MECHANISM OF BLOCKAGE DURING PUMPING OF CONCENTRATED WATER–COAL SUSPENSIONS

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It is proved that blockages form in flow of concentrated water–coal suspension in a pipeline because the maximum possible flow rate of the solid phase is limited due to the fact that the viscosity of the suspension grows exponentially with increasing concentration.

A concentrated water–coal suspension (WCS) is a mixture of water and finely dispersed coal powder with particle size ranging from 20 to 300 μm; the volume concentration of the solid phase is equal to 55-60%. Such a suspension, which has the consistency of a paste, has two important properties: first, it flows, i.e., it can be transported along pipes; second, in contrast to other hydromixtures [1, 2], it does not separate when pumping stops, because the weak structure formed in it prevents the particles from settling. In addition, at the indicated concentrations WCS can be used as fuel in boiler systems without predehydration. Because of these circumstances, specialists have become interested in concentrated suspensions as an alternative fuel, making it possible, on the one hand, to conserve fuel oil and, on the other, to solve the problem of transporting coal from the richest, but remote deposits.

Many problems, such as pulverization of coal, preparation of suspensions with the required properties, burning of a mixture, etc. [3], have been solved in the course of the development of the technology of transportation of concentrated water–coal suspensions along pipes. But the first time these suspensions were pumped in practice, investigators encountered an unexpected problem – blockage. The essence of the complications arising, lies in the fact that when such suspensions are transported along a pipeline there form blockages, which block the main pipeline. When this happens, the pipeline is observed to contain alternating sections, occupied with an almost water-free solid phase or, conversely, a suspension with a low concentration.

Figure 1 shows the results of measurements of the concentrations of a suspension in trials of a 500 mm in diameter and 180 km long coal pipeline. Curve 1 gives the concentration of the suspension as a function of the volume of the liquid pumped into the pipe. Although the fluctuations of this concentration are insignificant, the average concentration remains more or less stable. Curve 2 was obtained by analogous measurements, but at a distance of 90 km from the start of the pipeline. Here the concentration fluctuates significantly, indicating formation of zones of increased and decreased density in the pipe. In such a situation the pipeline is usually shut down after some time.

The mechanism of blockage formation is still not completely clear. There are many diverse opinions. Some investigators believe that this phenomenon is associated with separation of the suspension (though under static conditions separation has not been observed over the time intervals studied). Other investigators attribute blockage to breakdown of the granulometric composition when the suspension is prepared for transport. Still other investigators attribute blockage to high ash content of the coal, etc. We believe that blockage occurs for a different reason: the mobility of the solid phase of the suspension decreases abruptly when the concentration of the suspension exceeds some limiting value. We found that the flow rate of the solid phase in the pipeline has a maximum point as the concentration increases. Up to some value of the concentration the flow rate increases monotonically and beyond this point it drops. For this reason, as the suspension concentration is increased at the pipe entrance there comes a time when the pipe can no longer pass the quantity of coal pumped into it, the concentration of the suspension in the pipe increases abruptly, and a blockage is formed.

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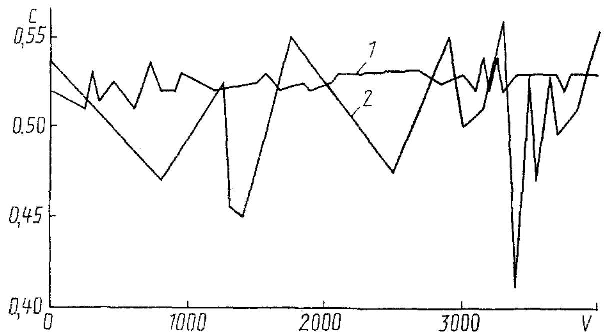

