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PROCESSES AND EQUIPMENT OF CHEMICAL INDUSTRY

Evaluation of the Adhesion Interaction of Dispersed Particles with Cellulose Fibers

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Abstract—Theoretical analysis of the adhesion interaction of dispersed particles with cellulose fibers and of hydrodynamic conditions for detachment of the particles from the fiber surface was performed. The force of the adhesion interaction of the components with the fiber surface was calculated for particles of different configurations with known values of the Hamaker–van der Waals constant. The attraction force of spherical particles to a cellulose fiber wall is 300–400 times lower than that of flat particles. The velocity of flow around the fibers, required for detachment of flat dispersed particles from the fibers, is approximately 1000 times higher than that required for detachment of spherical particles.

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In paper forming on high-speed papermaking machines, stringent requirements are imposed upon the quality of paper stock. Mineral contaminations are removed from the stock by precipitation or centrifugation; paper recycling involves deinking of secondary raw material. Optimization of pulp and paper production processes (screening, filtration, particle washing from the aqueous fiber slurry, paper stock deinking) requires theoretical analysis of regularities of dispersed particles adhesion to the fiber surface. The majority of studies of paper stock purification and dewatering had applied character and were aimed at improvement of existing and development of new equipment [1–3]. The interaction of colloidal particles with cellulose fibers was considered in studies dealing with principles of water treatment and flotation [4–6]. The calculations performed in this study can be used for understanding the mechanism of interaction of fibers with particles of any shape (mineral inclusions, printing ink, pigments, etc.) and development of optimum procedures for removal of foreign inclusions from fibrous stock.

Adhesion interaction. The force of attraction of a platelike particle to the flat fiber surface per unit surface area was calculated according to [7]. The adhesion force was calculated for inorganic components with known values of the Hamaker–van der Waals constant: Si_3N_4, SiO_2, $CaCO_3$, TiO_2, mica $R_1(R_2)_3[AlSi_3O_{10}](OH)_2$, where R_1 = K, Na; R_2 = Al, Mg, Fe [8]. Water slurry of cellulose fibers and mineral particles is considered as a coarsely dispersed system. Particles are assumed to have spherical or lamellar shape of size 1.0–5.0 μm.

Churaev [9] noted that, the more hydrophilic the surface is, the more pronounced is the contribution of the structural constituent of the particle interaction energy. Repulsion forces arising in thin interlayers between the surfaces of dispersed particles are caused by disturbance of the water structure in these interlayers relative to the water structure in the free aqueous phase. The results of experimental studies and theoretical analysis of the structural repulsion forces are summarized in [10] as a formula for the repulsion pressure.

The total force of particle interaction with the fiber surface is an algebraic sum of forces of intermolecular attraction and structural repulsion:

$$F_i = K_i \exp\left(-\frac{H_i}{L_i}\right) - \frac{A_k}{6\pi H_i^3}, \qquad (1)$$

where K_i is a constant proportional to the degree of molecular ordering at the surface of the water

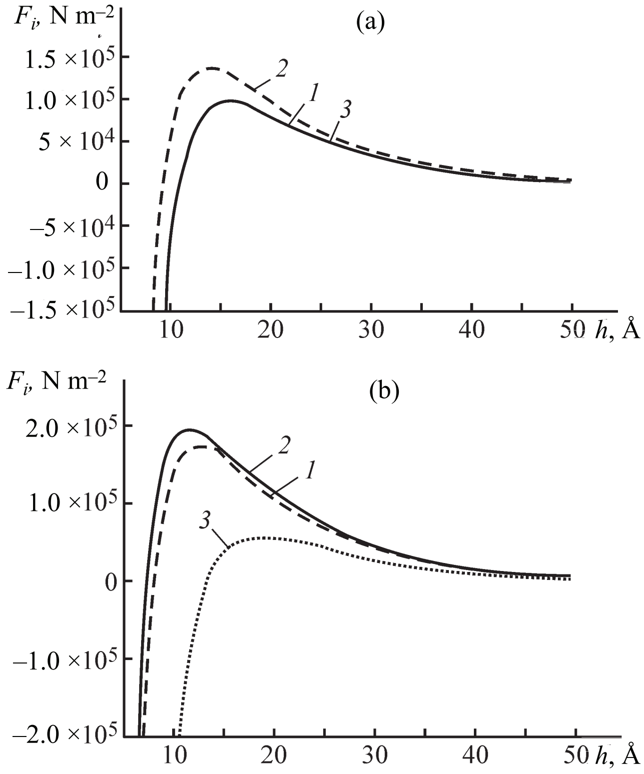

Fig. 1. Total force F_i of interaction of flat particles with a flat fiber wall as a function of the thickness h of the water interlayer between the interacting surfaces (short distances). Material of interacting particles: (a) (*1*) cellulose–cellulose, (*2*) cellulose–$CaCO_3$, and (*3*) cellulose–Si_3N_4; (b) (*1*) cellulose–SiO_2, (*2*) cellulose–mica, and (*3*) cellulose–TiO_2.

