

A FLUIDIZED LAYER OF GRANULAR MATERIAL USED FOR THE SEPARATION OF PARTICULATE IMPURITIES IN DRINKING WATER TREATMENT

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This paper deals with the application of a fluidized layer of granular material (FLGM) for the direct separation of destabilized impurities during drinking water treatment. Further, it investigates the effect of operation parameters (fluidized layer grain size, technological arrangement, velocity gradient, retention time, dosage of destabilisation reagent and temperature) on the aggregation and separation efficiency of the layer. The tests were carried out in a pilot plant scale. Aluminium sulphate was used as the destabilisation reagent. The highest separation efficiencies were achieved, when the particles entered the fluidized layer immediately after the dosing of the destabilisation reagent, when they had the lowest degree of aggregation. The separation efficiency (φ) also increased with increasing velocity gradient and the maximal value was reached at the velocity gradient of about 250 s^{-1} . The most efficient separation of aluminium was achieved at 5°C , but the effect of temperature on the efficiency of organic matter separation (φ_{TOC}) was not very significant. The maximal efficiency of separation on the layer grains reached the values $\varphi_{\text{Al}} = 0.81$ at the optimal dosage $D_{\text{Al}} = 1.55 \text{ mg L}^{-1}$ and $\varphi_{\text{TOC}} = 0.31$ at the optimal dosage $D_{\text{Al}} = 2.36 \text{ mg L}^{-1}$. The indisputable advantage of using FLGM for the separation of impurities is that they are intercepted on the layer grains in a form of solid, water-free shell (or coat) with the density of 2450 kg m^{-3} , and there is no need to deal with the sludge dewatering.

KEY WORDS: Aggregation, Destabilization, Fluidized Layer, Separation, Water Treatment.

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Príspevek se zabývá využitím fluidní vrstvy zrnitého materiálu (FLGM) pro přímou separaci destabilizovaných nečistot při úpravě vody a vlivem provozních parametrů (velikost zrn náplně, technologické uspořádání, gradient rychlosti, doba zdržení, dávka destabilizačního činidla, teplota) na agregační a separační účinnost vrstvy. Testy byly prováděny na poloprovozním modelu fluidní vrstvy. Jako destabilizační činidlo byl použit síran hlinitý. Nejvyšší separační účinnosti byly dosahovány, pokud částice nečistot vstupovaly do fluidní vrstvy bezprostředně po nadávkování destabilizačního činidla, kdy byl jejich stupeň agregace nejnižší. Separační účinnost (φ) se také zvyšovala s narůstající hodnotou gradientu rychlosti ve fluidní vrstvě a maximální hodnoty dosáhla při gradientu kolem 250 s^{-1} . Hliník byl nejúčinněji separován při nízké teplotě (5°C), nicméně na účinnost separace organických látek (φ_{TOC}) teplota příliš velký vliv neměla. Maximální účinnost separace na zrnech fluidní vrstvy dosáhla hodnot $\varphi_{\text{Al}} = 0.81$ při optimální dávce $D_{\text{Al}} = 1,55 \text{ mg L}^{-1}$ a $\varphi_{\text{TOC}} = 0.31$ při optimální dávce $D_{\text{Al}} = 2,36 \text{ mg L}^{-1}$. Nespornou výhodou využití fluidní vrstvy jako separačního prvku je skutečnost, že nečistoty jsou na zrnech FLGM zachycovány ve formě pevné skořápky (hustota 2450 kg m^{-3}), která neobsahuje kapalnou vodu, a kal tudíž nemusí být odvodňován.

KLÍČOVÁ SLOVA: agregace, destabilizace, fluidní vrstva, separace, úprava vody.

1. Introduction

Intensification of the formation of separable aggregates in water treatment has led to the application of a fluidized layer of granular material

(FLGM) as an agitating element (Monk and Trussell, 1991; Ahsan et al., 1996; Mutl et al., 1999; Pivokonsky et al., 2008). Agitation with FLGM is based on the fact that every grain of the layer is a source of both hydraulic impulses and the forma-

tion of tangential forces (and thus a velocity gradient). A relatively uniform distribution of grains in the fluidized layer then also allows a uniform distribution of this velocity gradient (*Monk and Trussell*, 1991; *Mutl et al.*, 1999; *Pivokonsky et al.*, 2008). FLGM has shown a high ability to aggregate impurities into small compact aggregates, which are either suitable for direct separation with sand filtration (*Pivokonsky et al.*, 2008), or can be used as basic elements in the creation of compact rapidly-settling aggregates formed in the processes of IHDS (Inline High Density Suspension) (*Polasek and Mutl*, 1995, 2005; *Polasek*, 2007). Research on the application of FLGM as an agitation element has found that a portion of destabilized impurities can be intercepted on the surface of fluidized layer grains, while the other fraction aggregates into separable particles (*Mutl et al.*, 1999, 2000, *Pivokonsky et al.*, 2008).

