GENERATION OF GAS NUCLEI DURING THE FLOW OF WEAK AQUEOUS SOLUTIONS OF POLYMERS AROUND A SURFACE

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The effect of polymer additives (reducing the tangential forces of friction) on the generation of boundary gas nuclei (prospective centers of cavitation) in the flow of weak aqueous solutions around solid surfaces is considered. Relationships are derived between changes taking place in the size and frequency of formation of the nuclei and the reduction in the tangential stresses.

Experimental investigations into the cavitation effects taking place on solid surfaces subjected to a flow of weak aqueous polymer solutions [1, 2] indicate that the conditions governing the onset of cavitation are substantially altered by these polymers. It is well known [3] that cavitation (breaks in the continuity of a liquid) arises at weak points, such as gas and vapor-gas nuclei, some of which are generated by solid surfaces. In this paper we predict changes in the composition of such boundary nuclei, attributable to the changes introduced by the polymer solution into the flow close to the body; these should have a marked influence on the development of cavitation.

The possibility that gas nuclei might be encountered in cracks and pores of a solid surface immersed in a liquid was demonstrated theoretically by Harvey [4]. We are also well acquainted with experimental investigations [5] in which high-speed motion-picture photography revealed a region (situated further up the flow than the zone of cavitation visible to the unaided eye), in which stationary microbubbles appeared periodically on the surface; the bubbles then grew, and after reaching a certain diameter were carried away in the flow, in which they were transformed into visible cavitation bubbles. The method of analyzing this generation of boundary gas nuclei proposed by Van der Welle [6] is used in this paper as a basis for determining the changes taking place in the size distribution and the frequency of formation of the nuclei as a result of introducing small quantities of polymer into the flow passing around a solid surface.

The conditions of mechanical equilibrium at the boundary of a gas bubble in a pore may be approximately written

$$p_g + p_s \cong p + 2\sigma/R_p.$$

It follows from this condition that, when the static pressure on the solid falls at the site of the pore

$$p \leqslant p_g + p_s - 2\sigma/R_p$$

the boundary of the bubble will move outward; the bubble will grow, being held in the mouth of the pore by surface-tension forces until the forces of hydrodynamic resistance take it away. Gas dissolved in the neighboring liquid will diffuse into the nucleus so formed, so that after its detachment from the mouth of the pore the latter will retain a constant quantity of gas, and after a certain period of time another bubble with be created. This generation of bubbles from the pore is mainly controlled by the hydrodynamic resistance, which determines the size of the escaping bubble, and the diffusion of gas from the flow into the growing nucleus, which controls the frequency of nucleation.

We may determine the size of the nucleus from the conditions of its detachment from the mouth of the pore

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$$R_{p}\sigma \sim c_{w}\bar{q}R^{2}. \tag{1}$$

The left-hand side of this equation characterizes the forces of surface tension holding the nucleus in the mouth of the pore, and the right-hand side characterizes its hydrodynamic resistance. We neglect the Archimedes forces and forces due to the pressure gradient along the flow in Eq. (1) as small quantities.

Since the size of the nuclei is of the order of 10 μ [5], we may assume that they are located inside the laminar sublayer. On allowing for the well-known velocity distribution in the sublayer $u = y\tau_{W}/\mu$, we may accordingly obtain the dynamic pressure averaged over the height of the nucleus

$$\bar{q} = \frac{1}{2R}\int_{0}^{2R}\frac{\rho u^{2}}{2}\,dy = \frac{2}{3}\rho\left(\frac{\tau_{w}R}{\mu}\right)^{2}, \tag{2}$$

and a relationship for the resistance coefficient of a sphere in the range Re = 10-1000

$$c_{w} \cong 13\,\mathrm{Re}^{-1/2} = 8.6\rho^{-1/2}\tau_{w}^{-1/2}R^{-1}\mu. \tag{3}$$

Substituting (2) and (3) into (1) we obtain a relation for the size of the nucleus on detachment

$$R \sim (R_{p}\sigma\mu)^{1/3}\rho^{-1/6}\tau_{w}^{-1/2}. \tag{4}$$

By considering the condition governing the diffusion of the gas dissolved in the liquid to the growing nucleus

$$V \sim Dc'_{R}ST,$$

and allowing for the fact that the volume of the nucleus $V \sim R^{3}$ while its surface area $S \sim R^{2}$, we may derive a relationship for the frequency of formation of gas nuclei from the pore

$$\omega = T^{-1} \sim Dc'_{R}R^{-1}. \tag{5}$$

The diffusion coefficient in (5) may be expressed as the sum of two components: molecular and turbulent diffusion. The latter is the dominant component, so that if, for example, we use the data of [7], we find that

$$D \cong D_{T} = ay_{+}^{3} \sim aR^{3}\mu^{-3}(\rho\tau_{w})^{3/2}. \tag{6}$$

If from dimensional considerations we put $c'_{R} \sim c_{0}R^{-1}$ in (5) and use (4) and (6) we obtain

$$\omega \sim a(R_{p}\sigma)^{1/3}\mu^{2}\rho^{4/3}c_{0}\tau_{w}. \tag{7}$$

Equations (4) and (7) indicate that the size distribution and the frequency of formation of the gas cavitation bubbles depend on the tangential stresses of friction, which are considerably reduced when weak polymer solutions flow around the surface.

The ratios $\mu_{*}/\mu \cong 1.1$, $\sigma_{*}/\sigma \cong 0.85$, $\tau_{W*}/\tau_{W} \cong 0.3$ given in [1] represent the changes in the properties of a solution of Polyox WSR-301 (100 g/m^{3}) relative to those of pure water (the asterisk denotes the parameters corresponding to the polymer solution); if we put these in (4) and (7) we find that the dimensions of the cavitation gas bubbles should increase by a factor of approximately two in the solution and their frequency of formation should diminish by a factor of three.

NOTATION

p_{g}, p_{s}, p	are the pressure of the gas in the bubble, the saturated vapor pressure, and the static pressure (on the body at the site of the pore);
σ	is the surface tension;
R_{p}	is the pore radius;
c_{w}	is the resistance coefficient of a sphere;
$\bar{q}$	is the dynamic pressure averaged over the height of the nucleus;
R	is the radius of the nucleus on detachment;
u	is the average longitudinal component of the local velocity in the boundary layer;
y	is the ordinate of the boundary layer;
τ_{w}	is the local tangential stress on the surface;
μ	is the dynamic viscosity;
ρ	is the mass density of water;
V	is the volume of the nucleus;

D	is the diffusion coefficient;
S	is the surface area of the nucleus;
T	is the period of growth of the nucleus;
ω	is the frequency of formation of nuclei from a specified pore;
c'_R	is the volume concentration gradient of the gas diffusing to the bubble;
$y_+ = yu_*/\nu$	is the dimensionless coordinate of the boundary layer;
c_0	is the volumetric concentration of the gas dissolved in the water.

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