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ON THE IMPORTANCE OF VELOCITY GRADIENT IN THE COAGULATION PROCESS

The flocculation process is analysed with dependence on coagulation methods. Equations for velocity gradients allowing for establishment of the flocculation conditions are given. Basic parameters deciding the course and effectiveness of coagulation are determined.

NOTATIONS

α — probability of particle collisions,
ε — filtration bed porosity,
μ — absolute viscosity coefficient, $kg \cdot m^{-1} \cdot s^{-1}$,
ν — kinematic viscosity coefficient, $m^2 \cdot s^{-1}$,
$\varrho, \varrho_k, \varrho_s$ — density of water, flocs and filtration material, respectively,
v — water flow velocity in flocculation chambers, filtration velocity, water flow velocity in the sludge blanket, $m \cdot s^{-1}$,
V — volume of water in flocculation chamber,
b — experimental constant depending on the bed type,
C — volumetric concentration of flocs,
d — diameter of bed grains, m,
F — filter surface, m^2,
g — acceleration of gravity, $m \cdot s^{-2}$,
G — velocity gradient, s^{-1}
ΔH — pressure head loss, m,
K — Kozena–Carman constant,
L — height of filtration bed,
n — number of partitions in flocculation chamber,
N — power , $N \cdot m \cdot s^{-1}$,
N_0 — initial number of particles, m^{-3},
N_t — number of particles after time t, m^{-3},
Δp — filtration pressure drop, $N \cdot m^{-2}$,
Q — flow rate , $m^3 \cdot s^{-1}$,
s — ratational speed , $rev \cdot s^{-1}$,

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t – flocculation time, s,
T – torque, N · m,
W – energy dissipation, $kg \cdot m^{-1} \cdot s^{-3}$.

1. INTRODUCTION

The coagulation described by Smoluchowski depends on the number of colloidal and suspended particles and the probability of their collision. In orthokinetic coagulation the collisions of particles, upon which the stability of their connections depends, result from the way and intensity of mixing. The change of the vector of liquid movement velocity during mixing determines the value of velocity gradient. Hence the liquid movement velocity gradient is the measure of mixing intensity. The choice of the appropriate gradient allows fo control the flocculation phase depending on the conduct of coagulation.

2. VELOCITY GRADIENT IN FLOCCULATION

2.1. FLOCCULATION METHODS

In a classical system of water treatment the volumetric coagulation medium is provided by the dispersion medium of the colloidal system. The flocculation phase takes place (due to the collisions of destablized particles) in separate installations, either mechanical or hydraulic, called the chambers of reaction or slow mixing.

Surface coagulation in which gel is originated not only in the dispersion medium but also on the contact mass surface forming instead of single flocs, an envelope structure filling up mass pores, is an extreme modification of the coagulation process. Contact mass is a porous medium of either granular or fibrous structure, most often provided by single- or multilayer beds. Apart from mixing in bed pores the course of flocculation is significantly conditioned by the adhesion and adsorption as well as the contact action of the material adsorbed on the surface of filtration beds. The greater are the coagulated particles the less probable is their attraction by the grains of filtration material, so also their adhesion, what lowers the process efficiency. The further course of coagulation is similar to that of volumetric coagulation.

An intermediate method is that of coagulation in the suspended deposit layer. The formation of gel in the dispersion medium allows to consideration of the method as a volumetric one. However, the adhesion and adsorption affecting the method make it similar to surface coagulation.

The coagulation process depends on the mechanism of flocculation whose effectiveness is predominatly conditioned by a proper value of the velocity gradient with respect to the way of directing the process.

2.2. FORMULAS OF THE MEDIUM VELOCITY GRADIENT

The liquid movement velocity gradient [8] is given by

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

The energy dissipation value depends on the type and geometry of mixers and stirrers.

