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MODELLING OF THE FLOCCULATION–FILTRATION PROCESS

Of the phenomena involved in the filtration process, flocculation has been distinguished as dominant in water treatment. To describe this process, mathematical models have been derived. On the basis of the models, optimum parameters of filter operation for flocculation have been determined.

Analysis of the zeta-potential effect has revealed that this parameter influences both the degree of particle removal by filtration and the dynamics of head loss. On considering the equilibrium of surface forces, the tangential stresses acting on the flocs in the pores of the filter bed have been determined and related to the velocity gradient of fluid motion. These have enabled determination of the strength of flocs during filtration. By virtue of the flocculation model, a number of relations, which may be useful for design purposes, have been established.

NOTATIONS

η – absolute viscosity,
ν – kinematic viscosity,
ε – porosity of filter bed,
ϱ – density of water,
ϱ_m – density of filter bed media,
σ – specific deposit,
τ – shear stress,
C – constant,
C' – constant,
d – grain size of the filter media,
G – velocity gradient of fluid motion,
$\Delta H/L$ – unit head loss,
n – compressibility coefficient of flocs,
K – Kozeny–Carman constant,
$\Delta p/L$ – unit pressure drop,
R – radius of capillary,
W – energy dissipation,
v – filtration rate,
1, 2 – subscripts denoting filter bed medium 1 and filter bed medium 2, respectively.

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1. INTRODUCTION

Flocculation is amongst the most common processes encountered in engineering practice, and many models are available for expressing the mathematical relationship between its variables. In water technology, the mathematical model accepted to flocculation includes the velocity gradient of fluid motion, which characterizes energy consumption during mixing. Thus,

$$G = \sqrt{\frac{W}{\eta}}. \tag{1}$$

Among the various phenomena involved in the filtration process, flocculation deserves attention as a contributing factor, the more so as no mathematical models have been reported so far to describe it.

The objective of this study was to bridge this gap by deriving a model which would describe the phenomenon of flocculation as a part of the filtration process. There is also included the basic model of the fluid motion velocity gradient measuring the intensity of mixing. In a certain range of the velocity gradient values (which depends on the flocculation method applied), agglomeration of flocs occurs: lower gradients yield their sedimentation, whereas higher values cause their destruction, which owes its origin to the action of shearing forces. Hence, we can say that the velocity gradient is a measure of the shearing forces which account for the damage of the floc structure when the floc strength value has been exceeded.

In the range of velocity gradients optimal for the agglomeration of particles, floc strength is substantially greater than the destructive action of shearing forces. Thus, we may assume that the velocity gradient is also an indirect measure of the floc strength.

2. VELOCITY GRADIENT OF FLUID MOTION IN THE FILTRATION PROCESS

Deriving a model to describe flocculation during the filtration process, it has been assumed that the increment of head loss is an adequate indicator of the energy necessary for the filtration of water carrying suspended solids. For the mathematical description of head loss, the modified Kozeny–Carman equation, making use of the theory of hydraulic radius, has been adopted. The Kozeny–Carman equation yields a good consistency of calculated and actual experimental values. Modifications of Kozeny–Carman equation take into account the presence of flocs in the water to be purified by filtration. Thus [1]

$$G = \frac{1-\varepsilon}{\varepsilon^2}\frac{v}{d}\sqrt{\frac{\varrho_m-\varrho}{\varrho}K}. \tag{2}$$

The relation quantifies the effect of filter media density, bed grain size, bed porosity and filtration rate on the flocculation in filter beds. To analyze the effect of bed density on the velocity gradient, relations for some filter media (their parameters are listed in table) have been determined. The relations hold for both initial and final filter runs (fig. 1) [2]. On the basis of these relations the following generalization can be made: identical flocculation conditions are maintained at increasing filtration rate and decreasing filter bed density.

