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EFFECTS OF TEMPERATURE, COAGULANT DOSAGE AND RAPID MIXING ON PARTICLE-SIZE DISTRIBUTION

The study on the effects of temperature, coagulant dose and mean velocity gradient G of rapid mixing is presented. The experiments were carried out at the experimental pilot-plant with a flow rate of 1 dm^3/min. The simulated raw coloured water was used for the experiments, performed according to the three-factor orthogonal composite design. Alum was used as coagulant.

Particle-size distribution was determined according to sedimentation velocity by normal gravity or by centrifugation. Aggregation test and coefficient of aggregation efficiency α with residual colour and COD were used for evaluation of experiments.

The decreasing water temperature was accompanied with decreasing optimal dose necessary for maximal portion of large flocs, as well as residual concentration of non-aggregated particles, COD and colour.

Increasing mean velocity gradient G of rapid mixing suppresses partially the negative influence of low water temperature.

1. INTRODUCTION

When treating drinking water we sometimes are faced with problems on efficiency of the treatment during the winter months, when the temperature of the raw water decreases. At lower temperatures the efficiency of water works decreases especially if alum is used as a precipitant. In Czechoslovakia, there are many plants for treatment of surface waters more or less coloured with humic substances.

In view of the above, some studies on interactions of temperature and particular technological parameters of coagulation-flocculation process during the treatment of coloured water have been undertaken.

The aim of an extensive experimental plane was to estimate the possibilities of neutralizing the negative effects of low water temperatures upon the processes of coagulation and sedimentation in the treatment of humic waters.

So far this problem has not been satisfactorily studied and discussed in the literature.

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The results obtained under different conditions and with various kinds of water, estimated according to different criteria, are sometimes not consistent.

This paper presents the results of the study on the interaction among the water temperature and two technological variables, i.e. dose of precipitant and the intensity of rapid mixing. The influences of these three variables on particle-size distribution of the effluent from the slow mixing tank have been presented in the form of three-dimensional schemes.

2. PILOT-PLANT

The experiments were conducted in a plexi-glass pilot-plant (fig. 1). Its principal components are: raw water storage tank *1* with controlled water temperature, constant head tank *3*, homogenizer *8* with three perforated plates and a rapid *11* and slow *12* mixing tanks.

The mean turbulent velocity gradient G in tanks was varied by changing the rotor velo-