The papers on FLGM published to date (*Mutl et al.*, 1999, 2000, *Pivokonsky et al.*, 2008, *Tambo and Matsui*, 1989, *Tambo and Wang*, 1993) have dealt with the practical application of the fluidized layer, i.e. they have evaluated the aggregation and separation efficiencies of FLGM used for treatment of different types of raw water. But the influence of parameters of FLGM (fluidized layer material, its grain size, the height of the fluidized bed in its stable and fluidized states, the surface area of fluidized layer grains, etc.) on its aggregation and separation efficiencies have not been investigated yet.

This paper is aimed at proving separation ability of FLGM and at an evaluation of the influence of mean velocity gradient, retention time, dosage of destabilization reagent, temperature, degree of aggregation and total grain surface area on the aggregation and separation efficiency achieved with FLGM.

2. Methods

The influence of individual factors on the aggregation and separation efficiency of FLGM was tested at a pilot plant installed at the Zelivka waterworks, which treats water from the Svihov reservoir (Czech Republic). Research was carried out during winter period (December – February), when raw water quality is stable, thus enabling a repetition of tests with high reproducibility. Raw water quality during the period of measurement is summarized in Tab. 1. Aluminium sulphate was used as a destabilization reagent. The optimal dosage was

determined by jar tests (*Hereit et al.*, 1980, *Polasek et al.*, 1995).

Table 1. Quality of raw water.

Parameter	Min.	Max.	Avr.
$T [^{\circ}\text{C}]$	2.6	4.1	3.3
pH [–]	7.2	7.5	7.3
Alkalinity [mmol L ⁻¹]	0.92	1.13	1.04
COD _{Mn} [mg L ⁻¹]	2.7	3.1	3.0
TOC [mg L ⁻¹]	4.2	4.7	4.5
Al [mg L ⁻¹]	0.02	0.03	0.03

The mean velocity gradient $\bar{G}$ was calculated according to the Eq. (1) from the change in the pressure drop (Δp) measured by a pressure probe in the fluidized and stable states.

$$\bar{G} = \sqrt{\frac{\Delta p}{\eta_w t}} = \sqrt{\frac{g(1-\omega_0)(\rho_g - \rho_w)v_{up}}{\eta_w(E-1+\omega_0)}}. \quad (1)$$

The retention time t used in the Eq. (1) was calculated according to Eq. (2).

$$\begin{aligned} t &= \frac{V_P}{Q} = \frac{V_E \omega_E}{Q} = \frac{V_E \omega_E}{v_{up} A} = \\ &= \frac{L_E \omega_E}{v_{up}} = \frac{L_0(E-1+\omega_0)}{v_{up}}. \end{aligned} \quad (2)$$

None of these quantities changes, if only aggregation occurs, but if separation also takes place, then the layer grains are covered by aggregates and the character of the fluidized layer changes. Increasing weight of the layer results in an increase of pressure drop, which reflects in increase of the mean velocity gradient as well. To maintain stable fluidized layer operation conditions, the increasing pressure drop has to be compensated from hydraulic point of view by a change in the upflow velocity.

2.1 Experimental device

The pilot plant consisted of a flow heater of raw water, a flow rate regulation unit, a dosing unit and a FLGM reactor, as illustrated in Fig. 1. Raw water was carried to the flow heater (1) enabling the regulation of water temperature. Pilot plant tests were carried out at temperatures of 5.0, 10.0 and 15.0 °C (deviation ± 0.2 °C). After heating, raw water entered the flow rate regulation unit, consisting of a header tank (2), regulation valve (3), flow-meter (4) and flow regulation system (5), which automati-

cally regulated the flow rate through the fluidized layer at increasing pressure drop. The destabilization reagent (aluminium sulphate) was dosed into a homogenizer (6) which was placed at the inlet to the FLGM reactor. A peristaltic pump (PD 5001, Heidolph Instruments, Schwabach, Germany) was used for dosing. Dosed raw water flowed through the feed pipe (7) into the FLGM reactor, made of a 3000 mm long Plexiglas tube with an inner diameter of 80 mm charged with silica sand of accurately assorted grain size. Individual sand fractions (given in Tab. 2) were obtained by sorting a mixed 0.31 – 0.71 mm fraction through analytical sieves. Fluidization of the sand bed (8) was caused by an upward flow of raw water through the feed pipe (7) leading to the bottom of FLGM reactor. In this FLGM reactor, the formation and separation of aggregates took place, and any non-intercepted suspension discharged away through an overflow (9) in the upper part of the reactor. This overflow suspension was either drained to a sluice in order to study factors influencing aggregation and separation in the FLGM, or drained to a rapid gravity sand filter to test practical FLGM applications aimed at enhancing water treatment technology. Partial results from this research were already published (Pivokonsky et al., 2008; Mutl et al., 2000). For the evaluation of fluidized layer aggregation and separation efficiency, samples were taken at the inlet (10) and at the outlet (11) from the FLGM. Pressure drop of the fluidized layer was measured using a pressure probe (12) installed over the bottom of the FLGM reactor.

