Environment Protection Engineering

Vol. 10 1984 No. 2

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ON FORCES ACTING IN FLOCCULATION–FILTRATION

Flocculation conditions determined by shear stresses in filter media were calculated. Shear stresses were found by a mathematical model, which was derived from the balance of shear and drag forces. The mathematical model relates the filter media grain size, density, porosity and hydraulic losses to the shear stresses. Numerical values of the shear stress calculated from this model varied from 0.044 Nm^{-2} to 5.320 Nm^{-2}. The values of shear stresses increased with the growing filter media density. Thus, filter media of the densities lower than sand are more suitable for a direct flocculation–filtration, since the flocs are exposed to smaller destruction forces. The flocculation conditions in the filter media were analysed by a model expressing shear stresses versus the velocity gradient of fluid motion. The developed model allows us to calculate the limiting value of floc compressibility leading to its destruction.

NOTATIONS

ΔH – head loss,
ΔL – bed layer element,
Δp – filtration pressure drop,
ε – porosity of the filter media,
η – absolute viscosity,
ϱ – density of water,
ϱ_m – density of filter bed media,
σ – specific deposit,
τ – shear stress,
A, C – constants dependent on the type of bed,
d – grain size of the filter media,
d_k – capillary diameter,
g – gravity,
G – velocity gradient of fluid motion,

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K – Kozeny–Carman constant,
n – compressibility coefficient of flocs,
R – radius of capillary,
v – filtration rate.

1. INTRODUCTION

Over the last few years filtration beds have been more and more often used to the so-called flocculation-filtration. Therefore, the analysis of flocculation phenomena occurring in the single and multi-media filter beds is advisable.

The course of the flocculation process is determined by the velocity gradient of fluid motion. The velocity gradient for volume flocculation varies from 20 to $60 s^{-1}$.

The flocculation model of the filtration process has been developed and discussed in the work by KOWAL and MAĆKIEWICZ [3], where the conditions of flocculation were determined from the velocity gradient of fluid motion during filtration, depending on the type and density of filtration beds:

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

The value of the velocity gradient, which describes the flocculation process in the filter media, depends on their density. At a filtration rate of 5 m/h, the velocity gradient values range from 110 to 550 s^{-1} for a sand filter, from 40 to 185 s^{-1} for an anthracite filter, and from 15 to 120 s^{-1} for an activated carbon filter [3].

The model presented is applicable in determining the optimal (for the purpose of flocculation) filtration rates and the required depths of multi-media filters [3].

The efficiency of flocculation is related to the size, density and strength of flocs, therefore the models constructed in the present paper define the shearing stresses affecting the process of destruction of the retained flocs.

2. SHEARING STRESSES IN FILTRATION BEDS

Shearing stresses acting in filter beds are responsible for the floc structure. When the stress value exceeds the floc strength value, the floc structure becomes damaged and a breakthrough takes place. That is why the konwledge of the shear stresses acting in the beds on one hand, and of the floc strength on the other hand enables an optimum run of the flocculation–filtration process.

For unidirectional flow of isothermal non-compressible media, when technological effects are neglected, the shearing stress was determined from the equilibrium of the forces acting in filtration beds, i.e., shearing and drag forces:

$$\pi d_k \Delta L \tau = \frac{\pi d_k^2}{4} \Delta p \,. \tag{2}$$

In the filter run, the capillary diameter was changed according to the changes occurring in filter bed porosity:

$$d_k = d \frac{\varepsilon - \sigma}{\varepsilon} \tag{3}$$

since

$$\tau = \frac{\Delta p}{4 \Delta L} d \frac{\varepsilon - \sigma}{\varepsilon} \,. \tag{4}$$

Parameter σ makes allowances for a decrease in bed porosity during a filter run which is due to the fact, that the flocs were retained in the pores of the bed.

It has been assumed that

$$\Delta p = \Delta H g (\varrho_m - \varrho) \tag{5}$$

where the $(\varrho_m - \varrho)$ term describes the effect of a threecomponent medium (filter media, water and flocs) on the pressure drop [3].

Considering the relation for pressure drop Δp, the shearing stresses are described by

$$\tau = \frac{d}{4} g \varrho \left(\frac{\varrho_m}{\varrho} - 1 \right) \frac{\Delta H}{\Delta L} \frac{\varepsilon - \sigma}{\varepsilon} \,. \tag{6}$$

The shearing stresses calculated from eq. (6) range from 0.233 to 5.320 Nm^{-2} for a sand bed, 0.125 to 1.954 Nm^{-2} – for anthracite and 0.044 to 0.574 Nm^{-2} – for activated carbon, the corresponding shearing times being: 22–11.5 s, 20.2–9.2 s and 32.5–15.8 s. The obtained values indicate that the decreasing bed density is accompanied by the decrease of shearing stresses, therefore the structure of flocs, including those of low strength, is not subject to damage. Thus, for the flocs to be retained in the filter the conditions are better. A similar conclusion was drawn from the analysis of flocculation conditions which had been determined by the velocity gradient of fluid motion G given by the eq. (1).