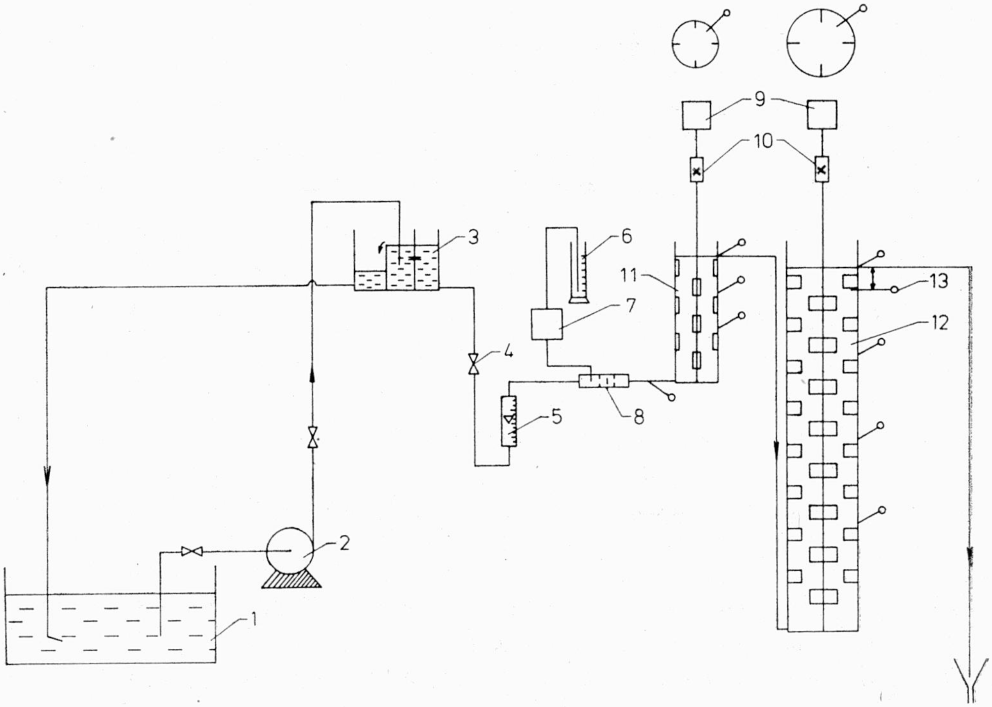

Fig. 1. Pilot-plant lay-out

1 — water storage tank (120 dm^3) with controlled temperature, *2* — pump, *3* — constant head tank, *4* — flow control valve, *5* — rotameter (flow of 1 dm^3/min), *6* — precipitant storage cylinder (alum 1.5%), *7* — precipitant dosing pump, *8* — initial homogenizer (residence time 1 s), *9* — motors, *10* — strain gauge torquemeters, *11* — rapid mixing (max volume 2.8 dm^3), *12* — slow mixing (max volume 20 dm^3), *13* — sampling point for aggregation test determination

Rys. 1. Schemat zakładu doświadczalnego

1 — zbiornik zasobnikowy wody (120 dm^3) z kontrolowaną temperaturą, *2* — pompa, *3* — zbiornik o stałej różnicy spadu, *4* — zawór przepływu, *5* — rotametr (przepływ 1 dm^3/min), *6* — cylinder ze środkiem strącającym (1,5% ałun), *7* — pompa dozująca środek strącający, *8* — początkowy homogenizator (czas pozostawania 1 s), *9* — silniki, *10* — momentometr tensometryczny, *11* — szybkie mieszanie (max objętość 2,8 dm^3), *12* — wolne mieszanie (max objętość 20 dm^3), *13* — punkt pobierania próbek do testu agregacji city. The motors were equipped with transmission and thyristor regulators. The number of rotations of the rapid mixing was measured electronically.

To determine experimentally the relation among the G value and the number of rotations of paddles and temperature of water a strain gauge torquemeter was used. The theory of the strain gauge torquemeter was well described by AIBA, HUMPHREY and MIILLIS [1]. The laboratory use for G determination was published by ØDEGAARD [3].

The pilot-plant used in this work enabled to range G within 60–1200 s^{-1} for rapid mixing and within 2–100 s^{-1} for slow mixing. The water flow applied was 1 dm^3/min. The maximum retention time was 2.8 min and 20 min in rapid and slow mixing tanks, respectively.

To determine the suspension characteristics during the mixing along the whole pilot-plant the sampling points were arranged according to fig. 1.

3. METHODS

In order to obtain the comparable results of two year experiments, the simulated raw coloured water was used. This water guaranteed the stability of all important factors during the treatment and also enabled their choice according to the requirements of the experiments.

The basic inorganics were introduced by fourfold dilution of tap water with demineralized water to reach the summary concentration of calcium and magnesium of 0.5 $mmol/dm^3$. When needed, pH of water was adjusted to 0.6 $mmol/dm^3$ by HCl and $NaHCO_3$.

A concentrate of humic substances was extracted from peat by the demineralized water applying the same extraction procedure and one kind of natural peat. By the addition of this extract to the mixture of demineralized and tap water it was possible to reach always the same characteristics and concentration of organics in the simulated raw water. The model water had the following parameters: colour 50 Pt (mg/dm^3), permanganate COD (according to Kubel) 9.0 mg/dm^3, and pH 6.75. As a precipitant $Al_2(SO_4)_3 \cdot 18\ H_2O$ in a 1.5% solution was used.

To investigate the effects of operational variables on the coagulation course, a three-factor orthogonal composite design was used. The results are expressed graphically in figs. 2–9.

4. CRITERIA INVESTIGATED

The influence of various factors on the formation and aggregation of suspensions has been analysed according to two most important criteria in sedimentation and filtration of water after flocculation: 1) the part of coagulant in the form of well settling flocs should be as big as possible, 2) the part the remaining coagulant that is unfeasible to remove by separation should be as small as possible.

The basic similarity criterion of the model or the technologies can also be formulated as follws: *Such processes and instalations are technologically similar, where suspensions of the same properties from the aspect of separation are rising* [2].

Thus, to evaluate the efficiency, apart from the commonly used parameters, i.e. residual COD and colour, two criteria suggested by HEREIT, MUTL and VÁGNER [2] were also applied.