2.2 Evaluation methods of aggregation and separation efficiency of FLGM

The aggregation efficiency is represented by the degree of aggregation α_A . It expresses the state of aggregation of impurities achieved by the system at any point of the treatment process. It is defined as the ratio of particles of impurities that aggregated to the total quantity of all particles of impurities originally present in the system. When expressed by concentration of parameters used for monitoring of the treatment process efficiency (Al, TOC), the degree of aggregation is calculated according to relationship (Hereit et al., 1980; Polasek et al., 1995).

$$\alpha_A = \frac{C_0 - C_F}{C_0}, \quad (3)$$

where A is the measured parameter – Al or TOC, C_0 represents the initial concentration of the parameter before aggregation and C_F is the concentration of the parameter determined in the sample after its centrifugation, which serve for removal of aggregated particles. Then the term $(C_0 - C_F)$ expresses the concentration of the parameter in the aggregates.

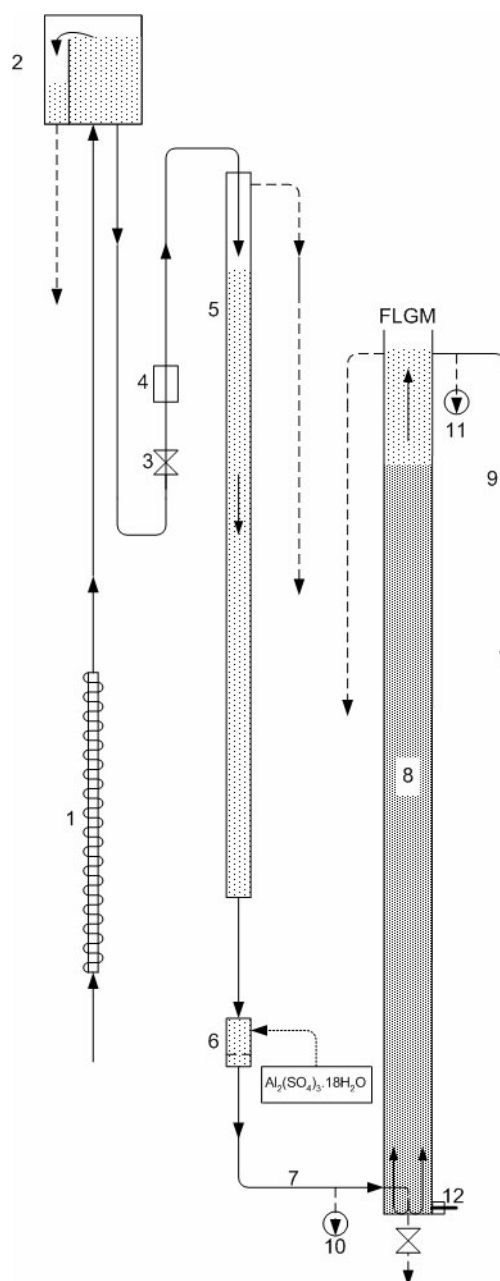


Fig. 1. Schematic diagram of the pilot plant; 1 – flow heater, 2 – header tank, 3 – regulation valve, 4 – flow-meter, 5 – flow regulation system, 6 – homogenizer with injection of destabilization reagent, 7 – feed pipe, 8 – fluidized sand, 9 – overflow pipe, 10 and 11 – sampling sites, 12 – pressure probe.

Table 2. Size characteristic of silica sand fractions.

d_g [mm]	0.31–0.40	0.40–0.50	0.50–0.63	0.63–0.71
d_{eqv} [mm]	0.337	0.426	0.587	0.674
S_{eqv} [mm ²]	0.357	0.570	1.082	1.426
ρ_g [kg m ⁻³]	2643	2648	2658	2652
V_{eqv} [mm ³]	0.020	0.040	0.106	0.160

The degree of aggregation is mainly influenced by the agitation conditions, i.e. intensity and duration. As the number of aggregated particles increases, the degree of aggregation increases, and under ideal conditions reaches $\alpha_A = 1.0$.

The separation efficiency φ_A is defined as the ratio of the separated portion of impurities (Al, TOC) and its total concentration (Hereit et al., 1980; Polasek et al., 1995).

$$\varphi_A = \frac{C_0 - C_E}{C_0}, \quad (4)$$

where C_0 represents the initial concentration of the parameter before separation and C_E is the concentration of the parameter determined in the sample after the separation on FLGM grains.

3. Results and discussion

It is assumed that both the separation and aggregation processes of destabilized particles in a fluidized layer are based on the similar principle. While particle-particle contacts play a decisive role in aggregation, particle-grain interactions are key for separation. The degree of aggregation of destabilized particles entering the fluidized layer most likely decides which process is dominant. It can be assumed that if only destabilized particles having high adhesion ability enter the layer, they will be separated on the grain surfaces due to interactions with the fluidized layer. On the contrary, if a sus-

pension in which the initial stages of orthokinetic aggregation have already taken place enters the layer, the fluidized layer will rather aggregate (Mutl et al., 1999, 2000). It is probable that both processes, i.e. both the aggregation and separation of impurities, cannot be completely isolated from each other and they will proceed concurrently, with one or the other prevailing depending on the FLGM operational conditions.