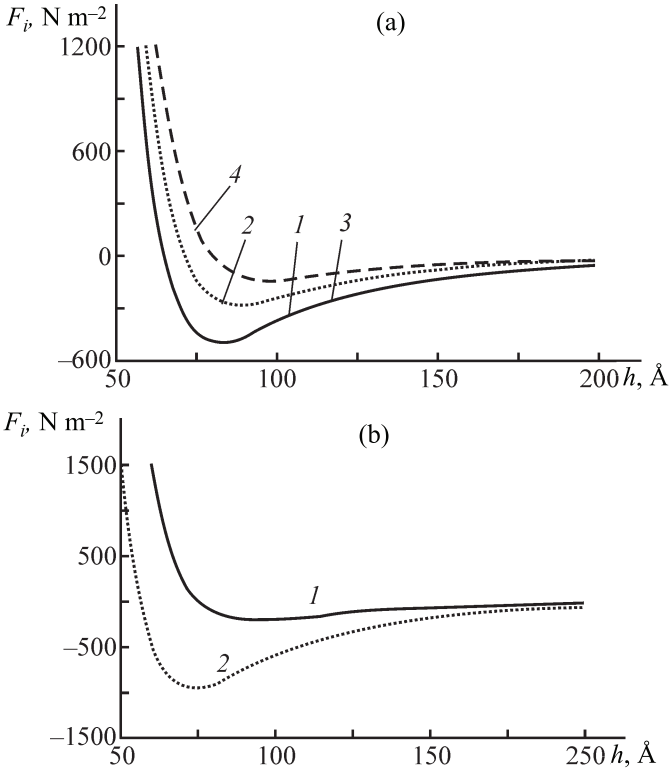

Fig. 2. Total force F_i of interaction of flat particles with a flat fiber wall as a function of the thickness h of the water interlayer between the interacting surfaces (long distances). Material of interacting particles: (a) (*1*) cellulose–cellulose, (*2*) cellulose–$CaCO_3$, (*3*) cellulose–Si_3N_4, and (*4*) cellulose–SiO_2; (b) (*1*) cellulose–mica and (*2*) cellulose–TiO_2.

interlayer ($K_i = 10^6$ N m^{-2}), L_i, correlation length of the orientation ordering of water molecules in the boundary layer ($L_i = 10^{-9}$ m); A_k, Hamaker–van der Waals constant (N m); and H_i, distance between the interacting particles (m).

The calculated total force of interaction of flat particles with cellulose fiber walls is plotted in Figs. 1a and 1b vs. thickness of the water interlayer between the interacting surfaces.

It follows from Figs. 1a and 1b that the attraction force prevails at the thickness of water between the particle surfaces and cellulose fiber wall smaller than 8 Å. The force of structural repulsion of the particles from the plane reaches a maximum at the water interlayer thickness of 10–15 Å and rapidly decreases as the distance between the particle surface and fiber wall increased. The calculated plots of the total interaction force of flat particles with the flat wall of a cellulose fiber per unit surface area of the particles at the water interlayer thickness larger than 50 Å are shown in Figs. 2a and 2b.

At the water interlayer thickness larger than 60 Å, attraction forces between the cellulose fiber wall and flat dispersed particles prevail.

The absolute value of the interaction force of spherical dispersed particles with a plane depends on the surface curvature radius of the particles. Interaction of a spherical particle with a plane is approximated by interaction of ring zones of the sphere with centers located on the symmetry axis of the contact zone. The following expression for the force of structural repulsion of a sphere from a plane, F_{push}, was obtained taking into account the fact that the distance of the interaction of a sphere with a plane is much shorter than the sphere radius:

$$F_{\text{push}} = 2\pi r_{\text{p}} K_i L_i \exp\left(-\frac{H_i}{L_i}\right), \tag{2}$$

where r_{p} is the radius of the spherical particle (m).