VOLUMETRIC COAGULATION

For the flocculation chambres most often used in volumetric coagulation the energy dissipation is determined as follows — for a mechanical chamber

$$W=\frac{N\cdot 2\pi s}{V} \tag{2}$$

— for hydraulic chambers
a watertwisting chamber and a turbulent one

$$W=\frac{Qv^2\varrho g}{2V} \tag{3}$$

— for a chamber with partitions

$$W=\frac{[nv_1^2+(n-1)\,v_2^2]Q\varrho g}{2V}. \tag{4}$$

VELOCITY GRADIENT IN THE SUSPENDED DEPOSIT LAYER

To determine flocculation in the suspended deposit layer Tesařik and Vostřcil have derived an equation for velocity gradient [7]

$$G=\sqrt{\frac{\mathrm{V}Cgv(\varrho_k-\varrho)}{(1-C)\varrho}} \tag{5}$$

based on the definition of velocity gradient. The energy dissipation has been determined from the increment in potential energy of particles in a fluid layer.

VELOCITY GRADIENT IN FILTRATION BEDS

Filtration is a complex operation consisting of a number of elementary processes (coagulation, sedimentation, cohesion, adhesion). Because of the process complexity there are no explicit criteria describing both the character and results of filtration. The application of filtration beds, especially multilayer ones, to surface coagulation has become more and more popular recently.

To determine the flocculation conditions during filtration an equation for medium velocity gradient was derived based on the assumption that an increment in filtration pressure drops describes adequately the energy consumed during the flow of water with suspension through the bed. For the determination of energy losses the Kozeny–Carman equation was applied, which ensures high conformity with practice [6]. The equation was modified by substituting ϱ with the factor $(\varrho_s-\varrho)$ that indicates the effect of suspension in a three-component mixture (filtration bed, water, suspension) used in the filtration process.

$$\Delta p = \frac{KL(1-\varepsilon)^2}{\varepsilon^3}\frac{V}{d^2}(\varrho s-\varrho). \tag{6}$$

Based on eq. (6) the energy dissipation at water flow through the bed was determined what, in turn, allowed derivation of an equation for the mean velocity gradient in the filtration process [1]

$$G = \frac{1-\varepsilon}{\varepsilon^2}\frac{v}{d}\sqrt{\frac{\varrho s-\varrho}{\varrho}K}. \tag{7}$$

The velocity gradient may be also derived from the capillary theory assuming the laminar flow

$$G = \frac{v}{d}\frac{1-\varepsilon}{\varepsilon^2}b. \tag{8}$$

Eq. (8) obtained for water flow through capillary tubes approximates eq. (7) derived for mixing conditions in a filtration bed which confirms the assumptions made. However the capillary theory, unless simplified, cannot be applied to the filtration process since the capillaries in the bed are irregular. Hence, considering also the fact that both theoretical and practical determination of energy losses in the filtration of water through the bed is not difficult, eq. (7) may be applied to interpretation of the filtration process and the results, especially those concerning the effects of bed density and velocity, may be compared with the practical data.

3. FLOCCULATION ANALYSIS BASED ON THE VELOCITY GRADIENT

By means of the equation for liquid movement velocity gradient we may solve the equation of flocculation

$$\frac{N_t}{N_0} = \exp\left(-\frac{\alpha}{\pi}GCt\right). \tag{9}$$

As it may be seen flocculation effectiveness depends on the concentration of flocs and suspensions, the flocculation time and the velocity gradient. The parameters cannot exceed certain optimum values determined by the character of experiments and testing equipment.

The size and consistence of flocs are conditioned by the gradient value, at high G value small but cohesive flocs are formed, whereas at low G value bigger and more loose ones. The cohesion of flocs may be increased by applying flocculating agents as polyelectrolytes which enables flocculation at higher values of the gradient and a shortened mixing time. The latter parameter is extremely important, especially in classical volumetric coagulation.

