated.

In the discharge of a gas jet from a nozzle immersed in a liquid we distinguish the bubble (I), transitional (II), and jet (III) interaction regimes, where the gas volumes (i.e., bubbles) form immediately at the nozzle lip or at the end of some jet section [1]. The regime of interaction of the gas jet and the liquid [1] and the dimensions of the bubbles formed [2] depend only slightly on the direction of the injected gas, so that one can postulate a wave nature for the processes. It is well known that waves are formed in the interaction of a gas stream with a liquid surface.

One can postulate that in the bubble interaction regime (I), when the gas stream impinges on the liquid surface ahead of the nozzle, it creates capillary waves and acceleration waves whose minimum length is determined by expressions given in [3, 4], and whose maximum length $\lambda_{max} = d/2$ is independent of the nature of the waves.

The waves begin to propagate from the point of intersection of the nozzle axis with the liquid surface towards the nozzle rim. Since a bubble begins to form during the continuous arrival of gas, this motion occurs along the surface of a bubble being formed. When the waves reach the nozzle rim they cover it and bubble formation ends. The duration of travel of the wave on the surface of the bubble forming is

$$\tau_{run} = \pi D/2w_{\lambda}, \tag{1}$$

and the duration of the actual bubble formation is

$$\tau_{form} = \pi D^3\rho_b/6q\rho_0. \tag{2}$$

From the condition $\tau_{run} = \tau_{form}$ we can find D, and substituting this value into Eq. (2), we find the corresponding bubble formation frequency.

The velocity of motion of the capillary waves is greater, the shorter is their length, and therefore the waves of minimum length are the first to reach the nozzle rim and cover it. For them we have

$$\frac{D_{1cap}}{d} = \frac{(3)^{1/2}\pi^{1/2}(\mathrm{WL})^{1/2}}{(2)^{1/3}\beta^{1/6}}\left(\frac{\rho\rho_l}{\rho_0^2}\right)^{1/4}, \tag{3}$$

and the corresponding bubble formation frequency in dimensionless form is

$$F_{1cap} \equiv \frac{f_{1cap}q^{1/2}\mu_l^{3/2}}{\sigma^{3/2}} = \frac{\beta^{1/2}}{(3)^{1/2}\pi}(\mathrm{WL})^{1/2}\left(\frac{\rho_b}{\rho_0}\right)^{1/2}. \tag{4}$$

For acceleration waves w_λ increases with increase of wavelength. Therefore, the first to reach the nozzle rim are waves of maximum length for which

$$\frac{D_{1acc}}{d} = \frac{(3)^{1/2}\pi}{(2)^{3/4}}\left(\frac{n}{C_D}\right)^{1/4}\left(\frac{\rho_l\rho}{\rho_b^2}\right)^{1/4} \tag{5}$$

and

$$F_{1acc} = \frac{(2)^{1/4}(\mathrm{WL})^{3/4}}{(3)^{1/2}\pi^{5/2}}\left(\frac{C_D}{n}\right)^{3/4}\left(\frac{\rho_b}{\rho_0}\right)^{1/2}. \tag{6}$$

As the gas jet velocity increases conditions are set up at the nozzle rim to break up waves traversing the nozzle. The duration of wave breakup is

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$$\tau_{\text{break}} = k_\tau \frac{\lambda \rho_l^{1/2}}{(\rho w^2)^{1/2}}, \tag{7}$$

and the duration of wave motion along the nozzle radius until the wave merges with others on the nozzle axis is

$$\tau_{\text{mot}} = d/2w_\lambda. \tag{8}$$

If $\tau_{\text{break}} \leqslant \tau_{\text{mot}}$, the wave will be broken up as soon as it covers the nozzle. This condition holds when

$$(\mathrm{WL})^{\mathrm{I-II}}_{\text{cap}} \geqslant \frac{(2)^{16/5}\pi^{6/5} k_\tau^{6/5}}{\beta^{2/5}(\mathrm{Lp})^{6/5}} \tag{9}$$