3.1 The effect of dosage of destabilization reagent and temperature

The separation efficiency of FLGM definitely depends on the efficiency of destabilization of undesirable particles. It is determined by the dosage of the destabilization reagent, and is not dependent on the layer parameters (Gregory and Duan, 2001). The destabilization efficiency reflects the number of particles which were destabilized to the extent that they are able to combine into separable aggregates or to be intercepted on FLGM grains (Hereit et al., 1980; Polasek et al., 1995). When the dosage is optimal, the highest destabilization efficiency is achieved, and naturally maximal separation efficiency of FLGM can be accomplished under defined conditions.

Tab. 3 and Fig. 2 show a simultaneous dependence of the separation efficiency of Al on a dosage of the destabilization reagent and temperature. The highest separation efficiency ($\varphi_{Al} = 0.81$ at $T = 5.0$ °C) was achieved at the dosage $D_{Al} = 1.55$ mg L⁻¹, which was considered as the optimum. Tab. 3 shows that higher temperature causes lower extent of separation on the fluidized layer grains. Dosages of destabilization reagent – both lower and higher than the optimum – result in significantly lower separation efficiency of aluminium.

Table 3. Influence of Al dosage and temperature T on the separation efficiencies φ_{Al} and φ_{TOC} , and aggregation efficiency α_{Al} of FLGM.

Al dosage [mg L ⁻¹]	$T = 5.0$ [°C]			$T = 10.0$ [°C]			$T = 15.0$ [°C]		
	φ_{Al}	φ_{TOC}	α_{Al}	φ_{Al}	φ_{TOC}	α_{Al}	φ_{Al}	φ_{TOC}	α_{Al}
1.22	0.49	0.11	0.37	0.47	0.11	0.35	0.44	0.16	0.40
1.38	0.78	0.12	0.49	0.71	0.15	0.51	0.62	0.17	0.62
1.55*	0.81	0.17	0.66	0.74	0.22	0.67	0.63	0.22	0.69
1.71	0.77	0.24	0.66	0.72	0.23	0.68	0.61	0.24	0.68
1.87	0.73	0.25	0.63	0.70	0.26	0.64	0.60	0.25	0.66
2.00	0.70	0.26	0.62	0.66	0.27	0.62	0.57	0.27	0.63
2.20	0.62	0.29	0.52	0.60	0.27	0.58	0.55	0.28	0.59
2.36	0.57	0.31	0.41	0.52	0.28	0.44	0.49	0.30	0.48

* Optimal Al dosage determined by jar test

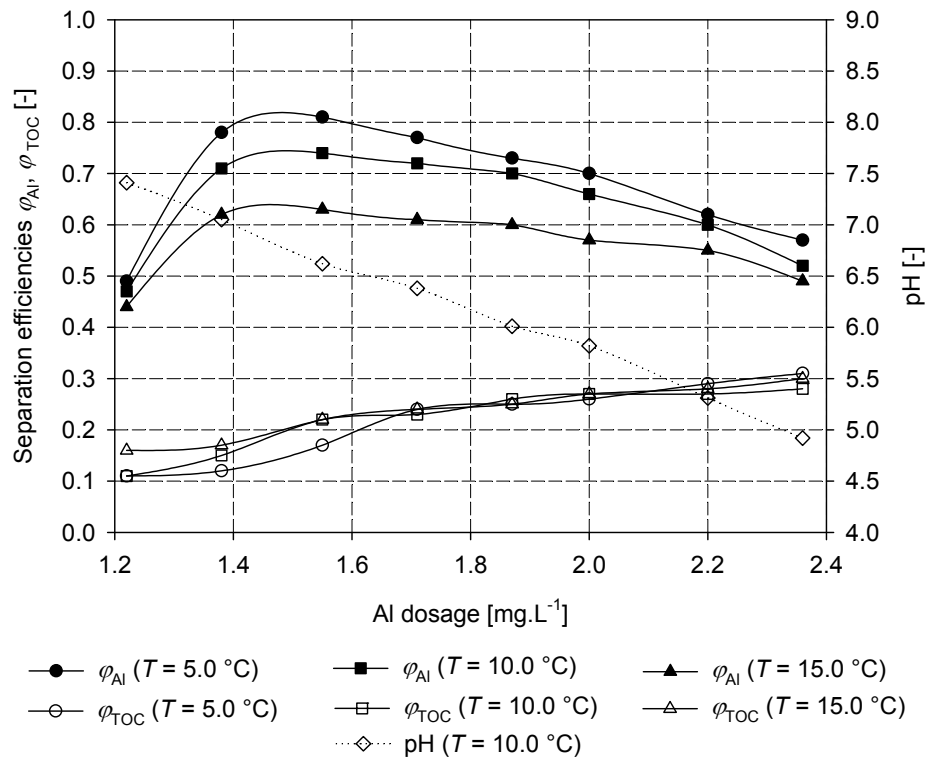


Fig. 2. Dependence of separation efficiency ϕ_{AI} and ϕ_{TOC} on the Al dosage at different water temperature T .