3.1. VOLUMETRIC COAGULATION

Volumetric coagulation is characterized by precisely defined intervals for both its parameters and by the criterion number determined by Camp ($C_a = G \cdot t$). The relation results from two opposite processes taking place during mixing i.e. the formation of flocs and their destruction. Formation and destruction are repeated many times, and the final effect depends on their interrelation. At the velocity gradient higher than a certain limiting value, the destruction of flocs is more rapid than their formation, what lowers the whole process effectiveness. Too long a time of mixing, causing too frequent repeatability of flocs formation and destruction, results also in the decrease of coagulation velocity and the size of stable flocs. With the use of classical hydrolyzing coagulants the optimum flocculation time for volumetric coagulation is equal to 15–20 min. The application of polyelectrolytes as auxiliaries or independent coagulants allows the shortening of the flocculation time to 10 min or below [2]. From the investigations of WEJCER and LUCENKO [9] it follows that the optimum values of the Camp number for wastewater coagulated by aluminium sulphate vary from 8,000 to 10,000 and for those coagulated by ferric chloride — from 30,000 to 50,000. This is due to the higher strength of $Fe(OH)_3$ flocs with respect to that of $Al(OH)_3$ flocs. The strength of the alum flocs may be increased by applying polyelectrolytes; then the Camp number approximates the values obtained in coagulation by ferric chloride. The optimum velocity gradient for waste water coagulation, as found by WEJCER [9], is equal to about 50 s^{-1}. Mixing at lower gradients (about 10 s^{-1}) is permissible only for coagulation alum. From the investigations of KOWAL and MAĆKIEWICZ [3] it follows that the of water alum coagulatin takes place practically at the gradients 20–60 s^{-1}. The lower gradient values cannot resist sedimentation even in slow mixing chambers. When polyelectrolytes are applied, low gradients cannot ensure the formation of flocs of a proper structure and resistance [9].

3.2. COAGULATION IN THE SLUDGE BLANKET

In the sludge blanket flocculation the velocity gradient values are low, of about several s^{-1}, due to joining of the processes of flocculation and sedimentation into one installment. The velocity gradient depends on the concentration and density of the formed flocs (eq. (5)). It may vary with the changing flow rate which, in turn, is conditioned by the fluid state of the sludge blanket.

An increase of the gradient, resulting from the increased suspension concentration makes the collisions more probable. On the other hand, a higher gradient value being due to a higher density of flocs (e.g. by the addition of weighting agents) explains the improvement of coagulation effects at a low level of pollution.

The analysis of velocity gradient also points at the unnecessity of applying contact settling tanks with the suspended deposit layer to waters of low level of pollution. By solving the equation of flocculation, the theoretical dependence of coagulation effectiveness on the height of the sludge blanket may determined (fig. 1). It is seen that an increase in the flocs concentration results by the increase of treatment effectiveness and the decrease of influence of the sludge blanket height on flocks removal.

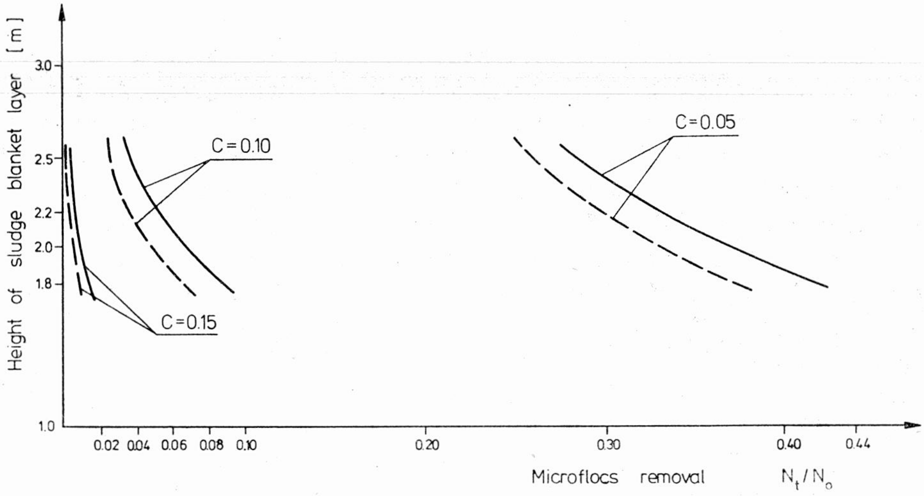

Fig. 1. The removal of particles vs. the height of suspended deposit layer, depending on the volumetric concentration of flocs