for capillary waves of minimum length, the first to reach the nozzle rim, and when

$$\frac{C_D}{n} \leqslant \frac{2\pi^2}{k_\tau^2} \tag{10}$$

for maximum-wavelength acceleration waves. Substituting Eq. (10) into Eqs. (5) and (6) we obtain

$$\frac{D_{1\text{acc}}}{d} = \frac{(3)^{1/2}\pi^{1/2} k_\tau^{1/2}}{2} \left(\frac{\rho_l \rho}{\rho_b^2}\right)^{1/4} \tag{11}$$

and

$$F_{1\text{acc}} = \frac{(2)(\mathrm{WL})^{3/4}}{(3)^{1/2}\pi k_\tau^{3/2}} \left(\frac{\rho_b}{\rho_0}\right)^{1/2}. \tag{12}$$

If the waves reaching the nozzle rim first are broken up, they cannot cover the nozzle. Therefore, for capillary waves the nozzle is covered by waves that are larger than the wave that will break up, but since their velocity of propagation is less, they reach the nozzle later, and therefore the bubble size increases. Finding the wavelength from Eqs. (7) and (8) which in the state of covering the nozzle will not be broken up, and substituting this value into Eqs. (1) and (2), and solving them simultaneously, we obtain the result that in regime II, when some fraction of the waves are broken up prior to covering the nozzle, for the capillary waves

$$\frac{D_{2\text{cap}}}{d} = \frac{(3)^{1/2}(\mathrm{WL})^{1/2}(\mathrm{Lp})^{1/2}}{(2)^2 k_\tau^{1/2}} \left(\frac{\rho \rho_l}{\rho_0^2}\right)^{1/4} \tag{13}$$

and

$$F_{2\text{cap}} = \frac{(2)^4 \pi^{1/2} k_\tau^{3/2}}{(3)^{1/2}(\mathrm{WL})^{3/4}(\mathrm{Lp})^{3/2}} \left(\frac{\rho_b}{\rho_0}\right)^{1/2}. \tag{14}$$

The acceleration waves in regime II create conditions for formation of bubbles of size

$$\frac{D_{2\text{acc}}}{d} = \frac{(3)^{1/2}\pi^{5/6} k_\tau^{1/6}}{(2)^{5/6}} \left(\frac{n}{C_D}\right)^{1/2} \left(\frac{\rho \rho_l}{\rho_b^2}\right)^{1/4} \tag{15}$$

with dimensionless frequency

$$F_{2\text{acc}} = \frac{(2)^{1/2}(\mathrm{WL})^{3/4} C_D^{1/2}}{(3)^{1/2}\pi^2 k_\tau^{1/2} n^{1/2}} \left(\frac{\rho_b}{\rho_0}\right)^{1/2}. \tag{16}$$

The bubble formation regime II evidently corresponds to transition [1]. Under these conditions a gas jet flowing into a bubble begins to introduce liquid drops into it some time after the initial formation of the bubble.

With subsequent increase of the dynamic head of the gas stream we reach conditions when all the waves formed at the initial time of bubble formation can be broken up on their way to the nozzle rim and therefore they cannot cover the gas stream. For capillary waves this occurs when a wave with $\lambda_{\max}$ is broken up, to which corresponds the condition

$$(\mathrm{WL})^{\mathrm{II-III}}_{\text{cap}} \geqslant \frac{4\pi k_\tau^2}{(\mathrm{Lp})}. \tag{17}$$

For an acceleration wave of minimum length, the last to travel to the nozzle, we obtain

$$(\mathrm{WL})^{\mathrm{II-III}}_{\text{acc}} \geqslant \frac{(2)^{20/3} k_\tau^{2/3}}{\pi^{2/3}\beta^2(\mathrm{Lp})} \left(\frac{C_D}{n}\right)^{4/3}. \tag{18}$$