Table

Characterization of filter bed media

Filter type	Density g cm^{-3}	d_{10} mm	d_{60} mm	ε
sand	2.65	0.70	0.90	0.35
anthracite	1.65	0.80	1.10	0.40
activated carbon	1.30	0.75	0.95	0.45

In the course of the filter run, flocculation conditions undergo unfavourable changes, and the maintenance of a constant velocity gradient (i.e., constant conditions of flocculation) requires decrease of the filtration rate in the filter run to a half or even to one third of the original value (fig. 1).

Analyzing the velocity gradient, it is possible to state:

1) low-density filter beds are best suited for flocculation (activated carbon may

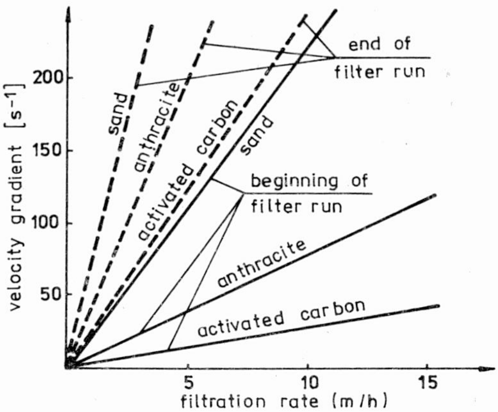

Fig. 1. Velocity gradient of fluid motion versus filtration rate for various filter beds

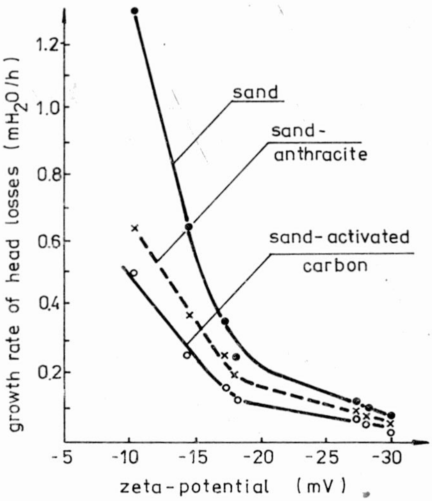

Fig. 2. Effect of zeta-potential on the dynamics of head loss

be of utility: this medium is generally considered applicable as a sorbing material; on the other hand, irrespective of sorption capacity variations, activated carbon is believed to be a good filter medium),

2) application of sand to maintain optimal flocculation conditions may be taken into account at filtration rates $\leqslant 3$ m/h (which are considerably lower than those applied in engineering practice),

3) for the flocculation it would be advisable to operate the filters at a filtration rate decreasing with time.

Another flocculation model is determined by mathematical definition as the derivative of the filtration rate (unit flow by Hagen–Poiseuille law) by the capillary radius. Thus, [3]

$$G = \frac{(2n-1)\,C}{4\eta}\frac{\Delta p}{L}R^{4n-3}. \tag{3}$$

Model (3) relates the flocculation effects to compressibility of suspended solids (which characterizes the specific deposit) and capillary radius (which is a feature of the filter bed). Assuming that the capillary radius is a linear function of grain size, and considering model (2) and model (3), we obtain a formula describing the head loss as a function of the following factors: filtration-rate, floc properties and bed parameters:

$$\frac{\Delta p}{L} = \frac{1-\varepsilon}{\varepsilon^2}v\sqrt{\left(\frac{\varrho_m}{\varrho}-1\right)K\frac{4}{(2n-1)\,C}d^{2(1-2n)}}. \tag{4}$$

In this model there are included two additional parameters which have not been considered so far, i.e., bed density and floc compressibility. Each of them exerts an influence on the head loss in the course of the filter run.

3. ELECTROKINETIC POTENTIAL

On the basis of experiments, the dynamics of head loss increment has also been related to the zeta-potential, a parameter characterizing the electrical properties of colloids and flocs (fig. 2) [2].