The effect of temperature on organic matter separation efficiency (ϕ_{TOC}) is not very significant (Fig. 2). However, there is a dependence of organic matter separation on aluminium dosage; ϕ_{TOC} increases with increasing dosage at all temperatures. This increase in organic matter separation efficiency is probably related to a decrease in pH due to hydrolysis of the destabilization reagent. The reason is that natural organic matter (NOM), with an isoelectric point usually lying in the acidic pH range (Edwards and Amirtharajah, 1985; Gregor et al., 1997; O'Melia et al., 1999; Gregory and Duan, 2001), is efficiently destabilized at acidic pH (Fig. 2). A maximum separation efficiency of organic matter ($\phi_{TOC} = 0.31$) was achieved at the aluminium dosage $D_{AI} = 2.36 \text{ mg L}^{-1}$.

It is clear that 100% efficiency for the separation of impurities on FLGM grains cannot be obtained. The efficient aggregation of the remaining particles into aggregates that can be separated during subsequent water treatment stages, e.g. sand filtration, should proceed alongside separation. It is evident from Tab. 3 that the degree of aggregation of impurities not-intercepted on the fluidized layer is highest in the range of optimal destabilization reagent dosage. The increase in aggregation efficiency with

temperature is also apparent. At low temperature, the reaction rates leading to the formation of destabilizing hydroxopolymers are lower, and they also partly proceed in the fluidized layer. The majority of destabilized particles adheres to the surface of FLGM grains and do not interact with each other, so aggregates are not formed (Tab. 3). With increasing temperature, the reaction rates leading to hydroxopolymer formation increase. Velocity of destabilization also increases, and consequently so does the formation of the first level of aggregates, leading to further aggregation into larger units.

3.2 The effect of mean velocity gradient and retention time

The basic operational factors influencing the aggregation and separation efficiency of a fluidized layer are the magnitude and distribution of the mean velocity gradient $\bar{G}$, and the retention time in the layer t (Monk and Trussell, 1991; Mutl et al., 1999). These factors also have a fundamental effect on the character and structure of the aggregates formed (Coufort et al., 2005; Jarvis et al., 2005; Mutl et al., 2006).

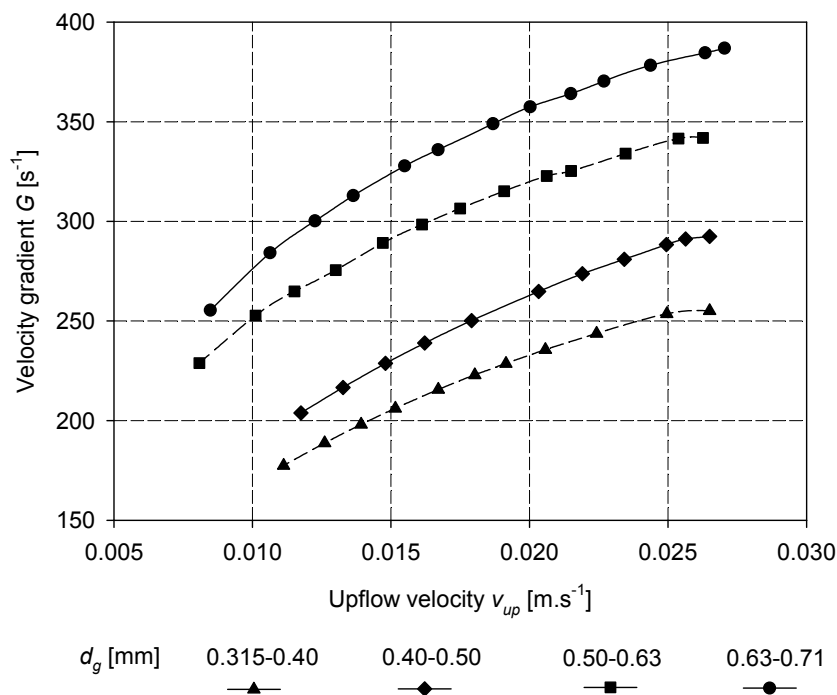


Fig. 3. Influence of grain size – dependence of the mean velocity gradient $\bar{G}$ on upflow velocity v_{up} and grain size d_g .