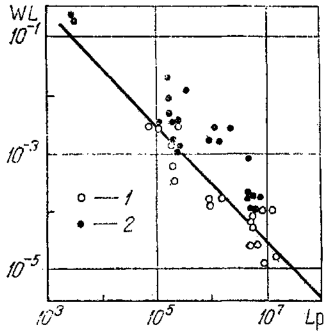

Fig. 1

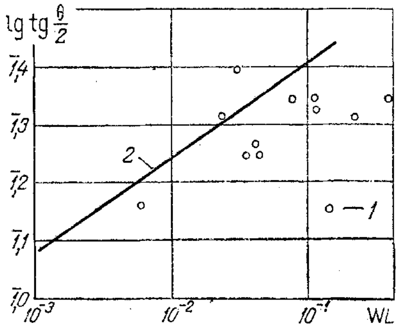

Fig. 2

Fig. 1. Regimes of interaction of a jet with a liquid: 1) bubble; 2) jet.

Fig. 2. The opening angle of the gas jet in the liquid: 1) data of [1, 5, 6, 10, 13-15]; 2) from Eq. (21).

According to Eq. (10), in this regime $\frac{C_D}{n} \geqslant \frac{2\pi^2}{k_\tau^2}$, and tentatively

$$(\mathrm{WL})_{\mathrm{acc}}^{\mathrm{II-III}} \geqslant \frac{(2)^8\pi^2}{k_\tau^2\beta^2(\mathrm{Lp})^2}. \tag{19}$$

Comparing Eqs. (17) and (18), we find that transition to the jet regime is given by the condition of Eq. (17).

From the moment when condition (17) holds, bubble formation at the nozzle rim becomes impossible and one observes jet interaction regime III, where the jet forms a jet section in the liquid, and at the end of this a bubble is formed. References [1, 5-11] present data on conditions where one finds a jet regime of interaction of a gas jet and a liquid. Figure 1 shows these results and also data (lines) constructed from Eq. (17) with $\beta = 0.2$ [3] and $k_\tau = 5$ [12]. Taking into account that these values are approximate, the agreement between the calculations from Eq. (17) and the experimental data must be considered satisfactory.

In moving along the jet section the gas stream creates waves at the interface with the liquid. Since the angle between the gas stream and the liquid is zero, acceleration waves are not formed [4]. In a time τ_{grow} during the motion the capillary wave amplitude increases to the value $\alpha \approx \lambda$, which, according to [3], is the condition for the waves to separate from the liquid surface and form drops which will be broken up by the gas stream in a time τ_{break}. Using the expressions for τ_{grow} given in [3], and Eq. (7) for τ_{break}, it can be shown that $\tau_{\mathrm{grow}} \ll \tau_{\mathrm{break}}$. Taking into account that the time for propagation of the wave along the surface of the jet section, during which time the wave grows, separates from the liquid surface, and is broken up, is approximately equal to τ_{break}, and knowing the speed of propagation of the wave, we can determine the distance $S = w_\lambda\tau_{\mathrm{break}}$ which it traverses. Clearly, as a result of the separation and breaking up of the wave in this section the radius of the jet section is increased by $\lambda/2$, and the opening semiangle of the jet section is

$$\mathrm{tg}\frac{\theta}{2} = \frac{\lambda}{2S}. \tag{20}$$

Substituting into Eq. (16) an expression for λ and w_λ from [3, 4], we obtain

$$\mathrm{tg}\frac{\theta}{2} = \left(\frac{2}{\beta}\right)^{1/3}\frac{(\mathrm{WL})^{1/6}}{k_\tau}. \tag{21}$$

The agreement between the results calculated from Eq. (21) and the data for $\mathrm{tg}\frac{\theta}{2}$ from [1, 5, 6, 10, 13-15], as shown in Fig. 2, must be considered satisfactory, if we take into account the variation (WL) of the section length in which the angle θ was measured experimentally.