Rys. 1. Usuwanie cząstek w funkcji wysokości warstwy osadu zawieszonego zależnie od stężenia objętościowego kłaczków

With the increasing of flocks concentration, the influence of temperature decreases. It may be seen that the concentration of flocks should be increased, especially in winter, to increas e of treatment effectiveness. Theoretically, the total removal of particles seems possible at the layer not higher than 2.5 m. In practice, due to the deposit layer instability the effectiveness of particle arrestment is lower.

3.3. SURFACE COAGULATION IN FILTRATION BEDS

Analysis of the flocculation velocity gradient indicates the importance of the filtration bed density (fig. 2). Since the flocculation proceeds in water medium, the density of water is assumed to be a limiting value. When bed density is close to water density, the gradient is low and approaches 0. The sludge blanket may be considered as the bed of low density. The advantages of applying low gradients ensuring proper floculation and sedimentation of flocs have already been indicated [2].

With increasing material density the gradient increases as well. Flocculation conditions may be kept constant by applying the filtration velocity appropriate to bed density, e.g. in the case of pure filtration beds the respective velocities are equal to 1–3 m/h in the sand bed, 3–7.5 m/h in the anthracite bed, and 7.5–15 m/h in the activated carbon bed [1].

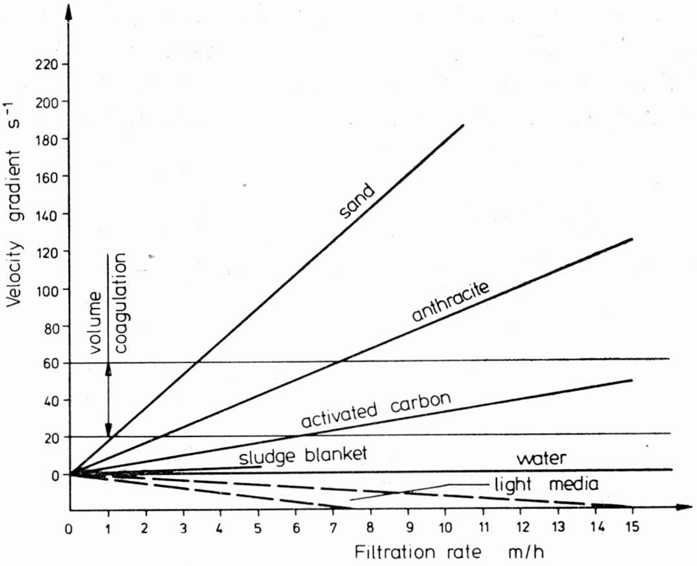

Fig. 2. Filtration velocity vs. velocity gradient, depending on the density of filtrations beds

Rys. 2. Wpływ prędkości filtracji na wielkość gradientu prędkości zależnie od gęstości złóż filtracyjnych

At materials density lower than water density, the sign of the expression, and hence also the direction of the filtration velocity vector are reversed. The character of the process is then changed since the bed tends to float and must be protected from uplifting. Attemps at practical application of the beds lighter than water have alredy been made [10].

4. SIMULATION OF FLOCCULATION IN FILTER BEDS

The determination of both the filtration velocity and the heights of each layer in multimedia beds is of great importance for flocculation in filter beds [4].