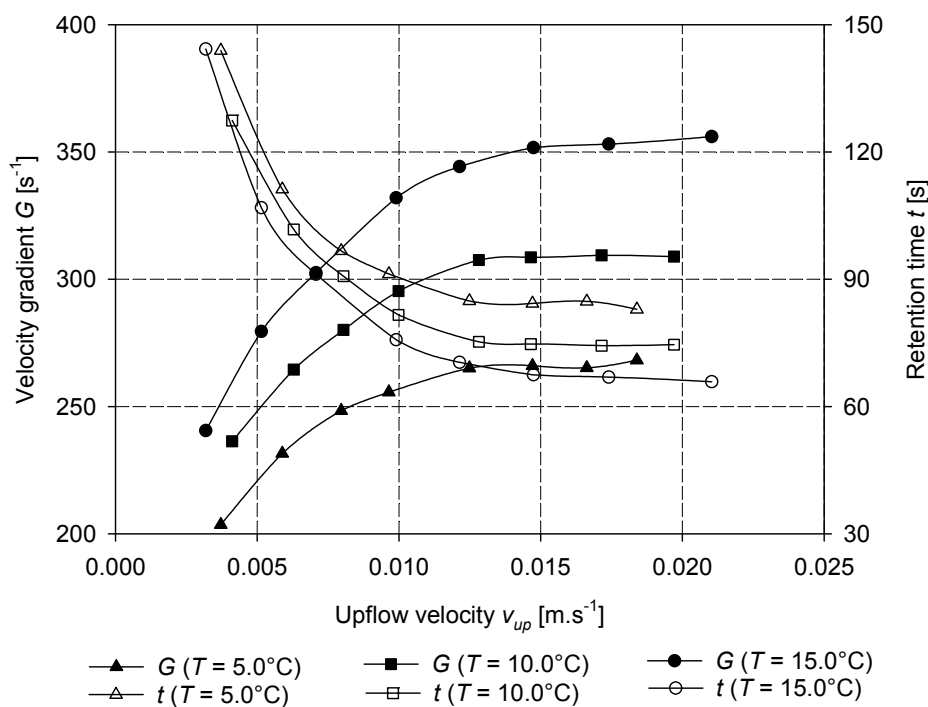


Fig. 4. Influence of temperature – dependence of retention time t and mean velocity gradient $\bar{G}$ on upflow velocity v_{up} and water temperature T for grain size 0.31–0.71 mm.

It follows from the Eq. (1) and (2) that velocity gradient and retention time depends on several other quantities, such as upflow velocity, density and size of the layer grains, or temperature, which need to be considered as well. Figs. 3 and 4 illustrate the dependence of $\bar{G}$ and t on v_{up} . (They represent experimental data, even if they could be theoretically calculated, and they are presented for better image of the effect of other quantities on $\bar{G}$ value.) It is obvious that with increasing v_{up} , $\bar{G}$ also increases, and t decreases. But the influence of grain size (Fig. 3) and temperature (Fig. 4) could escape observation. For given v_{up} , velocity gradient increases with both increasing grain size (d_g) and increasing temperature (T). For example, for temperatures $T = 5 - 15^\circ\text{C}$, it ranges between $\bar{G} = 223 - 278 \text{ s}^{-1}$ at $v_{up} = 0.005 \text{ m s}^{-1}$, and $\bar{G} = 248 - 302 \text{ s}^{-1}$ at $v_{up} = 0.015 \text{ m s}^{-1}$.

In waterworks operation (where a constant flow rate is required), the mean velocity gradient can be

influenced either by changing the size fraction of sand grains used (see Fig. 3), or by replacing sand grains with another material with higher or lower density than silica sand. Lower-density grains of expanded polystyrene have been successfully tested as well as high-density bauxite grains (Muti and Polasek, 1993). The retention time t can be then changed (while keeping a constant velocity gradient) only by changing the layer height L_0 .

The influence of $\bar{G}$ on the separation of destabilized impurities is illustrated in Fig. 5. It shows that the efficiency of separation of destabilized aggregates on the layer grains increases with increasing $\bar{G}$. The maximal separation efficiencies ($\varphi_{Al} \sim 80\%$ and $\varphi_{TOC} \sim 30\%$) were achieved at $\bar{G} \sim 250 - 260 \text{ s}^{-1}$ with the layer grain size in range of $0.31 - 0.63 \text{ mm}$, but for reaching the same efficiency with the grain size of $0.63 - 0.71 \text{ mm}$, the velocity gradient $\bar{G} \sim 320 \text{ s}^{-1}$ was needed.

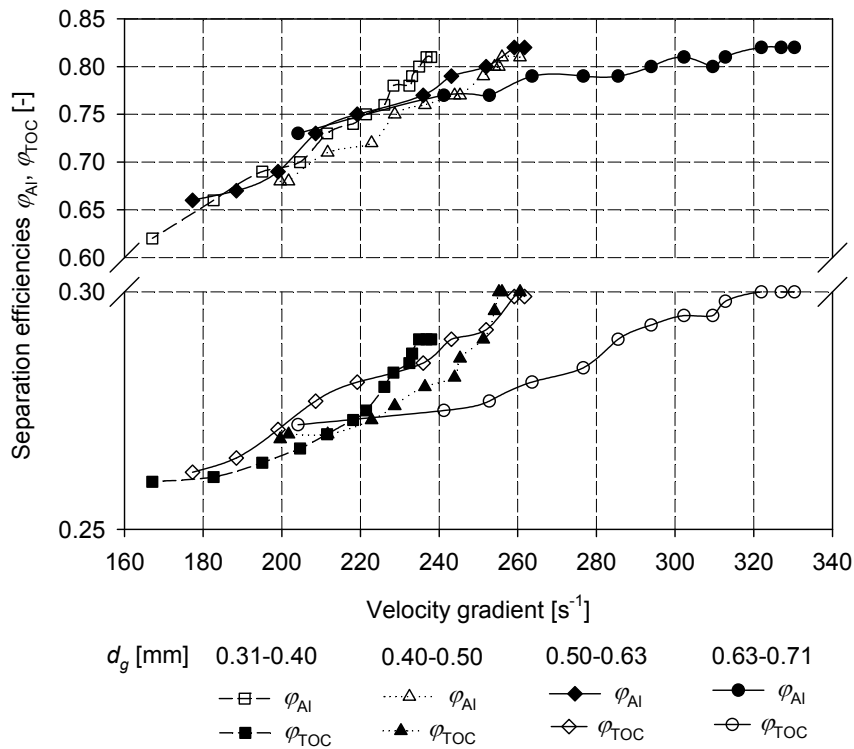


Fig. 5. Dependence of separation efficiency φ_{Al} and φ_{TOC} on the mean velocity gradient $\bar{G}$ for different grain size (optimized reaction conditions: $D_{Al} = 1.55 \text{ mg L}^{-1}$, $\text{pH} = 6.7$ and $T = 10.0^\circ\text{C}$).