Thus, in the jet section the gas stream forms a kind of diffusor in the liquid with an opening angle θ, and as a result the gas stream velocity decreases with increasing distance from the nozzle. At the end of the jet section the gas stream, impinging on the liquid surface, covers its cross section and forms capillary and acceleration waves, i.e., the mechanism for formation of a gas bubble is analogous to that described above for the bubble regime.

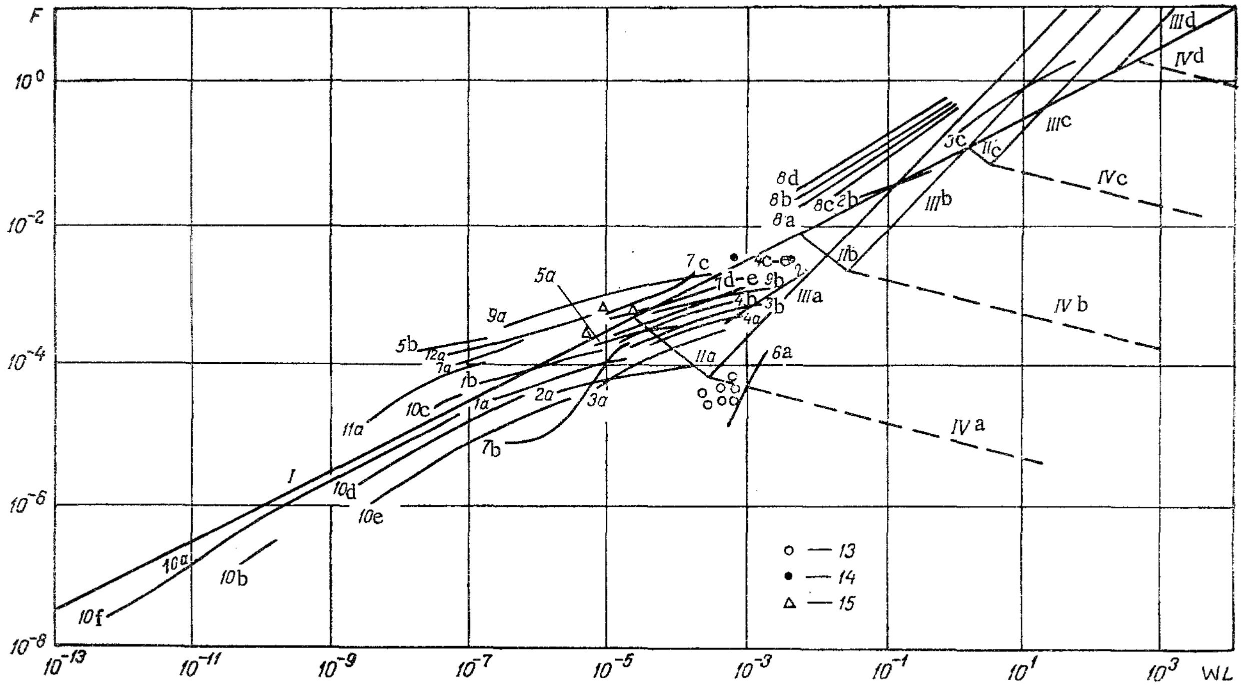

Fig. 3. Bubble formation frequency.