The force of intermolecular attraction of a spherical particle to a plane is given by the relationship

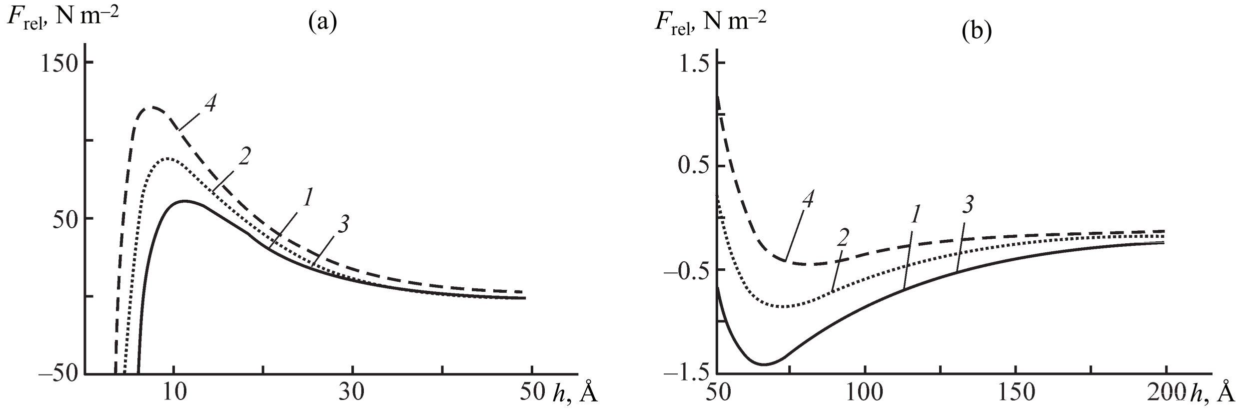

Fig. 3. Total force F_{rel} of interaction of spherical dispersed particles with a flat fiber wall as a function of the thickness h of the water interlayer between the interacting surfaces. Material of interacting particles: (*1*) cellulose–cellulose, (*2*) cellulose–$CaCO_3$, (*3*) cellulose–Si_3N_4, and (*4*) cellulose–SiO_2. (a) Short and (b) long distances.

$$F_{attract} = -\frac{A_k r_p}{6H_i^2}. \quad (3)$$

The total interaction force of spherical particles with a plane is

$$F_i = 2\pi r_p K_i L_i \exp\left(-\frac{H_i}{L_i}\right) - \frac{A_k r_p}{6H_i^2}. \quad (4)$$

To compare the interaction forces of flat and spherical dispersed particles with the cellulose fiber wall, the total interaction force of a spherical particle with the fiber wall was divided by the cross section of the spherical particle:

$$F_{rel} = \frac{F_i}{\pi r_p^2}. \quad (5)$$

Figures 3a and 3b show plots for the total interaction force of spherical particles with a flat wall of a cellulose fiber per unit area of the particle cross section. The curvature radius of the dispersed particle surface was taken equal to 5 μm. Comparison of Figs. 1a and 3a shows that the total interaction force of spherical dispersed particles with a wall plane through a 10 Å thick water interlayer is 1000 times lower than in interaction with flat dispersed particles.

Comparison of the calculated plots in Figs. 2a and 2b shows that the force of attraction of spherical particles to a cellulose fiber wall is 300–400 times smaller than that of flat particles to the fiber wall.

Thus, theoretical analysis of the adhesion interaction of dispersed particles with the cellulose fiber surface shows that dispersed particles should adhere to the fiber wall owing to intermolecular attraction forces acting through the water interlayer of thickness larger than 60 Å.

The maximal force of intermolecular attraction of dispersed particles to fibers was determined. The minimum in the curves of the intermolecular interaction force vs. distance between the surfaces corresponds to

Table 1. Parameters of adhesion interaction of flat and spherical (radius 5 μm) dispersed particles with the cellulose fiber wall

Material interacting with cellulose	Distance between flat particle and fiber surface, Å	Force of attraction of flat particle to fiber, N m^{-2}	Distance between spherical particle and fiber surface, Å	Force of attraction of spherical particle to fiber, N m^{-2}	$A_k \times 10^{-21}$, N m
Cellulose	81.1	495.3	64.5	1.41	8.0
$CaCO_3$	81.9	293.0	70.6	0.87	5.7
Si_3N_4	81.1	495.3	64.5	1.41	8.0
SiO_2	96.5	142.2	78.8	0.45	3.5
Mica	93.0	192.2	75.4	0.59	4.3
TiO_2	73.1	961.0	56.3	2.58	12.0

Table 2. Water flow velocity ensuring detachment of dispersed particles from the fiber surface

Material interacting with cellulose	Detachment of flat particles		Detachment of spherical particles	
	velocity of flow around fibers, m s^{-1}	Reynolds number	velocity of flow around fibers, m s^{-1}	Reynolds number
Cellulose	1.35	40.5	1.2×10^{-3}	0.036
$CaCO_3$	0.95	28.5	7.2×10^{-4}	0.022
Si_3N_4	1.35	40.5	1.2×10^{-3}	0.036
SiO_2	0.59	17.7	3.7×10^{-4}	0.011
Mica	0.72	21.6	4.9×10^{-4}	0.015
TiO_2	2.10	63.0	2.1×10^{-3}	0.060

maximal values of the attraction force between the fiber surface and dispersed particles. The distance at which the interaction force reaches the largest negative value is determined by the condition $dF_i/dH_i = 0$.