The filtration velocities determined for various beds by assuming identical hydraulic gradients in beds ($\Delta H/L = \text{const}$) and identical floculation conditions ($G = \text{const}$) are given by

$$\frac{v_2}{v_1} = \frac{\varrho_1 - \varrho}{\varrho_2 - \varrho} \frac{\varepsilon_2}{\varepsilon_1}. \tag{10}$$

In multilayer filters the filtration velocity for each layer is constant ($v = \text{const}$). The maintaining of the same conditions, both hydraulic ($H = \text{const}$) and flocculation ones ($G = \text{const}$) at the layer contact allows to determination of the required heights of the layers

$$\frac{L_2}{L_1} = \frac{\varrho_2 - \varrho}{\varrho_1 - \varrho} \frac{\varepsilon_1}{\varepsilon_2}. \tag{11}$$

Filtration velocities and layer heights are given in table 1, for beds of the densities equal to 2.65 g/cm^3 for sand, 1.65 g/cm^3 for anthracite and 1.3 g/cm^3 for activated carbon. Surface flocculation is compared with the volumetric one based on the dimensionless criterion of similarity i.e. the Camp number. In volumetric coagulation the Camp number equals 18,000–24,000 to 54,000–72,000 and is constant in the whole process of slow mixing; whereas in filtration beds it varies (i.e. decreases with the increasing bed depth and increases for each depth in filter run cycle) due to changing hydraulic conditions in beds, affecting the flocculation effectiveness. The results of determining the Camp number in filter beds of the height 1 m and filtration velocity 5 m/h [4] are presented in table 2. It is seen that carbon and anthracite filters ensure the proper progress of coagulation in the whole cycle, whereas the sand filters only in the initial phase.

Table 1

Velocities and height of layers for typical filtration beds

Zestawienie prędkości i wysokości warstw dla typowych złóż filtracyjnych

Layer ratio	Ratio of		
	porosities	velocities	layer heights
$\frac{\text{carbon}}{\text{sand}}$	$\frac{0.45}{0.35}$	7.07	$\frac{1}{7.07}$
	1	5.54	$\frac{1}{5.5}$
$\frac{\text{anthracite}}{\text{sand}}$	$\frac{0.40}{0.35}$	2.90	$\frac{1}{2.90}$
	1	2.54	$\frac{1}{2.54}$

When applying aluminium sulphate, lower values of the Camp number (9,000–12,000) are recommended. Therefore, sand beds are of little usefulness in coagulation since they require the application of multilayer beds and polyelectrolytes.

5. CONCLUSIONS

The determination of liquid movement velocity gradient greatly helps both analytical and experimental examination of the flocculation mechanism.

The effectiveness of properly controlled flocculation may be increased by the application of new techniques and technologies of water and wastewater treatment. The velocity gradient should decrease with flocculation time, since the growing flocs are

Table 2

Camp number in filtration beds
Liczba Campa w złożach filtracyjnych

Specification			Beds		
			sand	anthracite	carbon
Bed porosity %	initial cycle stage		0.35	0.40	0.45
	final cycle stage		0.16	0.185	0.22
Flocculation time s	initial cycle stage	min	252	288	324
		max	398	455	512
	final cycle stage	min	115	133	158
		max	182	210	250
Velocity gradient s^{-1}	initial cycle stage		110	40	15
	final cycle stage		550	185	120
Camp number	initial cycle stage	min	27,720	11,520	4,860
		max	43,780	18,200	7,680
	final cycle stage	min	57,500	24,605	18,960
		max	91,100	38,850	30,000

less resistant to coagulation. This accounts for the sectional structure of slow mixing chambers as well as for the triangular or trapezoidal section of clarification tanks deposit, e.g. Koskoski's and cylindrical clarifiers, and of some types of activated sludge chambers, e.g. sometimes in biological flocculation.

In filtration, the condition of the velocity gradient decreasing with time is also satisfied since the former decreases with bed depth. The process conditions, however, get worse with time.

In flocculation conducted at constant high gradient the dosage of polyelectrolytes should be delayed with respect to coagulant. A polyelectrolyte contacts with the flocs which are already formed in water and increases their strength to destruction.