One of them is coefficient of aggregation efficiency α, defined by the formula:

$$\alpha = \frac{C_0 - C_F}{C_0},$$

where C_0 is the total coagulant dose, and C_F is the residual contents of coagulant in centrifugate (supernatant). Its value increases from 0 to 1 with progressing aggregation.

The other criterion, i.e. particle-size distribution due to HEREIT, MUTL and VÁGNER [2], is determined from aggregation test which is conducted applying routine sedimentation procedure. To exclude vertical aggregation the sampilng point is located 4 cm below the water surface in each experimental vessel or under the outlet from the slow mixing tank of a pilot-plant.

When the mixing process is stopped (time zero), the sedimentation of flocs starts. The decrease of aluminium concentration at this depth after 5 min of sedimentation is due to the settling of the coarse flocs — macroparticles (settling velocity above 0.13 mm/s). Their diameters are of order of some milimeters.

The microparticles are those deposited within 5–60 min. Their sedimentation velocity is above 0.011 mm/s and diameters of order of 5×10^{-1} mm.

The primary particles (settleable after 60 min of the sedimentation) are determined by the centrifugation. Their sedimentation velocity is about 10^{-3} mm/s and their diameters are of order of 10^{-2}–10^{-3} mm.

The residual concentration of aluminium in the water sample after centrifugation is called non-aggregated fraction.

5. EXPERIMENTAL RESULTS

Experiments with simulated raw water were performed at interval ranging within 1.7–16.3°C, dose of alum — 16–52 mg/dm^3 and G value of rapid mixing — 60–315 s^{-1}. Other parameters were held constant; retention times in rapid and slow mixing were 2.8 min and 20 min, respectively; G value of slow mixing was 7 s^{-1}.

The experimental results of the coagulation-flocculation investigations are presented in figs. 2–9.

Figure 2 displays the effects of water temperature and alum dose upon the fraction of macroparticles. It clearly shows that the drop of the temperature reduces simultaneously the macroparticle fraction. The dot-and-dash line marks the positions of the optimal

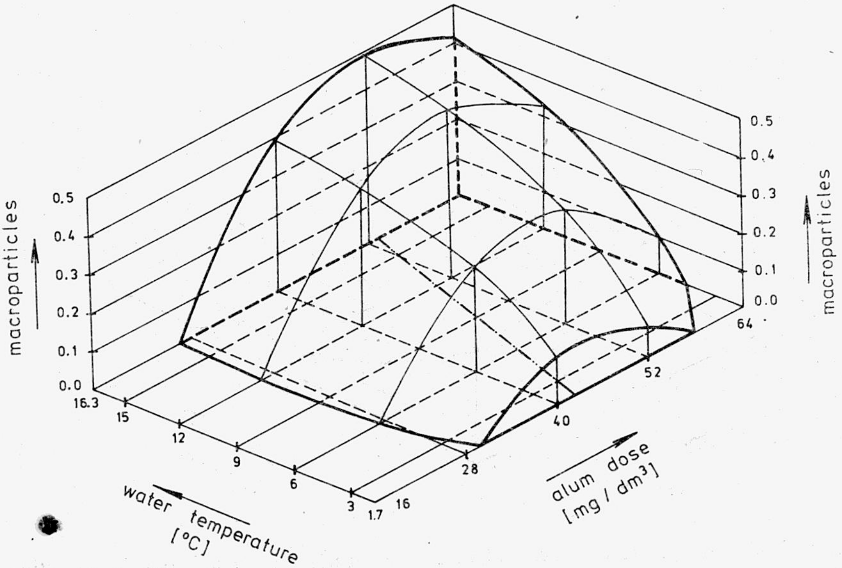

Fig. 2. Effects of water temperature and alum dose upon the fraction of macroparticles