Fig. 1

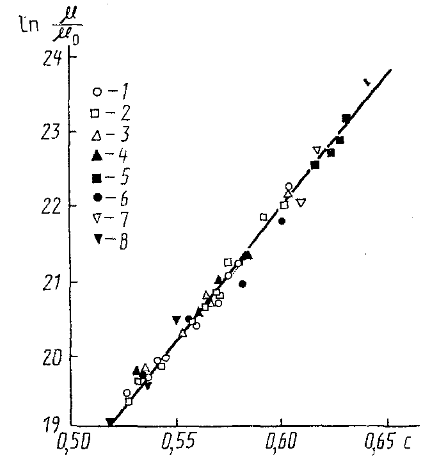

Fig. 2

Fig. 1. Experimental dependence of the volume concentration of the suspension as a function of the volume of the water–coal suspension pumped into the pipeline: 1) at the pipe entrance; 2) at a distance of 90 km from the start of the pipe. V, m^3.

Fig. 2. Experimental curve of the viscosity versus the concentration for different WCS with coal from the Kuznets basin: 1) ash content of the initial coal A = 11.2%; 2) 16.3%; 3) 16.0%; 4) 19.5%, grade D coal, NFU plasticizer added; 5) 11.5%, USHCHR plasticizer added; 6) 12.5%, grade G coal, NFU plasticizer added; 7) 19.5%, NFK plasticizer added; 8) 8.7%. no additives).

In order to prove this assertion we examine the equations describing an incompressible mixture of a liquid and solid particles in the flow of the liquid. These equations have the form

$$\frac{\partial c}{\partial t}+\frac{\partial vc}{\partial x}=0;\quad \frac{\partial(1-c)}{\partial t}+\frac{\partial u(1-c)}{\partial x}=0. \tag{1}$$

Adding the equations term by term, we obtain the condition

$$vc+u(1-c)=u_m \tag{2}$$

which means that the volume flow rate of the mixture along the pipeline remains constant, and without loss of generally, the volume flow rate u_m of the suspension can be assumed to be constant.

The velocities u and v of the phases can be found, if Eqs. (1) are supplemented with the equations of motion of the liquid and the particles. Neglecting acceleration of the components these equations have the form

$$-\frac{\partial p}{\partial x}-\frac{4\tau_m}{d}(1-c)-f_{int}-\rho_1(1-c)g\sin\alpha=0,$$

$$-\frac{4\tau_m}{d}c+f_{int}-\rho_2 cg\sin\alpha=0, \tag{3}$$

where f_{int} is the interaction force acting between the phases, and, as a rule, this force is proportional to the difference of the velocities of the phases and can be written in the form $f_{int} = k(u - v)$, where k is the coefficient of proportionality.

The equations presented above imply the following equalities:

$$\frac{4\tau_m}{d}=-\frac{\partial p}{\partial x}-\rho_m g\sin\alpha=\frac{f_{int}}{c}-\rho_2 g\sin\alpha.$$

Expressing f_{int} in terms of the difference of the phase velocities, we find

$$u-v=-\frac{c}{k}\left[\frac{\partial p}{\partial x}-g\Delta\rho(1-c)\sin\alpha\right], \tag{4}$$

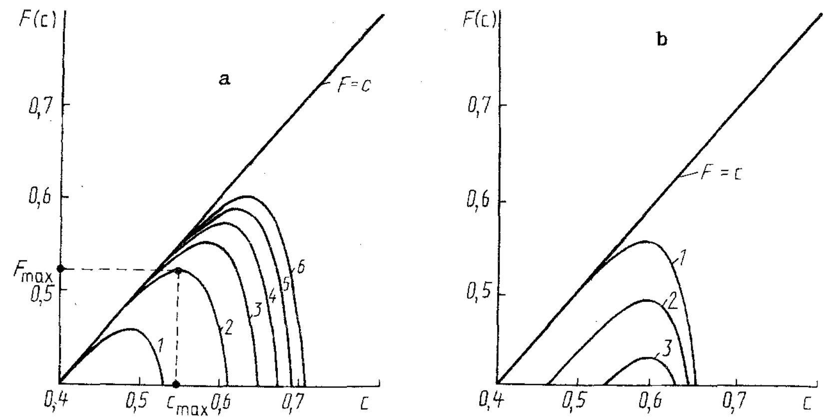

Fig. 3. Mobility F(c) of the solid phase versus the suspension concentration in pipelines of different diameters and versus the slope angles with respect to the horizontal plane: a) $\alpha = 0°$, u = 1 m/sec, k = 400; 1) d = 0.1 m; 2) 0.3; 3) 0.5; 4) 0.7; 5) 0.9; 6) d = 1.1 m; b) d = 0.5 m, u = 1 m/sec, k = 400; 1) $\alpha = 0°$; 2) 10; 3) 20.