TABLE 1. Experimental Values and Corresponding Laplace Numbers

Curve number	a	b	c	d	e	f	Literature source
1	$4{,}94\cdot10^6$	$5{,}93\cdot10^6$					[7]
2	$4{,}94\cdot10^6$	$3{,}09\cdot10^3$	$2{,}34\cdot10^5$				[9]
3	$8{,}76\cdot10^4$	$5{,}87\cdot10^4$	0,99				[16]
4	$1{,}44\cdot10^5$	$2{,}88\cdot10^5$	$4{,}32\cdot10^5$	$5{,}76\cdot10^5$			[17]
5	$1{,}44\cdot10^5$	$7{,}2\cdot10^5$					[18]
6	$3{,}85\cdot10^5$						[19]
7	$1{,}66\cdot10^5$	$1{,}66\cdot10^5$	$1{,}83\cdot10^6$	$1{,}37\cdot10^6$	$2{,}14\cdot10^5$		[20]
8	3,26	4,35	3,26	4,35			[2]
9	$1{,}37\cdot10^6$	$4{,}56\cdot10^5$					[21]
10	$1{,}06\cdot10^6$	$5{,}45\cdot10^5$	$1{,}03\cdot10^6$	$5{,}78\cdot10^5$	$3{,}85\cdot10^5$	$4{,}8\cdot10^6$	[22]
11	$1{,}48\cdot10^7$						[23]
12	$2{,}42\cdot10^6$						[24]

13– data of [25]; 14–[9]; 15–[11]

For the incident waves to cover the area at the end of the jet section when bubble formation finishes we require that condition (17) hold for $(WL)_l$, $(Lp)_l$.

If the stream velocity at the nozzle exit is less than sonic, the jet section operates as a subsonic diffusor. Using the law for variation of the dynamic head we find that condition (17) holds at the diameter of the exit area of the jet section

$$d_{3l} \geqslant d \frac{(WL)^{1/3}(Lp)^{1/3}}{(2)^{2/3}\pi^{1/3}k_\tau^{2/3}} \left(\frac{\rho}{\rho_b}\right)^{1/3}. \tag{22}$$

Evidently, only a wave of maximum length can cover the jet section, i.e., $\lambda_{max} = d_l/2$. If this is a capillary wave, then

$$\frac{D_{3cap}}{d} = \frac{(3)^{1/2}\pi^{1/6}(WL)^{1/3}(Lp)^{1/3}}{(2)^{5/3}k_\tau^{1/6}} \left(\frac{\rho^4\rho_l^3}{\rho_b^7}\right)^{1/12} \tag{23}$$

and

$$F_{3cap} = \frac{(2)^3 k_\tau^{1/2}}{(3)^{1/2}(WL)^{1/4}(Lp)} \left(\frac{\rho_b^3}{\rho_0^2\rho}\right)^{1/4}, \tag{24}$$

and for an acceleration wave

$$\frac{D_{3\,\text{acc}}}{d}=\frac{(3)^{1/2}\pi^{7/12}k_\tau^{2/3}}{(2)^{5/6}(\mathrm{WL})^{1/12}(\mathrm{Lp})^{1/12}}\left(\frac{\rho^2\rho_l^3}{\rho_b^5}\right)^{1/12}, \tag{25}$$

$$F_{3\,\text{acc}}=\frac{(2)^{3/4}(\mathrm{WL})(\mathrm{Lp})^{1/4}}{(3)^{1/2}\pi^{3/4}k_\tau^{5/2}}\left(\frac{\rho_b\rho}{\rho_0^2}\right)^{1/4}. \tag{26}$$

After a gas jet has been set up at the exit from a sonic nozzle the initial part of the jet section operates as a supersonic diffusor until the pressure in the jet reaches that of the surrounding medium, and subsequently as a subsonic diffusor. At the end of the jet section we must satisfy condition (17) as before for the values $(\mathrm{WL})_l$ and $(\mathrm{Lp})_l$ corresponding to this section, and this is achieved for

$$d_{4l}=d\,\frac{(\mathrm{WL})^{1/3}(\mathrm{Lp})^{1/3}\varkappa^2}{(4)^{1/3}\pi^{1/3}k_\tau^{2/3}}\left(\frac{\rho_{\text{sup}}}{\rho_b}\right)^{1/3}. \tag{27}$$