Rys. 2. Wpływ temperatury wody i dawki ałunu na frakcję makrocząsteczek

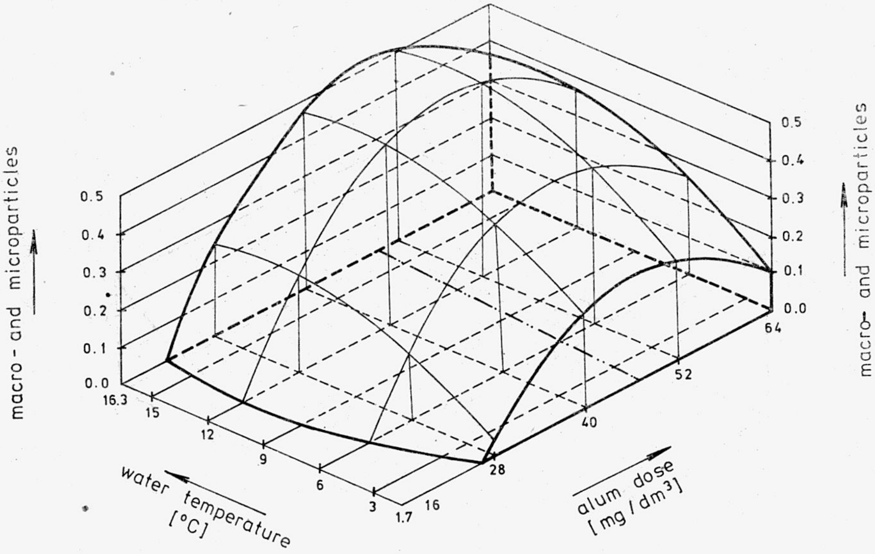

Fig. 3. Effects of water temperature and alum dose upon the total fraction of sedimentable macro- and microparticles

Rys. 3. Wpływ temperatury wody i dawki ałunu na całą frakcję makro- i mikrocząsteczek zdolnych do sedymentacji

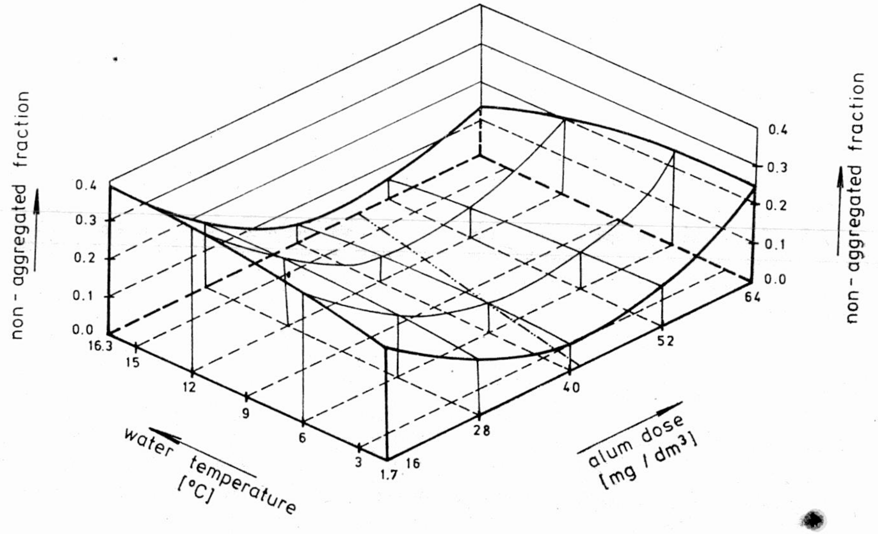

Fig. 4. Effects of water temperature and coagulant dose upon non-aggregated coagulant fraction after the 60 min sedimentation

Rys. 4. Wpływ temperatury wody i dawki koagulanta na niezagregowaną frakcję koagulanta po 60 min sedymentacji