where $\Delta\rho = \rho_2 - \rho_1$ is the difference of the densities of the particles and the liquid.

We note that Eq. (4) is, to a certain extent, equivalent to Darcy's filtration law, and the problem so obtained is equivalent to the Bakley–Leverett problem in the theory of two-phase filtration [4].

Solving Eqs. (2) and (4) simultaneously, we obtain the following expressions for the velocities of the solid and liquid phases separately:

$$u = u_m - \frac{c^2}{k}\left[\frac{\partial p}{\partial x} - g\Delta\rho(1-c)\sin\alpha\right],$$
$$v = u_m + \frac{c(1-c)}{k}\left[\frac{\partial p}{\partial x} - g\Delta\rho(1-c)\sin\alpha\right]. \quad (5)$$

The pressure gradient in these formulas can be eliminated, if it is expressed in terms of the hydraulic resistance of the suspension. Confining our attention to laminar flow, which corresponds to the situation in practice, we set

$$\frac{\partial p}{\partial x} = -\frac{32\mu(c)u_m}{d^2}.$$

Here $\mu(c)$ is the dynamic viscosity of the suspension, which depends on the concentration c of the solid phase. Substituting these expressions the formulas (5) can be rewritten in the final form

$$u = u_m\left[1 + \frac{c^2}{k}\left(\frac{32\mu}{d^2} + \frac{g\Delta\rho}{u_m}(1-c)\sin\alpha\right)\right],$$
$$v = u_m\left[1 - \frac{c(1-c)}{k}\left(\frac{32\mu}{d^2} + \frac{g\Delta\rho}{u_m}(1-c)\sin\alpha\right)\right]. \quad (6)$$

It follows from the obtained expressions that the velocity u of the carrying liquid is always higher than the velocity u_m of the mixture, and the velocity v of the solid phase is always lower than this value. The difference depends on the concentration of the suspension and a number of other parameters.

Substituting the second expression in Eqs. (6) into the first equation of the system (1), we obtain a nonlinear equation for the concentration of the suspension:

$$\frac{\partial c}{\partial t} + u_m\frac{\partial F(c)}{\partial x} = 0. \quad (7)$$

In this equation the function F(c) determines the so-called "mobility" of the solid phase:

$$F(c) = c[1 - c(1-c)(32\mu/d^2k + g\Delta\rho(1-c)\sin\alpha/u_m k)].$$

Continuing the filtration analogy, we note that the obtained quasilinear equation (7) is characteristic for the well-known problem of two-phase filtration; the general theory of such equations is given in [5] and is applied to the Bakley–Leverett problem in [6]. In particular, it is well known that the solutions of Eq. (7) are determined by the form of the function F(c), and for this reason we examine this question in greater detail.

It has been established experimentally that the suspensions under study retain Newtonian properties right up to high (of the order of 70%) concentrations of the solid phase, though the viscosity μ of these suspensions depends strongly on the solid-phase concentration. Of course, it has not been excluded that at low shear velocities, for example, "structuring" of the flow, resulting in blockage, can occur on the axis of the flow. However, it is shown below that blockage develops even when this effect is neglected.* Figure 2 shows the viscosity μ as a function of the concentration c in the working range of concentrations. One can see from this plot that the viscosity $\mu(c)$ changes strongly with small changes in concentration. Thus, for example, when c is varied by only 2% the viscosity can change by almost a factor of two. In this case this dependence can be approximated by the formula

$$\mu = \mu_0 \cdot \exp\left[\frac{37{,}742(c - 0{,}555)}{0.25c + 1}\right]. \tag{8}$$

In particular, for the suspension under study μ_0 can be set equal to 0.5 kg/(m·sec); for other suspensions the parameters in Eq. (8) can be of a similar order of magnitude.

