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INVESTIGATION OF DEEP FILTRATION BY COMPUTER EXPERIMENT

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Deep filtration is investigated by imitating an actual process on an electronic computer. Using the results obtained, the well-known factors and ideas are explained, and a number of new concepts are introduced. A simple equation is suggested that can be used in the practice of the design and calculation of filters.

Filtration as the basic method of cleaning water of suspended substances has recently been challenged by more stringent standards [1, 2], requiring reconsideration of its possibilities and of basic principles underlying the calculation and design of filters. As is usually the case, mathematical simulation turns out to be effective. In [3, 4] a model is described that adequately presents the transfer of inert particles through granular media of a filter and suggests the application of such a criterion for the quality of water as the number density of particles and/or their size distribution in a filtrate. The present work describes the results of simulation in more detail. This is an experiment representing a computer imitation of an actual process of filtration in which the transfer equation is solved by the method of static tests.

Let us turn our attention to Fig. 1. From this figure it is seen that after engaging the filter, its filling with a filterable suspension begins. The concentration front moves deep into the filter media. Simultaneously, the cleaning process proper starts in the preceding layers. The decrease of the concentration of particles follows an exponential law.

The current concentration changes from the initial one C_0 to a virtually nondecreasing concentration C_{min}, with the latter being attained only at a sufficient height of the filter media layer. The portion of the layer over which the process takes place can be called the cleaning zone*. As the above-lying layers are exhausted, they cease to participate in the cleaning process. The concentration of particles in them increases, i.e., the rear front of the zone starts to move. Beginning from this moment, a steady-state motion of the concentration front takes place [6]. In this case the magnitude of concentrations at the exit of the filter remains equal to the nondecreasing one. If the height of the filter media layer is insufficient, we do not observe the period of constant concentration at the exit. When the rear front of the cleaning zone moves by a distance $1 - l/L$, the concentration of particles in the filter begins to increase. The velocity of the front is determined directly. This can be conveniently done for a point lying on a steep portion of the exponent, for example, one at which $C/C_0 = 0.5-0.6$. Thus, in the B1.1 experiment (Fig. 2) the velocity is equal to 0.8–0.9 cm/min (the numbering of the experiments is that used in [2]). It is clear that the front can start to move before the formation of the cleaning zone stops (to a full or not full depth). The time of the appearance of the assigned concentration in the filtrate, i.e., the time of protective action [7], is also determined directly. The higher the efficiency of cleaning, the higher the accuracy of determining all of the values. The efficiency of cleaning is regarded to be satisfactory if the concentration of particles in the filtrate is at least by two orders of magnitude lower than in the original water.

Figure 1 clearly shows the statistical nature of filtration. It manifests itself in both the fluctuations of the current concentration and their decrease with an increase in the period of averaging. Due to the statistical nature

* The formation of this zone is accounted for in N. A. Shilov's equation [5].

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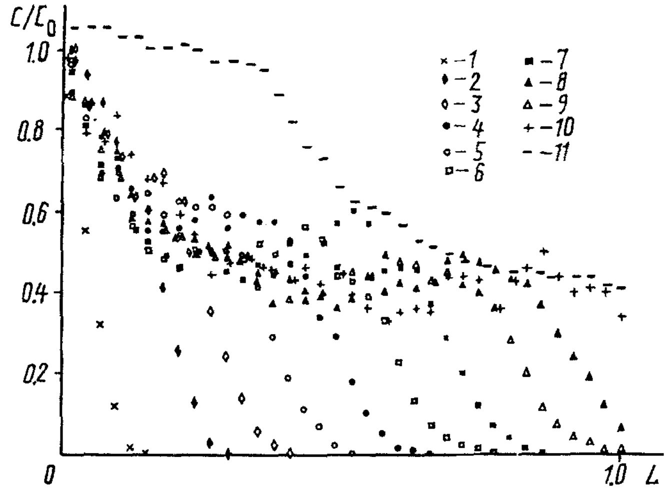

Fig. 1. Variation in time of the concentration of particles over the height of the filter media; experiment A5 (here and below the numbering of experiments and the parameters correspond to those used in [3]): $\tau = 15$ (1), 45 (2), 75 (3), 105 (4), 135 (5), 165 (6), 195 (7), 225 (8); 285 (10); $\Delta\tau = 30$; $\tau = 1050$ (11), $\Delta\tau = 300$.