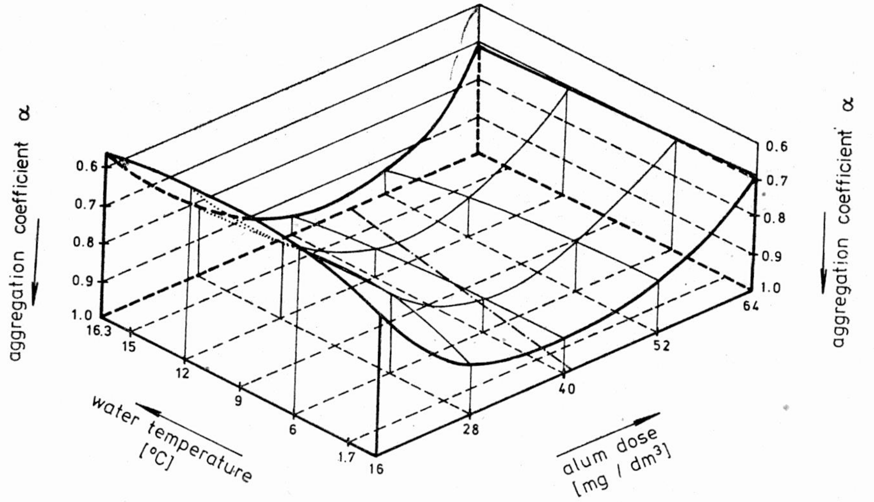

Fig. 5. Dependence of coefficient of aggregation efficiency α on the water temperature and alum dose

Rys. 5. Zależność współczynnika wydajności agregacji α od temperatury wody i dawki ałunu

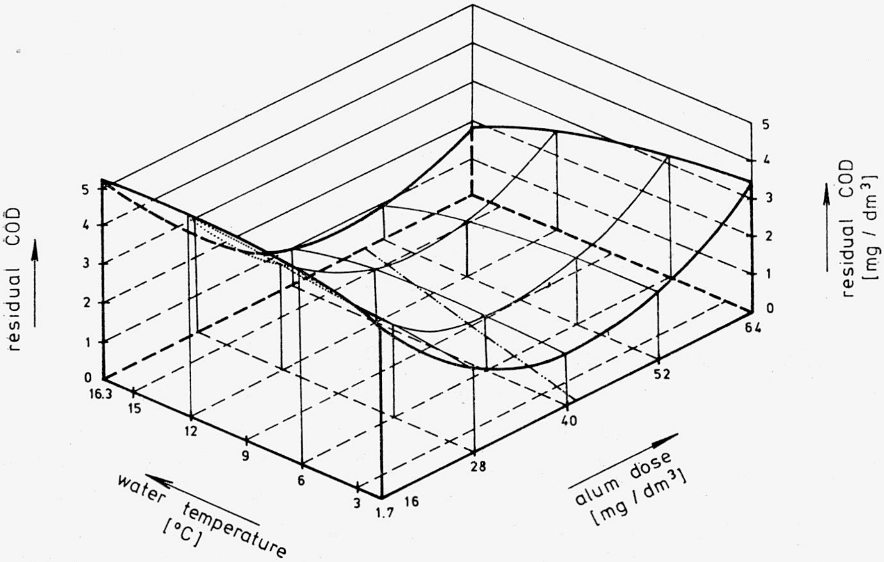

Fig. 6. Dependence of residual permanganate COD on the water temperature and alum dose

Rys. 6. Zależność resztkowej utlenialności nadmanganianowej od temperatury wody i dawki ałunu