Figure 1 relates the shearing stresses occurring in the bed to the velocity gradient. From the analysis of these parameters it is evident that at $G = 220\ s^{-1}$ ahere is a change of working conditions in the bed and the stress is then 1.2 Nm^{-2}.

According to other authors [1] the determined flocs strength was of about 180 Nm^{-2} at shearing time of about 2 min. Increase in shearing time caused a rapid drop of admissible shearing stresses. The shearing times calculated for the filter media were substantially shorter and the shearing stress values were lower. This is an indication that there exist favourable conditions for the formation and retention of flocs in the filter bed.

In studies on the flocs strength during flocculation the shearing stresses were related to the velocity gradient and the amount of chemicals added. The greatest shearing stress 1.134 Nm^{-2} was observed at $G=219\ s^{-1}$ [6].

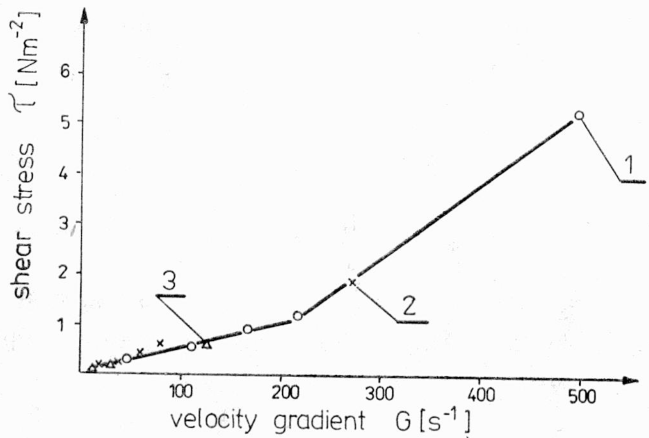

Fig. 1. The effect of velocity gradient on shearing stresses
1 – sand, *2* – anthracite, *3* – activated carbon

Rys. 1. Wpływ gradientu prędkości na naprężenia ścinające
1 – piasek, *2* – antracyt, *3* – węgiel aktywny

In the case of three-layer beds, activated carbon–anthracite–sand, the stresses were analysed as a function of the bed depth [2]. Based on the relations derived by the authors [2], it was observed that the greatest shearing stresses occurred in activated carbon and sand layers, while the smallest ones in anthracite layer. This fact, according to the authors' opinion, testified to the smallest forces which washed the flocs out of the intermediate layer.

Different strength of flocs, which is due to their properties and different conditions in the filter beds, indicates that both the shearing stresses and flocs strength should be related to the velocity gradient of fluid motion and to the flocs compressibility. The following relation describing the velocity gradient was thus applied [4]:

$$G = \frac{(2n-1)C}{4\eta} \frac{\Delta p}{\Delta L} R^{4n-3}. \tag{7}$$

The substitution of eq. (2) into eq. (7) yields the relation describing the shearing stresses as the function of the velocity gradient, flocs compressibility and radius of capillary:

$$\tau = \frac{2\eta G}{(2n-1)C} R^{4(1-n)}. \tag{8}$$

From eq. (8) one can determine the limiting compressibility of flocs at which their structure must be destroyed. This happens when $n = 0.5$ (then $\tau \to \infty$). On the other hand, when $n = 1$, then τ depends neither on flocs compressibility nor on the radius of capillary, and the eq. (8) reads:

$$\tau = \frac{2\eta G}{C}. \tag{9}$$

This case concerns the shearing which appears during a relative motion of fluid layers ruled by the Newton law. Here, a volume flocculation could be considered.

Equation (8), which includes floc compressibility, reduces to the form of the generalized Newton model (eq. 9) when $n = 1$, i.e. when the flocs are non-compressible or they do not interact with one another. Thus, eq. (9) substantiates the validity of both the assumptions and the procedure of derivation for all the equations considered in this paper.

3. FILTRATION PARAMETERS

Sand is the most popular filter bed. Therefore, it was sand for which the fundamental relations between grain-size, filtration rate and velocity gradient-dependent flocculation conditions were determined from eq. (1) and presented in fig. 2. From the relations obtained it follows that flocculation in sand beds

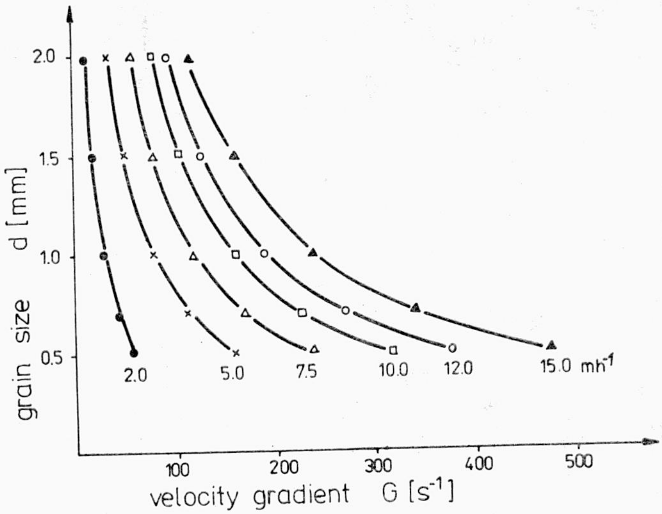

Fig. 2. Velocity gradient and filtration rate versus the grain-size of sand filter
Rys. 2. Wpływ gradientu prędkości i szybkości filtracji na uziarnienie złoża