While analyzing the rate, at which head loss increased, it became evident that the optimum operation conditions of the filter beds under study were at the particle potential equal to or higher than -17.5 mV. A further decrease in particle zeta-potential brought about a rapid increment in head loss. This relation holds for turbidity removal (fig. 3) in the whole range up to -17.5 mV. COD removal was achieved at the zeta-potential of coagulated particles, i.e., at -14.0 mV, in all of the filter beds studied.

At higher zeta-potential, the COD removal depended on the type of the filter bed applied. Sand-and-carbon beds yielded the best results. Zeta-potential was an

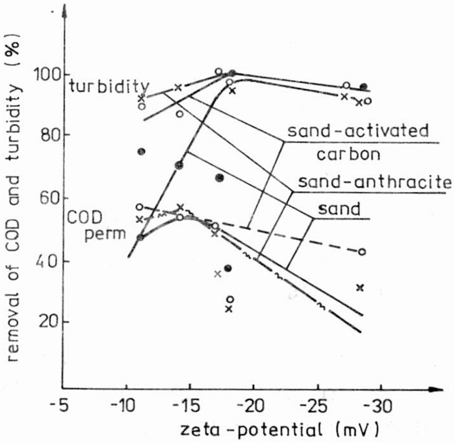

Fig. 3. Turbidity and COD removal versus zeta-potential

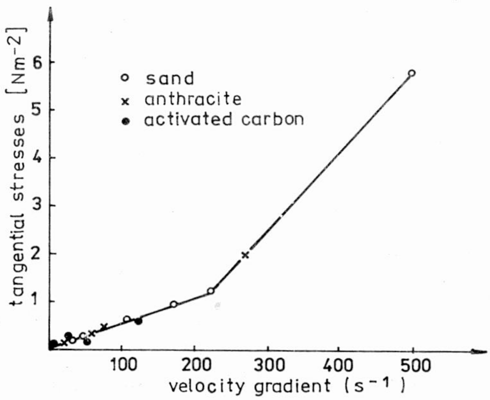

Fig. 4. Effect of velocity gradient of fluid motion on tangential stresses

indicator that enabled us to make a distinction between flocculation and sorption effects in the filtration process.

The optimum zeta-potential values for the particles removed by filtration differ markedly from those for the particles coagulated in a volume system (coagulation and sedimentation). The efficiency of flocculation in a volume system increases considerably when the zeta-potential value approaches zero. In the filtration process a strong decrease in the zeta-potential value of coagulated particles accounted for the following statements:

1) sorption properties of the bed were not utilized,

2) flocculation occurred in the upper layers of the bed, thus contributing to surface clogging,

3) head loss increased rapidly (which was not necessarily associated with the phenomenon described in item (2)).

As a result of excess head loss, as well as the disturbed balance of forces acting in the bed, the flocs retained may be destructed and can cause a deterioration of water quality (break-through of the filter bed).

4. TANGENTIAL STRESSES

Considering the balance of forces that act during the filtration process, it is possible to determine the tangential stresses acting in the bed pores. They take the form [3]:

$$\tau = \frac{d}{4}\left(\frac{\varrho_m}{\varrho}-1\right)\frac{\Delta p}{L}\frac{\varepsilon-\sigma}{\varepsilon}. \tag{5}$$

In a successive step the tangential stresses were related to the velocity gradient (combination of (5) and (3))

$$\tau = \frac{2\eta G}{(2n-1)C} R^{4(1-n)}. \tag{6}$$

Relation (6) shows that the tangential stresses acting in the pores are proportional to the velocity gradient and inversely proportional to the compressibility of flocs. Thus, it may be assumed that there exists a relationship between the compressibility of flocs and their strength. The effect of velocity gradient on tangential stresses is shown in fig. 4.

There exists an indication that the filtration conditions change at the gradient of 220 s^{-1}. In the literature, $G = 219$ s^{-1} is reported to be the limit value for the filtration process [4]. We may, therefore, assume that in engineering practice (at filtration rate of 5 m/h, filter bed parameters those as in table, and alum coagulation) the strength of the flocs is equivalent to the tangential stresses acting on them (~ 1.2 N/m^2). Increase of tangential stresses may lead to destruction of flocs and their washout from the filter bed (this process has been observed for sand filters).