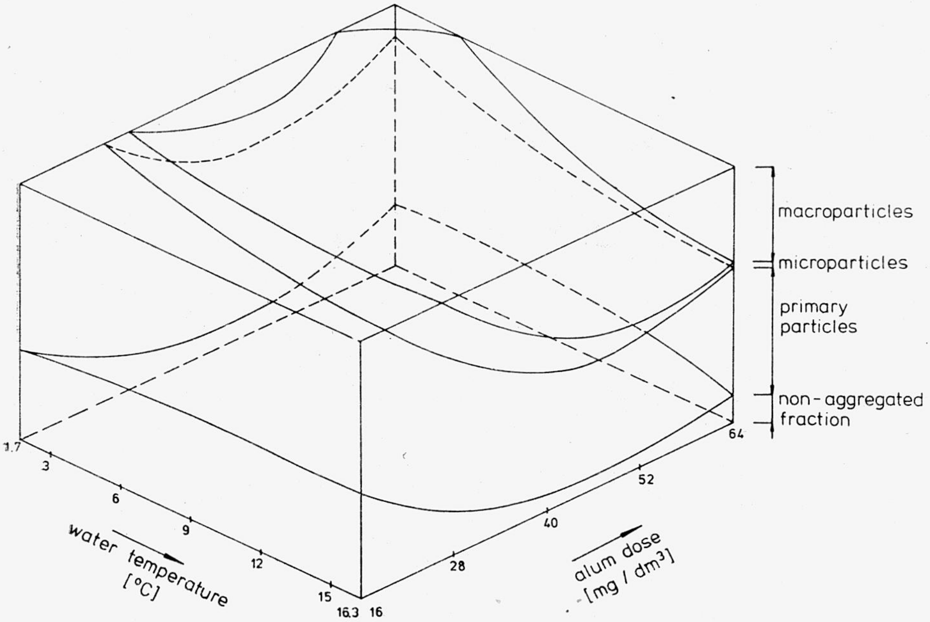

Fig. 7. Relation between alum dose and water temperature

$G_{RM} = 110\ s^{-1}$

Rys. 7. Zależność między dawką ałunu a temperaturą wody

$G_{RM} = 110\ s^{-1}$

doses of coagulant plotted against the temperature. The maximal fraction of the macroparticles was achieved for the doses of 43 mg/dm^3 and 54 mg/dm^3 of alum at temperatures 1.7°C and 16.3°C, respectively. From fig. 2 it follows that the temperatures up to 8°C remarkably deteriorate the macroparticle formation and settling. Above 8°C this negative influence is less pronounced (see also fig. 3).

Figure 3 shows the effects of water temperature and alum dose upon the total fraction of sedimentable macro- and microparticles. The dot-and-dash line indicates small change of the optimal dose with the varying water temperature for this fraction. For the temperatures of 16.3°C and 1.7°C the optimal alum doses are 50 mg/dm^3 and 47 mg/dm^3, respectively.

Non-aggregated coagulant fraction after 60 min sedimentation time is presented in fig. 4. The dot-and-dash line indicates again the change of the optimal doses which results in minimal residual concentration of "dissolved" coagulant. According to this criterion they are equal to 50 mg/dm^3 and 41 mg/dm^3 for 16.3°C and 1.7°C, respectively.

Figures 5 and 6 show the dependence of coefficient of aggregation efficiency α and of the residual permanganate COD on the temperature and the alum dosage.

Figures 4, 5 and 6 show an interesting phenomenon. Within the doses below 30 mg/dm^3 (about 70% of the optimal dose) the coagulation performance, as far as residual concen-

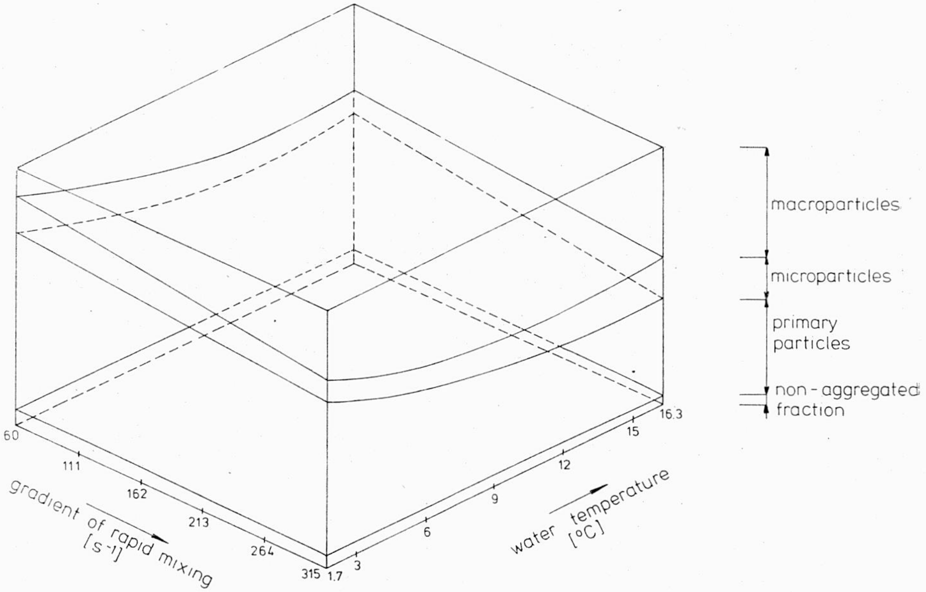

Fig. 8. Relation between water temperature and gradient of rapid mixing

Alum dose 40 mg/dm^3

Rys. 8. Zależność między temperaturą wody a gradientem szybkiego mieszania

Dawka ałunu 40 mg/dm^3

trations of alum and COD are concerned, improves with the decreasing temperature. On the other hand, however, the formation of aggregates larger than primary particles is suppressed.