Substituting expression (1) for the total interaction force in (2), we obtain

$$H_i^4 \exp\left(-\frac{H_i}{L_i}\right) = \frac{A_k L_i}{2\pi K_i}. \quad (6)$$

Equation (6) is a transcendent equation. Its numerical or graphical solution gives the value of H_i, the distance between the surfaces at which the repulsion and attraction forces acting between the particle and fiber reach maxima. The parameters of the interaction of dispersed particles (radius 5 μm) with a flat area of a cellulose fiber wall, calculated using the known values of the Hamaker–van der Waals constant [8], are given in Table 1.

As seen from Table 1, for spherical particles the force of attraction to the fiber wall is approximately 300 times lower than that for flat particles. In paper repulping and deinking the size and shape of ink particles cannot be controlled, but in practice efforts are made to obtain fine particles by dispersion with special devices or adding chemicals [11, 12].

Hydrodynamic conditions of particle detachment from the surface. A simple method for separation of dispersed particles from the pulp is filtration of water through a bed of fibers. Dispersed particles will be detached from the fibers, provided that the force of hydrodynamic pressure on a dispersed particle fixed on a fiber exceeds the force of its attraction to the fiber. The tangential stress force $F_{\text{hydro.plate}}$, by which the laminar flow passing around a flat particle acts on it can be calculated with the formula [13]

$$F_{\text{hydro.plate}} = L_{\text{across}} \sqrt{V_w^3 \rho_w L_{\text{along}} \mu_w}, \quad (7)$$

where L_{across} is the plate size in the direction perpendicular to the water flow direction (m); L_{along}, plate size in the direction along the water flow direction (m); V_w, velocity of water flow passing around the plate (m s^{-1}); ρ_w, water density (kg m^{-3}); and μ_w, dynamic viscosity of water (kg s^{-1} m^{-1}).

The tangential stress force by which the water flow acts on the unit plate area, $\sigma_{\text{hydro.plate}}$, is

$$\sigma_{\text{hydro.plate}} = \sqrt{\frac{V_w^3 \rho_w \mu_w}{L_{\text{along}}}}. \quad (8)$$

The velocity of the flow passing around a lamellar dispersed particle required for its detachment from the fiber surface, is given by

$$V_w \ge \sqrt[3]{\frac{L_{\text{along}} F_i^2}{\rho_w \mu_w}}. \quad (9)$$

The force of resistance to water flow passing around the sphere (per unit cross section area) is [14]

$$\sigma_{\text{hydro.sphere}} = \frac{6\mu_w V_w}{r_p}. \quad (10)$$

A spherical dispersed particle will be detached from the fiber surface at the flow-around velocity

$$V_w \ge \frac{r_p}{6\mu_w} F_{\text{rel}}. \quad (11)$$

The calculated flow-around velocities required for the detachment of lamellar and spherical dispersed particles from the fiber surface and the Reynolds numbers

$$\mathrm{Re} = \frac{V_\mathrm{w} d_\mathrm{f}}{\nu_\mathrm{w}}, \quad (12)$$

where V_w is the mean velocity of water in the flow passing around the fiber (m s^{-1}), d_f is the fiber diameter (m), and ν_w is the kinematic viscosity of water (m^2 s^{-1}), are given in Table 2.

When calculating the Reynolds numbers, the fiber diameter was taken equal to 30 μm. The calculation results (Table 2) show that detachment of flat dispersed particles from fibers required approximately 1000 times higher flow-around velocity than detachment of spherical particles. The Reynolds numbers higher than 10 indicate that the inertial forces of the water mass flowing around fibers are 10 times larger than the viscosity forces arising at shear flow of water. At Reynolds numbers of 1.0 and lower, the water flow can be characterized as "creeping" [13], at which the water flow lines follow the shape of the body around which the water flows. The majority of forming and dewatering devices of the paper machine wet end operate at $\mathrm{Re} \leq 1.0$, allowing maintenance of product quality [1]. The flow is also laminar in such processes as washing, filtration, and dewatering of the pulp slurry. Their productivity is enhanced by using vacuum, multistage processing, and high-tech equipment [3].

CONCLUSIONS

(1) The theoretical analysis of the adhesion interaction of dispersed particles with cellulose fibers and of the hydrodynamic conditions of detachment of dispersed particles from the fiber surface shows that, to detach the dispersed particles, it is necessary to ensure the hydration of the fibers and to create a hydrated layer of thickness no less than 10 Å on their surface determining structural repulsion of dispersed particles.

(2) The most complete separation of dispersed particles from the fibers can be reached only via filtration of water through a fiber bed in the "creeping" flow mode, provided that the dispersed particles to be separated are predominantly spherical.

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