In water filtration, directly after flocculation, satisfactory results are obtained when flocs are fine and very cohesive because their penetration is then deeper and no masking of the filter surface is observed. In this case polyelectrolytes should also be applied both to coagulation and to bed impregnation.

The impregnation of beds, which makes them more absorptive, is of special importance for waters of higher pollution indices that in the direct filtration require higher doses of coagulants. Due to the improved sorptive capacity it also helps the removal of refraction compounds. The impregnation may be forecasted to yield fairly good results in the case of coarse-grained beds of homogeneous materials to be used in the filtration of biologically treated wastes as well as in the process of water reconditioning.

The possibility of increasing the filtration velocity for the impregnated beds follows from the strength analysis of flocs based on the velocity gradient. The degree of bed impregnation may be also designed based on the velocity gradient. The maintanance of too high gradients resulting from the excessive impregnation of beds does not arrest the particles. This is due to hydrodynamic forces that dominate considerably over the flocculation forces, which results from the decreased porosity of beds, this being a natural consequence of their overimpregnation. The lack of balance between forces results in the destruction of flocs. In this case the treatment efficiency may also be lowered and the advantage may not be taken of the whole capacity of less porous beds due to the masking of the filter bed surface by flocs.

The assumption of too low velocity gradients for impregnation does not assure the satisfactory degree of using the bed capacity. The knowledge of the velocity gradient allows the balance of the hydrodynamic and flocculation forces, which results in the optimization of the impregnation process.

The separation of flocculation from the filtration process, based on the velocity gradient, allows for a more complete application of filtration beds into coagulation as well as for new studies especially of the applications of light beds.

A sure advantage of the velocity gradient is that it determine quantitatively the effect of density on filtration velocity. Up till now, this dependence has been manifested only qualitatively during investigations.

The relations concerning the bed density, filtration velocity and filtration layer height may be applied to filter projecting.

The application of pipe hydraulics to flocculation seems to be worthy of more careful consideration especially from the viewpoint of the economy of small plants [5].

REFERENCES

[1] Kowal A. L., Maćkiewicz J., *Średni gradient prędkości w filtracji wody*, Inżynieria Chemiczna, Vol. VII (1977), No. 3, p. 643.

[2] Kowal A. L., Dzieglewska B., Dziubek A., *Technologiczne zasady stosowania flokulantów do intensyfikacji procesów oczyszczania*, Konf. Nauk.-Techn. PZITS „Intensyfikacja zaopatrzenia w wodę miast i osiedli", Wisła 1977.

[3] Kowal A. L., Maćkiewicz J., *Warunki flokulacji w koagulacji ścieków*, Gospodarka Wodna Vol. 3 (1978).

[4] Kowal A. L., Maćkiewicz J., *Modelowanie flokulacji w złożach filtracyjnych*, Communication, Institute of Environment Protection Engineering, Technical University of Wrocław, Wrocław 1978.

[5] Kowal A. L., Sozański M., *Krytyczne wartości prędkości płynięcia wód koagulowanych*, Mat. Konf. Nauk.-Techn., Jelenia Góra 1978.

[6] Maćkiewicz J., Sozański M., *Analiza zjawisk hydraulicznych w procesie filtracji pospiesznej*, Gaz, Woda i Technika Sanitarna Vol. 4 (1973).

[7] Tesařik J., Vostřcil J., *A theoretical consideration on entrapment of flocs in the sludge blanket*, Water Research, Vol. 10 (1975).

[8] *Wastewater Engineering*, Mc Graw Hill. Inc. 1972.

[9] Wejcer J. I., Lucenko G. N., *Optymalnyje uslovia obrazovania khlopiev pri koagulirovanii stochnykh wod*, Vodosnabzhenie i Sanit. Techn. Vol. 9 (1975).