Figures 7, 8 and 9 represent the distribution of the dosed alum flocs into four categories of particles (macroparticles, microparticles, primary particles, and non-aggregated fraction). The heights of the vertical segments in the picture are equal to the ratio of the special fraction to the total coagulant dose.

Figure 7 shows particle-size distribution plotted against water temperature and alum dose based on the results shown in figs. 2, 3 and 4.

Particle-size distribution against the water temperature and the *G* value of the rapid mixing is plotted in fig. 8. For very low levels of *G* (i.e. 60 s^{-1}) the negative influence of the decreasing temperatures occurs from 9°C downward. At higher *G* level (i.e. 315 s^{-1}) the negative influence of decreasing temperature occurs below 6°C.

In agreement with the results of many investigators the increase in *G* value up to a certain limit results in higher percentage of the well settling flocs. The influence on the fraction of non-aggregated particles is almost negligeable. The negative influence of low temperatures upon the formation of sedimentable flocs could be reduced by increasing the *G* value.

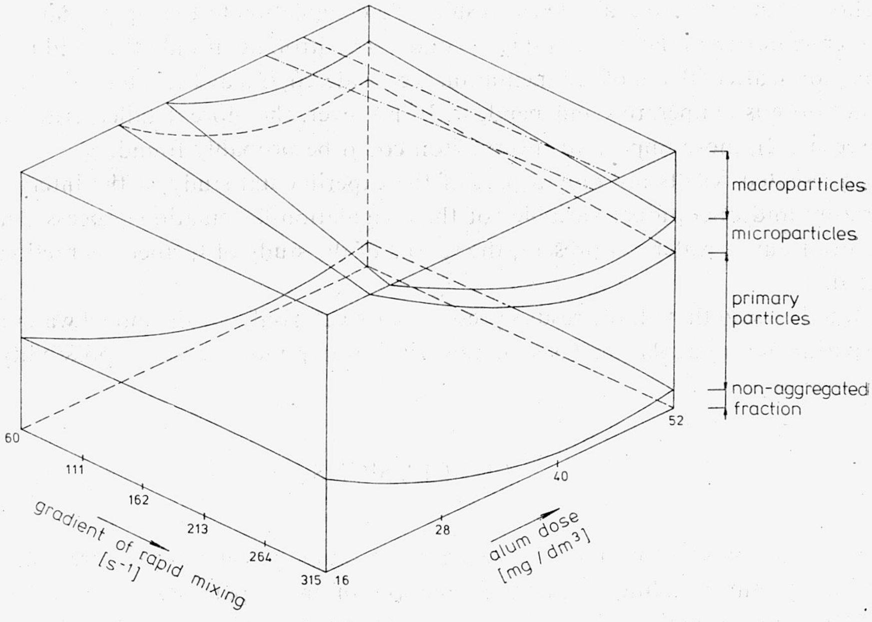

Fig. 9. Relation between gradient of rapid mixing and alum dose
$T = 3°C$

Rys. 9. Zależność między gradientem szybkiego mieszania a dawką ałunu
$T = 3°C$

Figure 9 shows the distribution of the particles plotted against the dose of coagulant and the *G* value for 3°C. At a very low value of *G* the formation of macroparticles starts at the dose of 31 mg/dm^3; at higher *G* formation is started at the dose as low as 23 mg/dm^3. Both dotted and dashed lines are practically parallel and relatively not influenced by the increasing *G* values.

6. DISCUSSION

The results of the classical jar test after 15–60 min of settling are much worse than those obtained in the operation of water treatment plants. Paper filtration or ultrafiltration of the supernatant results in the effluent of the excellent quality of chemical characteristics which deviate also far from validity. As far as non-aggregated alum fraction is concerned solely, centrifugate characteristics of the supernatant sample after 60 min corresponds to that of the discharge from the operational filters. The centrifugation permits to unify procedures of the jar test, pilot-plants and real water treatment plant investigations and thereby their comparison.

Figure 3 presents also the residual portion of alum after 60 min sedimentation at the 4 cm depth, the criterion well known from the classical jar test. The comparison of figs. 2 and 3 shows that when we evaluate the results of a coagulation test using primary criterion, some interacations or relations can stay beyond our control, i.e. if only the residual concentration of alum after 60 min of sedimentation is considered, it may be stated that the optimal coagulant dose is temperature independent. If, however, the more detailed criterion is applied (see fig. 2), more important informaiton could be probably found.