Figure 3 shows curves of F(c) for both horizontal ($\alpha = 0$) and inclined ($\alpha \neq 0$) pipelines with different diameters; the coefficient k is set equal to $4 \cdot 10^2$ N·sec/m⁴. One can see that the function F(c) has a maximum at $c = c_{max}$. Up to a certain concentration it is virtually identical to the straight line F = c and reaches a maximum value F_{max} only near concentrations for which $\mu(c)$ starts to increase rapidly, and beyond this point F decreases rapidly. The maximum value F_{max} of the function F(c) increases with increasing pipeline diameter, but it decreases with increasing slope angle of the pipeline with respect to the horizontal plane. For large values of c the function F(c) once again increases, so that F(1) = 1.

The behavior of the function F(c) has an obvious explanation. The flow rate $u_m F$ of the solid phase is determined by the product of two cofactors – an increasing factor (the concentration) and a decreasing factor (the velocity of the solid phase). For low concentration the first cofactor predominates; for $c > c_{max}$, when the viscosity of the suspension starts to increase strongly, the second cofactor predominates. For this reason, the curves F(c) have a maximum.

We examine first the stationary pumping of a concentrated water–coal suspension. It follows from Eq. (7) that the flow rate of the solid phase must be constant along the pipeline and equal to the flow rate of this phase at the entry into the pipeline: $u_m F(c) = u_m c_*$. Here c_* is the content of the solid phase in the flow, i.e., the concentration of the suspension that is fed into the pipeline. However, the true concentration c is established in the pipeline according to the equation

$$F(c) = c_*. \tag{9}$$

If $c_* < F_{max}$, then a solution of Eq. (9) exists and the concentration c_* is close to c; if c_* is significantly smaller than F_{max}, then c_* and c are virtually identical to one another, while for c_* close to F_{max} there is a difference. Thus, for example, for a pipeline with a diameter of 1100 mm and a flow concentration of 55%, the true content is equal to 55.1%, while in a pipeline with a diameter of 500 mm the true content is 57.5%. Such differences, in spite of the fact that they are seemingly small, can strongly affect the pumping states and the possibility of pumping the suspension at all.

If $c_* > F_{max}$, then the pipeline cannot support the flow rate of the solid phase fixed at the pipeline entrance. In this case the concentration increases abruptly up to values close to unity, and pumping becomes impossible.

Rising sections of the pipeline are even more dangerous for pumping concentrated suspensions. If pumping under these conditions is conducted with concentrations close to F_{max},

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* Professor Z. P. Shul'man called our attention to the possibility of "structuring" of the flow.

then the presence of a rise in the pipeline decreases the value of F_{max} by another several percent and there arises a real danger of blockage forming in the pipeline (Fig. 3b).

We shall make one other assertion without proof. It follows from the theory of hyperbolic quasilinear equations and consists of the following: if the conditions under which a stationary pumping state exists $c_* < F_{max}$ are satisfied in all sections of the pipeline, then any increase or decrease of the density arising in the suspension, that does not result in breakdown of this condition, vanishes in time, i.e., in this respect the pumping states are stable.

NOTATION

x, t, the spatial and time coordinates; c, the volume concentration of the solid phase in the suspension (true content); c_*, the content of the solid phase in the flow at the pipe entrance; u, v, the velocities of the liquid and solid phases; u_m, the volume velocity of the mixture; ρ_1, ρ_2, the densities of the liquid and particles, respectively; p, the pressure; τ_m, the tangential stress on the inner surface of the pipeline for the mixture regarded as a whole; f_{int}, the force of interaction between the phases; d, the pipeline diameter; α, the angle of inclination of the pipeline with respect to the horizontal plane; μ, the suspension viscosity; g, the acceleration of gravity; V, the volume of WCS pumped into the pipeline.

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