3.3 The effect of degree of aggregation of destabilized particles entering the FLGM

Since we assumed that the extent of aggregation of particles entering the FLGM fundamentally determines whether separation occurs along with aggregation, we investigated the influence of the degree of aggregation on the separation efficiency at the moment of inlet to the FLGM. The aggregation of particles entering the FLGM is affected by time of aggregation t_a achieved by the system prior to entry to the fluidized layer (Mutl et al., 1999). This change in aggregation time was achieved by changing the feed pipe length (the length of the pipe between destabilization reagent injection and inlet to the FLGM). The velocity gradient in the pipe fluctuated around the value of $\bar{G} = 400 \text{ s}^{-1}$ in dependence on temperature. The effects of temperatures $T = 5.0, 10.0$ and $15.0 \text{ }^\circ\text{C}$ on the extent of aggregation at an optimized aluminium dosage of $D_{Al} = 1.55 \text{ mg L}^{-1}$ are shown in Tab. 4.

It is evident from the test results that the degree of aggregation of destabilized particles in the inlet

to the fluidized layer increases with increasing aggregation time t_a before the suspension enters the FLGM. In the contrast, the separation efficiency of the fluidized layer decreases with increasing t_a . The highest FLGM separation efficiency is achieved with the shortest aggregation time before inlet to the FLGM, when particles entering FLGM have not been aggregated yet at all. The reason (similarly as for the effect of temperature) is that hydrolysis of the destabilization reagent, and the formation of hydroxopolymers able to destabilize the impurities, proceeds only in the fluidized layer and not before. Some of these hydroxopolymers with high adhesion abilities adhere to the fluidized layer grains, where hydroxopolymer-impurities interactions take place. This mechanism undoubtedly leads to the efficient interception of certain of the impurities in the fluidized layer.

When hydrolysis and the formation of hydroxopolymers proceed prior to the fluidized layer, interactions between particles occur and primary aggregates are formed before the layer, which then serves as an agitating element.

Table 4. Influence of degree of aggregation α_{Al} of particles entering the FLGM on the separation efficiency φ_{Al} of FLGM.

Aggregation time t_a [s]	$T = 5.0 \text{ }^\circ\text{C}$, $G = 385 \text{ [s}^{-1}\text{]}$		$T = 10.0 \text{ }^\circ\text{C}$, $G = 405 \text{ [s}^{-1}\text{]}$		$T = 15.0 \text{ }^\circ\text{C}$, $G = 424 \text{ [s}^{-1}\text{]}$	
	φ_{Al}	α_{Al}	φ_{Al}	α_{Al}	φ_{Al}	α_{Al}
50.0	0.07	0.89	0.02	0.94	0.03	0.93
36.0	0.15	0.79	0.08	0.89	0.07	0.88
21.0	0.19	0.78	0.14	0.82	0.11	0.85
12.5	0.23	0.71	0.21	0.74	0.18	0.78
6.5	0.30	0.65	0.25	0.71	0.21	0.75
3.5	0.46	0.50	0.37	0.56	0.33	0.61
1.5	0.53	0.44	0.47	0.48	0.43	0.53
0.5	0.62	0.33	0.54	0.41	0.49	0.47
0.3	0.76	0.21	0.62	0.32	0.58	0.36
0.1	0.81	0.17	0.73	0.24	0.65	0.31

3.4 The effect of total grain surface area

Another important factor in separation efficiency is the size of fluidized layer grains on which the surface separation occurs. The influence of surface area (porosity of the material is not considered in this paper) was experimentally tested by the increase in fluidized layer volume (number of layer grains) for individual silica sand grain size fractions (Tab. 2). Since sand grains have anisometric shape, their size was defined as an equivalent diameter d_{eqv} , calculated from the volume of 1000 sand grains for each fraction, which were determined by

pycnometric measurements (Viana et al., 2002). The magnitude of grain surface area was calculated as S_{eqv} , a surface of a spherical particle with the diameter d_{eqv} . The total grains surface area ΣS_{eqv} was then calculated from S_{eqv} and the total amount of grains in the layer.

The tests were carried out under optimised reaction conditions ($D_{Al} = 1.55 \text{ mg L}^{-1}$) in order to ensure that the results are not influenced by the extent of destabilization of impurities. Upflow velocity in the layer was $v_{up} = 0.013 \text{ m s}^{-1}$, and temperature $T = 10 \text{ }^\circ\text{C}$. The changes in total silica sand grains surface area were reflected in the change in layer

volume, i.e. by the change from the initial height L_0 . The total grain surface areas were then recalculated from the equivalent grain surface.