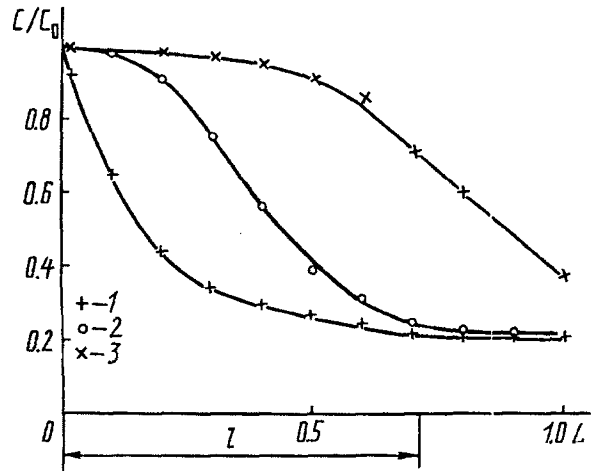

Fig. 2. Movement of the concentrational front, experiment B1.1, $d = 56$ μm; $\tau = 600$ (1), 2700 (2), and 6000 (3).

of filtration, the nondecreasing concentration is to be understood in a relative rather than absolute sense. It seems appropriate to assume that nondecreasing is that concentration whose change over the entire height of the filter media layer does not substantially exceed the fluctuations for a period of time equal to the characteristic filtration cycle.

According to the model adopted [2], the process of cleaning proper consists in the blockage of the openings of pores by active particles and subsequent accumulation of particles until the expansion of the capacity. Those particles are considered to be active (uncaptured, unabsorbed) at a certain time moment that are found to be in an elementary layer and that have not yet entered into the wedged mouth or have not wedged it, since they cease wandering in these cases.

As seen from Fig. 1, wedging starts when the density of active particles becomes sufficient. At a high efficiency of cleaning the dependence of the number of wedged mouths, which characterizes the probability of wedging, is of an extremal nature (Fig. 3). The maximum of wedged mouths corresponds to the steep portion of the concentration exponent and moves together with it. To the left of the maximum, there are no longer any mouths that could be wedged at a given concentration of particles of a given size. The concentration of particles to the right of the maximum is small. At different initial concentrations the extremum occurs at different places at the same

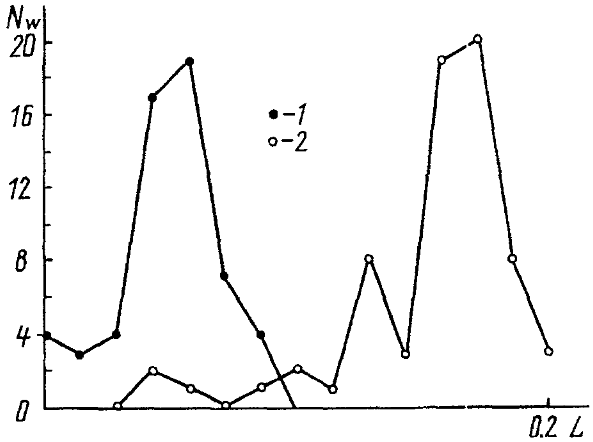

Fig. 3. Movement of the maximum of the number of wedged mouths over the height of the filter media: τ = 300 (1) and 1200 (2); experiment C1.3.

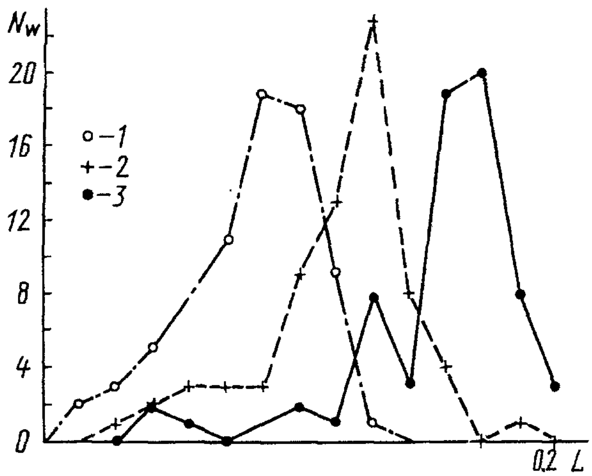

Fig. 4. Influence of initial concentration on the number of wedged mouths, τ = 1200: C_0 = 0.08 (1), 0.165 (2), and $0.25 \cdot 10^6$ liter^{-1} (3).