[10] Żubra T., Moroz S. J., Miagkij D. D., *Rozrabotka i vnedrenie plavayushchikh zagruzok v praktiku filtrovania vody*, Vodosnabzhenie i Sanit. Techn. Vol. 5 (1975).

ZNACZENIE GRADIENTU PRĘDKOŚCI W PROCESIE KOAGULACJI

W pracy przedstawiono analizę flokulacji na podstawie gradientu prędkości w koagulacji objętościowej, w warstwie osadu zawieszonego i w złożach filtracyjnych.

W koagulacji objętościowej wyjaśniono wpływ wielkości gradientu prędkości i czasu flokulacji zależnie od stosowanych koagulantów oraz uzasadniono celowość stosowania flokulantów, a także dawkowanie ich z pewnym opóźnieniem w stosunku do koagulantów podstawowych. Analiza flokulacji w warstwie osadu zawieszonego potwierdza niecelowość stosowania tego procesu dla wód o niskim poziomie zanieczyszczenia, bądź o dużym jego wahaniu. Określono skuteczność oczyszczania w zależności od wysokości warstwy osadu zawieszonego zależnie od stężenia objętościowego kłaczków. W koagulacji powierzchniowej gradient prędkości pozwolił na wyodrębnienie flokulacji od pozostałych procesów jednostkowych. Wykazano ilościowy wpływ gęstości materiału filtracyjnego na stosowane prędkości filtracji, określono niezbędne wysokości warstw filtracyjnych w złożach wielowarstwowych, a także uzasadniono stosowanie polielektrolitów do impregnacji złóż.

DER GESCHWINDIGKEITSGRADIENT UND SEINE BEDUTUNG IM KOAGULATIONSVERFAHREN

Während der Koagulation wurde der Einfluß des Wertes des Geschwindigkeitsgradienten und der Flockungszeit geklärt, je nach Art der benutzten Fällmitteln. Weiterhin wurde die Zweckmäßigkeit der Anwendung von Flockungshilfsmitteln begründet.

Was das Schwebstoffkontaktverfahren anbetrifft, so bestätigte sich die Ansicht, daß die Anwendung dieses Verfahrens bei wenig verschmutzten Wässern bzw. bei deren großen Schwankungen nicht zweckmäßig ist. Bestimmt wurde die Wirksamkeit der Aufbereitung als Funktion der Höhe der Schwebeschicht. Die Werte des Geschwindigkeitsgradienten im Filterbett, gestatteten die Absonderung der Flockung von anderen Einzelverfahren. Nachgewiesen wurde der quantitative Einfluß der Dichte des Filterbettmaterials auf die Filtrationsgeschwindigkeiten, bestimmt wurden die notwendigen Schichthöhen bei Mehrschichtfiltern; begründet wurde auch die Benutzung der Polyelektrolyte zur Imprägnierung von Filtern.

ЗНАЧЕНИЕ ГРАДИЕНТА СКОРОСТИ В ПРОЦЕССЕ КОАГУЛЯЦИИ

В работе представлен знализ флокуляции на основе градиента скорости в объемной коагуляции, в слое осадка, суспензированного и находящегося в фильтрационных слоях. При процессе объемной коачуляции выяснено влияние величины градиента скорости и времени флокуляции в зависимости от применяемых коагуляторов, а также обоснованы целесообразность применения и дозирование их с некоторым замедлением по отношению к основным коагуляторам. Анализ флокуляции в слое суспензированного осадка подтверждает нецелесообразность применения этого процесса для воды с низким уровнем загрязнения или с большим колебанием этого уровня. Определена эффективность очистки в функции высоты суспензированного слоя в зависимости от объемной концентрации хлопьев. При поверхностной коагуляции градиент скорости позволил выделить флокуляцию из числа других процессов. Показано количественное влияние плотности фильтрационного материала на применяемые скорости фильтрования; определены необходимые значения высоты фильтрующих слоев в многослойных фильтрах и обосновано применение полиэлектролитов для пропитки фильтров.