requires a relatively low filtration rate and greater grain-size. If, however, the sand grain-size is larger than 0.001 m, the flocculation accompanied by hydrolyzing coagulants is hardly effective, then the introduction of polyelectrolytes is recommended and the filtration rate should not exceed 5 m/h [5]. To increase the filtration multi-media filters should be applied. The grain size of different types of beds and the filtration rate can be calculated from the relation:

$$\frac{v}{d} = \frac{G}{A}. \tag{10}$$

At the filtration rate ranging within 2–15 m/h and the grain-size 0.5–2.0 mm, the constant A for sand bed, anthracite bed and activated carbon amounts to 57, 22.4 and 8.15, respectively.

4. CONCLUSIONS

The paper is concerned with the shearing stresses which after exceeding the limiting strength of the retained flocs cause their destruction and washing out of the bed. The shear stresses were defined from the equation of shear and drag equilibrium.

In the model the shear stresses depend on the filter grain-size, density, porosity as well as on the head loss.

The model-based shear stresses for three different types of beds varied from 0.044 Nm^{-2} to 5.320 Nm^{-2}.

The analysis relating the shear magnitude to the velocity gradient of fluid motion testifies the applicability of beds lighter than sand or of multi-media filters to the direct flocculation.

Also a mathematical model, expressed in the form of a generalized Newton law, has been developed. In this model, shear stresses are related to the velocity gradient and flocs compressibility (eq. 8).

The effects of grain-size and filtration rate on flocculation conditions are presented and described by mathematical formulae applicable to sand, anthracite and activated carbon.

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SIŁY DZIAŁAJĄCE W PROCESIE FLOKULACJI-FILITRACJI

Określono naprężenia styczne działające w złożach filtracyjnych podczas procesu filtracji. Wzór, opisujący naprężenia styczne, wyprowadzono z warunku równowagi sił ścinania i oporu. Uwzględnia on wpływ uziarnienia, gęstośći i porowatości złoża oraz strat ciśnienia na wielkość naprężeń stycznych. Wykazano, że w złożach o mniejszych gęstościach materiałów filtracyjnych naprężenia styczne działające na kłaczki są mniejsze niż w złożach o większych gęstościach. Zatem w złożach lżejszych zachowane są lepsze warunki do prowadzenia procesu flokulacji–filtracji. Warunki flokulacji, określone naprężeniami stycznymi, analizowano także w zależności od wartości gradientu prędkości i parametrów charakteryzujących kłaczki. Ustalono graniczne wartości ściśliwości kłaczków, przy których następuje zniszczenie struktury kłaczków.

KRÄFTE, DIE WÄHREND DES FLOCKUNGSFILTRATIONSPROZESSES WIRKEN

In der Veröffentlichung wurde die Schubspannung, die im Filterbett während des Filtrationsprozesses wirkt, bestimmt. Die Formel, die die Schubspannung beschriebt, wird aus der Gleichgewichtsbedingung zwischen Abscher und Widerstandskräften abgeleitet. Sie berücksichtigt den Einfluss von Granulation, Dichte und Porigkeit des Filterbettes sowie Druckverlust auf die Größe der Schubspannungen. Es wurde festgestellt, daß in Filterbetten mit niedrigen Dichten des Filtrationsmaterials die Schubspannungen, die auf die Flocken auswirken, kleiner sind als in Betten mit größeren Dichten. Also, in leichteren Betten entstehen bessere Bedingungen für den Flockungsfiltrationsprozeß. Flockungsbedingungen, die durch Schubspannung bestimmt sind, wurden auch in der Abhängigkeit vom Geschwindigkeitsgradient und von Parametern die die Flocken beschreiben, analysiert. Es wurden die Grenzwerte der Kompressibilität der Flocken, bei denen eine Vernichtung der Flockenstruktur auftritt, festgestellt.

СИЛЫ, ДЕЙСТВУЮЩИЕ В ПРОЦЕССЕ ФЛОКУЛЯЦИИ-ФИЛЬТРАЦИИ

В работе определено касательное напряжение, действующее в фильтрационных загрузках в процессе фильтрации. Формула, описывающая касательные напряжения, выведена из условия равновесия сил сдвига и сопротивления. Она учитывает влияние грануляции, плотности и по-

ристости загрузки а также потерь давления на величину касательных напряжений. Доказано, что в загрузках с меньшей плотностью фильтрационных материалов касательные напряжения, действующие на хлопья, меньше, чем в загрузках с большей плотностью. Следовательно, в более легких загрузках сохраняются лучшие условия для проведения процесса флокуляции-фильтрации. Условия флокуляции, определённые касательными напряжениями, анализировались также в зависимости от величины градиента скорости и параметров, характеризующих хлопья. Установлены предельные значения сжимаемости хлопьев, при которых происходит разрушение структуры хлопьев.