instant of time (Fig. 4), testifying further to the different rate of exhaustion of the filter media capacity. It should be noted that the maximum values of the number of wedged mouths at different values of C_0 for a given size of particles (90 μm) are equal. The probability of wedging of a mouth in an elementary layer of the filter media is

$$p \sim d^2 \underset{\sim}{C} (N - N_3) \,. \tag{1}$$

The maximum number of the mouths that can be wedged during deep filtering is not equal to the total number of mouths in a given elementary layer [4], since the distribution of mouths is polydisperse even in the case of monodisperse filter media. According to the data of computational experiments, large mouths form an infinite (percolation) cluster, and the probability of their wedging at a given particle size and maximum concentration is vanishingly small. Equation (1) is nonlinear, since the sections of the interaction of particles with the filter media depend on the flow of particles [3]. For example, at close values of the initial concentration in experiments A8.1 and C1.3.1 the number of wedged mouths is equal to 1 and 68, respectively (τ = 1200). If the equation had been linear, the numbers of wedged mouths would differ by nearly 4-fold. We will consider the influence of concentration on the number of wedged mouths for the cases of ineffective and effective cleaning. In the first case (experiments A51. and A8.1) the numbers of wedged pores 10–12 and 1 correspond to initial concentrations of 0.86 and $0.29 \cdot 10^6$ liter^{-1}. In the second case (experiments C1.2 and C1.3) an increase in the concentration by about a factor of 3 does not cause, as already mentioned above, a change in the number of wedged mouths. From Eq. (1) it is seen that a small concentration also makes the probability of wedging small.

TABLE 1. Results of Computational Experiments

No. of experiment	d, μm	$C_0 \cdot 10^{-6}$, liter^{-1}	l, cm	k, cm^{-1}	$C_{min} \cdot 10^{-6}$, liter^{-1}	v, cm/min
A5	44	0.86	4.5	0.4	~0.29	0.36
A8	44	0.29	–	–	0.29	–
B1.1	56	0.51	3–3.6	0.55	~0.1	0.8–0.9
C1.3	90	0.25	0.57	2.06	0	0.36

After the wedging of mouths, particles accumulate in the ordinary way. The mass of accumulated particles and the number of active particles change over the height similarly to the concentration, whereas their total number increases linearly in time up to the exhaustion of dirt-holding capacity. Saturation of the elementary layer and cessation of the wedging of pores in it are attained simultaneously in the computational experiments performed, although the first process can generally lag behind the second [4]. Possible separation of the particles accumulated [7, 8] does not influence the number of active particles (and current concentration), since it is indistinguishable against the background of substantial fluctuations characteristic of them.

Several equations are known that connect the distributions of the grains of the filter media with the particles that wedge (colmatage) these filter media:

$D_{60}/d \leq 5-6$ (A. N. Patrashev) [9],

$D_{15}/d_{85} \leq 4-5$ (M. M. Sokol'skii, S. N. Moiseev) [9],

$D_{60}/d_{70} \lesssim 7$ (V. V. Burenkova) [9],

$D_{15}/d_{85} \leq 5$ (Cedergen) [2].

The quantity $D_i(d_j)$ means that $i(j)$ % of the mass distribution of grains (particles) has a smaller diameter. The numerical values in V. V. Burenkva's conditions are given for homogeneous filter media.

The results of the computational experiments show that stable colmatage sets in when $D/d \lesssim 7.9$ (experiment C1), which approximately corresponds to V. V. Burenkova's condition. On the other hand, it is known that particles pass through the filter media when $D_{15}/d_{85} \geq 25$ [9]. In our case, we did not observe wedging when $D/d \geq 16$ (experiment A8). Thus, the experimental relations used in hydraulic engineering [2, 9] can also be applied to water-cleaning filters, but it should be taken into account that they provide some safety margin for calculations. Apart from these equations, we can recommend the following simple equation for designing filters:

$$C(z, \tau) = (C_0 - C_{min}) \exp(-k[z - v\tau]), \quad z \geq v\tau. \qquad (2)$$

The quantities entering into this equation are considered above and, when the equation is used in the practice of design, they are determined preliminarily in the course of a computational experiment for specific conditions. The coefficient k is attributable to the processes of the wedging of mouths and accumulation of particles. As an example, Table 1 contains the values of the quantities obtained in certain computational experiments.

Conclusions. A computational experiment, i.e., imitation of an actual process of deep filtration on an electronic computer by the method of statistical tests, makes it possible to confirm and explain the familiar facts and ideas from unique positions and to introduce a number of new concepts useful for the theory and practice of filtration.

For a simple model that takes into account the wedging of particles being filtered, the resulting quantitative characteristics of the process can be used for designing filters. The proposed approach makes it possible to adequately take into account such indices of water quality as the number density and size distribution of suspended particles.

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NOTATION

z, space coordinate along the height of the layer; τ, time; C_0, C, C_{min}, initial, current, and nondecreasing concentration, respectively; l, length of the zone of cleaning; L, height of filter media; d, diameter of a particle; N, N_w, maximum number of mouths that can be wedged and the number of the mouths wedged; D, diameter of a grain in the filter media; v, velocity of the rear front of the zone of cleaning.

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