5. APPLICATION OF MODELS TO DESIGN PRACTICE

Some of the relations described by mathematical models were utilized in the design of multi-media filters (this holds primarily for filtration rate and bed depth). Flocculation model (2), which enabled determination of filtration rate and grain size [3], was of particular usability. Another formulation of the model expressed as [5]

$$G = \sqrt{\frac{\Delta H}{L} \frac{\varrho_m - \varrho}{\varrho} \frac{vg}{\nu} \frac{1}{\varepsilon}} \tag{7}$$

made it possible to calculate the optimum depth of the filtration layers in multi-media beds and the optimum filtration rate (both for the purpose of flocculation). Assuming that $\Delta H/L =$ const and $G =$ const, relative filtration rate for multi-media beds takes the form [5]:

$$\frac{v_2}{v_1} = \frac{\varrho_1 - \varrho}{\varrho_2 - \varrho} \frac{\varepsilon_2}{\varepsilon_1}. \tag{8}$$

For double-media filters it is assumed that $v =$ const and $G =$ const. Thus, under conditions of continuous flow, the relation may be written as follows [5]:

$$\frac{L_2}{L_1} = \frac{\varrho_2 - \varrho}{\varrho_1 - \varrho} \frac{\varepsilon_1}{\varepsilon_2}. \tag{9}$$

It is worth noting that the activated carbon layer of a sand–carbon bed designed for flocculation is thiner than an activated carbon layer designed for sorption purposes.

6. CONCLUSIONS

1. The filtration process was described by flocculation models which include the mean velocity gradient of fluid motion. The flocculation models have the inherent advantage that they quantify the flocculation effects relating them to filter media density, grain size, filtration rate and compressibility of flocs.

2. Some of the relations included in the models were utilized in the design of the filtration process.

3. Analysis of the zeta-potential enables a distinction between flocculation effects and sorption effects in filter beds.

4. Considering the balance of surface forces in the filter bed, it is possible to determine the tangential stresses acting in the bed pores. On relating the tangential stresses to the velocity gradient, the strength of flocs was established.

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MODELOWANIE PROCESU FLOKULACJI–FILTRACJI

Ze zjawisk związanych z filtracją, flokulacja jest procesem dominującym w oczyszczaniu wody. Aby ją opisać, wyprowadzono modele matematyczne, na podstawie których określono optymalne parametry pracy filtru podczas flokulacji.

Analiza potencjału zeta dowiodła, że parametr ten wpływa zarówno na stopień usuwania cząstek w czasie filtracji, jak i na dynamikę filtracji. Rozważając równowagę sił powierzchniowych określono naprężenia styczne działające na kłaczki w porach filtru i powiązano je z gradientem ruchu cieczy. Pozwoliło to określić wytrzymałość kłaczków podczas filtracji. Na podstawie modelu flokulacji ustalono równania, które mogą być przydatne w projektowaniu.

МОДЕЛИРОВАНИЕ ПРОЦЕССА ФЛОКУЛЯЦИИ–ФИЛЬТРАЦИИ

Из явлений, связанных с фильтрацией, флокуляция является процессом, доминирующим в очистке воды. Для её описания введены математические модели, на основе которых определили оптимальные параметры работы фильтра во время флокуляции. Анализ дзета-потенциала доказал, что этот параметр влияет как на степень удаления частиц во время фильтрации, так и на динамику. Рассуждая равновесие поверхностных сил, определили касательные напряжения, действующие на хлопья в порах фильтра и связали их с градиентом скорости движения жидкости. Это позволило определить прочность клочков во время фильтрации. На основе модели флокуляции были установлены уравнения, которые могут пригодиться в проектировании.