To form a bubble at the end of the jet section for a capillary wave of maximum length we have

$$\frac{D_{4\text{cap}}}{d}=\frac{(3)^{1/2}\pi^{1/6}\varkappa^{1/2}(\mathrm{WL})^{1/3}(\mathrm{Lp})^{1/3}}{(2)^{5/3}k_\tau^{1/6}}\left(\frac{\rho^3\rho_l^3\rho_{\text{sup}}}{\rho_b^7}\right)^{1/12} \tag{28}$$

and

$$F_{4\text{cap}}=\frac{(2)^3k_\tau^{1/2}}{(3)^{1/2}\varkappa^{3/2}(\mathrm{WL})^{1/4}(\mathrm{Lp})}\left(\frac{\rho_b^3}{\rho_{\text{sup}}\rho_0^2}\right)^{1/4}, \tag{29}$$

and for an acceleration wave we have

$$\frac{D_{4\,\text{acc}}}{d}=\frac{(3)^{1/2}\pi^{7/12}k_\tau^{2/3}}{(2)^{5/6}\varkappa^{1/2}(\mathrm{WL})^{1/12}(\mathrm{Lp})^{1/12}}\left(\frac{\rho^3\rho_l^3}{\rho_b^5\rho_{\text{sup}}}\right)^{1/12}, \tag{30}$$

$$F_{4\text{acc}}=\frac{(2)^{3/4}\varkappa^{3/2}(\mathrm{WL})(\mathrm{Lp})^{1/4}}{(3)^{1/2}\pi^{3/4}k_\tau^{5/2}}\left(\frac{\rho_b\rho_{\text{sup}}}{\rho_0^2}\right)^{1/4}. \tag{31}$$

Figure 3 compares the theoretical relations obtained for the dimensionless bubble formation frequency, Eqs. (4), (12), (14), (16), (24), (26), (29), and (31), with experimental data from [2, 7, 16-25].

For small values of the (WL) parameter, bubbles form with a frequency given by Eq. (4) (curve I). Here the nozzle is covered by capillary waves of minimum length. On reaching condition (9) these waves begin to break up, and the nozzle is covered by capillary waves of length $\lambda_{min} < \lambda < \lambda_{max}$, and the bubble formation frequency is given by Eq. (14) (curves II, a, b, c) for values (Lp) = 10^6, 10^4 and 10^2, respectively. For very viscous liquids (Lp $\leqslant 10^0$) regime II is degenerate.

If condition (17) becomes an equality the nozzle can be closed only by a wave of maximum length $\lambda_{max} = d/2$. In this regime the nozzle is reached first by acceleration waves of the same maximum length and velocity, instead of by capillary waves of maximum length.

When the left side of condition (17) exceeds the right side, the capillary waves and the acceleration waves of maximum length break down, and the nozzle rim begins to receive acceleration waves of dimension less than λ_{max}. However, these break up, since conditions already hold at the nozzle rim for the break up of waves of maximum length, and therefore, waves of less than maximum length cannot cover the nozzle. Therefore the jet regime sets in, and bubbles are formed, not at the nozzle rim, but at the end of the jet section. In this regime the exit area of the jet section is covered by waves of maximum length $\lambda_{max} = d_l/2$, as determined by Eqs. (22) and (27) for subsonic and sonic jets. The transition from subsonic to sonic discharge of the gas jet from the nozzle occurs for different (WL) values for different gas-liquid pairs. However, taking into account the smallness of the error introduced by $\varkappa$ and ρ_{sup}, in calculations using Eqs. (24), (26) and (29), (31) at the blowing pressures ordinarily employed in practice, one can tentatively represent both these sections of the dependence F-WL in Fig. 3 by the lines corresponding to Eqs. (26) (lines III, a-d) and (24) (lines IV, a-d).