The presented results are only a part of the experimental study of the interactions of temperature and operational variables of the coagulation-flocculation process during the treatment of humic water. At present, the results of the study of further interactions being evaluated.

It should be said that all the results presented are valid only for the model water applied. The experimental coagulation tests of raw river water indicate some possibility to generalize the results.

7. CONCLUSIONS

1. There is a positive correlation between the humic water temperature and optimal dose of coagulant enabling maximal formation of macroparticles.

2. The same correlation is valid for the water temperature and coagulant dose resulting in minimal residual alum, COD, colour, and maximal value of the coefficient of aggregation efficiency.

3. The negative effect of low water temperature can be reduced by increasing the *G* value of rapid mixing.

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WPŁYW TEMPERATURY, DAWKI KOAGULANTA I SZYBKIEGO MIESZANIA NA FLOKULACJĘ

Przedstawiono badanie wpływu temperatury, dawki koagulanta i średniego gradientu prędkości G na flokulację. Badania wykonano w zakładzie doświadczalnym o przepływie 1 dm^3/min. W zaplanowanym, trójczynnikowym, ortogonalnym, kompleksowym doświadczeniu ścieki symulowano barwioną wodą. Jako koagulanta użyto ałunu.

Uziarnienie określono według szybkości sedymentacji cząsteczek przy normalnej grawitacji lub odwirowaniu. Doświadczenie oceniano przy użyciu testu agregacji i współczynnika skuteczności agregacji α uwzględniając barwę i COD.

Wraz ze spadkiem temperatury maleje zarówno dawka potrzebna do uzyskania maksymalnej frakcji dużych kłaczków, jak również resztkowe stężenie niezagregowanych cząsteczek oraz utlenialność i barwa. Rosnący gradient szybkiego mieszania G częściowo kompensuje negatywny wpływ niskiej temperatury wody.

EINFLUSS DER TEMPERATUR, DER FÄLLMITTELDOSE UND DES MISCHVORGANGES AUF DIE FLOCKENGRÖSSE

Im Beitrag wird der Einfluß der Temperatur, der Fällmittelmenge und des durchschnittlichen Geschwindigkeitsgradienten G auf die Flöckengrösse diskutiert. Die Versuche wurden im Durchflußbetrieb von 1 dm^3/min betrieben. Im orthogonalen Versuchssystem wurde anstatt von Abwasser gefärbtes Wasser getestet; als Fällmittel wurde Alaun angewandt.

Die Flockung wurde im Sedimentationsprozeß bzw. durch Zentrifugieren bestimmt. Die Versuche wurden nach dem Aggregationstest und mit Hilfe des Koeffizienten der Aggregation unter Zuhilfenahme von Färbung und COD bewertet.

Mit der Temperaturabnahme wird die Fällmitteldose, die für die Bildung von maximal großen Flocken verantwortlich ist kleiner; ebenso sind die Restkonzentrationen der aggregatfreien Partikeln, der Färbung und des Permanganatverbrauchs. Der wachsende Gradient G des Mischvorganges kompensiert zum Teil den negativen Einfluß der niedrigen Temperatur des Wassers.

ВЛИЯНИЕ ТЕМПЕРАТУРЫ, ДОЗЫ КОАГУЛЯНТА И БЫСТРОГО ПЕРЕМЕШИВАНИЯ НА ФЛОКУЛЯЦИЮ

Представлены исследования по влиянию температуры, дозы коагулянта и среднего градиента скорости G на флокуляцию. Испытания были произведены в экспериментальном отделе с расходом 1 дм^3/мин. В запланированном трёхреактивном ортогональкомплексном опыте сточные воды имитировались окрашенной водой. В качестве коагулянта был принят алун.

Флокуляция была определена по скорости седиментации частиц при нормальной гравитации или центрифугировании. Опыт оценивался при использовании критерия агрегации и коэффициента эффективности агрегации α при учёте окраски и окисляемости.

С понижением температуры уменьшается доза, необходимая для получения максимальной фракции больших хлопьев, и остаточная концентрация неагрегированных молекул, а также окисляемость и окраска.

Увеличивающийся градиент быстрого перемещивания G частично компенсирует отрицательное влияние низкой температуры воды.