The main mass of the experimental data corresponds to the bubble regime of interaction of a gas jet with a liquid, and is shown with insignificant scatter relative to the theoretical Eq. (4) (curve I). Here no dependence of F on the blowing direction was found. A tendency is observed for transition of F from regime I to regime III more smoothly without reduction of F, and not according to the theoretical curve II, which may be connected with the assumptions in the analytical model regarding conditions for covering of the nozzle rim by the incident waves.

The conditions for which the experimental data of [19] and [25] were obtained for melting of iron apparently correspond to the initial part of the jet regime. Taking into account the complexity of conducting these kinds of experiments, one must consider the qualitative and quantitative agreement between the experimental and the theoretical relations to be satisfactory.

The data on the frequency of fluctuations in the blowing supply system were obtained with blowing of melts in [9], and are also close to the theoretical values.

NOTATION

λ, α, w_λ, length, amplitude, and velocity of motion of the wave; p, p_{sur}, blowing pressure and pressure in the surrounding medium; d, D, diameters of the nozzle and the bubble; ρ_l, μ_l, σ, density, viscosity, and surface tension of the liquid; ρ, ρ_b, ρ_{sup}, ρ_0, gas density at the nozzle exit, in the bubble, at the end of the supersonic section, and under normal conditions; k, adiabatic index; f, bubble formation frequency; τ, time; q, mass flow rate of gas under normal conditions; θ, opening angle of the jet; $We \equiv \rho w^2 d/\sigma$, Weber number; $Lp \equiv \rho_l d\sigma/\mu^2_l$, Laplace number; $WL \equiv We/Lp \equiv \rho w^2 \mu^2_l/\rho_l \sigma^2$; $F \equiv f_q{}^{1/2} \mu_l{}^{3/2}/\sigma^{3/2}$; dimensionless frequency; $\varkappa = (2/(k+1))^{1/6(k-1)}(p/p_{sur})^{1/6k}$; β, constant from [3]; C_D, n, constants from [4]; k_T, constant from [12]. Subscripts: l, liquid; 1, 2, 3, 4, number of interaction regimes; c, capillary; acc, acceleration; run, running; form, formation; break, breakup; mot, motion.

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EFFECT OF THE TEMPERATURE ON THE HYDRODYNAMIC EFFICIENCY AND STABILITY OF POLYETHYLENE OXIDE AND POLYACRYL AMIDE

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The article describes a comparative study of the effect of the temperature on the hydrodynamic efficiency and stability of polyethylene oxide (PEO) and polyacryl amide (PAA).

A number of authors [1-7] studied the effect of the temperature on the ability of polymers to reduce the hydrodynamic drag of turbulent flow. In the review [1] it was stated that a change of temperature from 4 to 37°C does not affect the ability of polyethylene oxide, polyacryl amide, and guarana resin to reduce hydrodynamic drag. Later, aqueous solutions of polyethylene oxide were investigated most thoroughly. It was experimentally demonstrated that increasing temperature leads to reduced hydrodynamic efficiency of PEO [2, 3] and increased threshold frictional stress on the wall [4]. The authors brought that into connection with the change of the temperature parameters of the solubility of PEO in water [2] and with the reduced anisotropy of viscosity upon reduced size of the macromolecules [4].

It must be noted that a change of temperature of aqueous solutions of PEO leads to a noticeable change of their molecular characteristics. When the temperature increases from 20 to 90°C, the hydration numbers of PEO decrease; that indicates weakened interaction between the polymer and water. At the same time the virial coefficient, the characteristic viscosity, and the size of the molecular agglomerations also decrease [8]. The model of diluted aqueous solution of PEO, worked out by Toryanik [9], explains these changes by the destruction of the structure of water under the effect of the temperature.

The effect of the temperature on the hydrodynamic efficiency of polyacryl amide has been studied less thoroughly. The authors of [5-7] observed a drop of the effect of hydrodynamic drag reduction when the temperature rose.

In distinction to PEO, the corresponding molecular characteristics of polyacryl amide are much less subject to the effect of the temperature. An increase of the temperature to

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