As is evident from Figs. 6 and 7, separation efficiency increases with increasing ΣS_{eqv} (given by

increase in number of the layer grains) until a certain value, after which it has a constant character. For the grain sizes tested, this ranges with 10 – 20 m^2 , which represents the initial layer height L_0 range of 0.40 – 0.80 m.

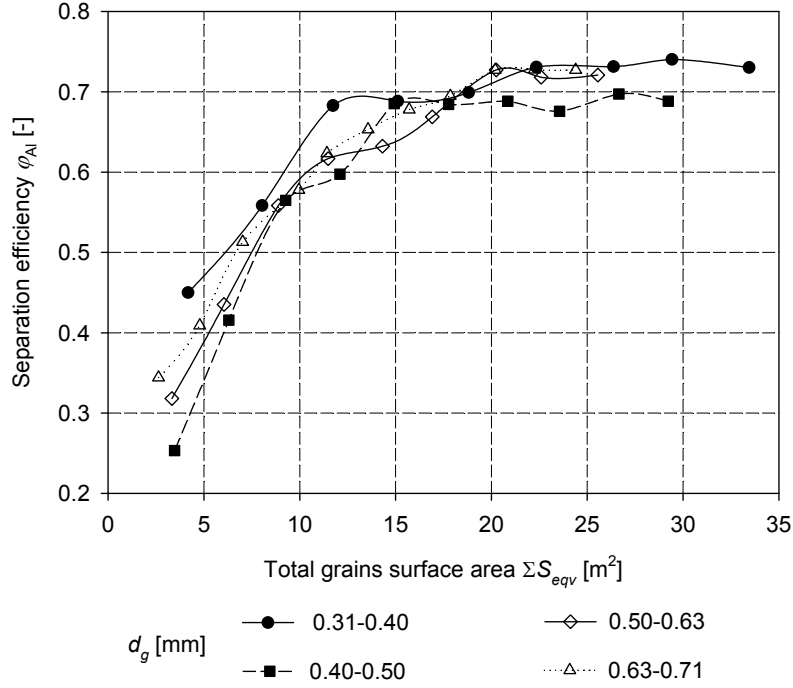


Fig. 6. Dependence of separation efficiency ϕ_{AI} on the total grains surface area ΣS_{eqv} .

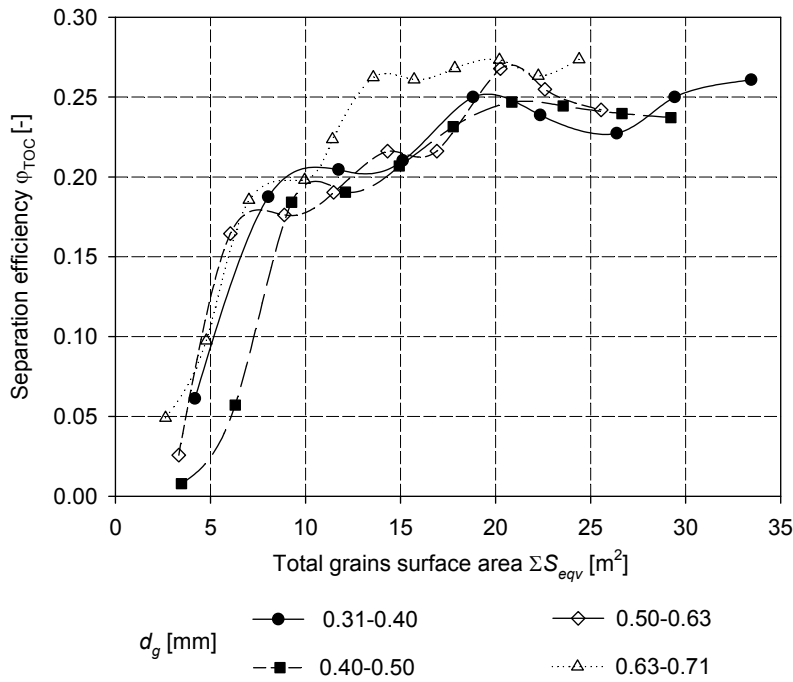


Fig. 7. Dependence of separation efficiency ϕ_{TOC} on the total grains surface area ΣS_{eqv} .

During separation in the fluidized layer, sand grains are covered with destabilized impurities, and the size of grains grows and their density and shape change. Fig. 8 exhibits the character of sand grains of the 0.40–0.50 size fraction after 1650 hours of layer operation. It is apparent that the originally anisometric shape of sand grains has gradually

taken the shape of spheres. The average increase of FLGM weight was $\Delta m = 0.61 \text{ g h}^{-1}$, the average change of pressure drop ranged around $\Delta p = 5.7 \text{ Pa.h}^{-1}$ and the height of the layer in expansion increased by about $\Delta L_E = 0.5 \text{ mm h}^{-1}$. The density of the shell formed on the surface of sand grains was 2450 kg m^{-3} .

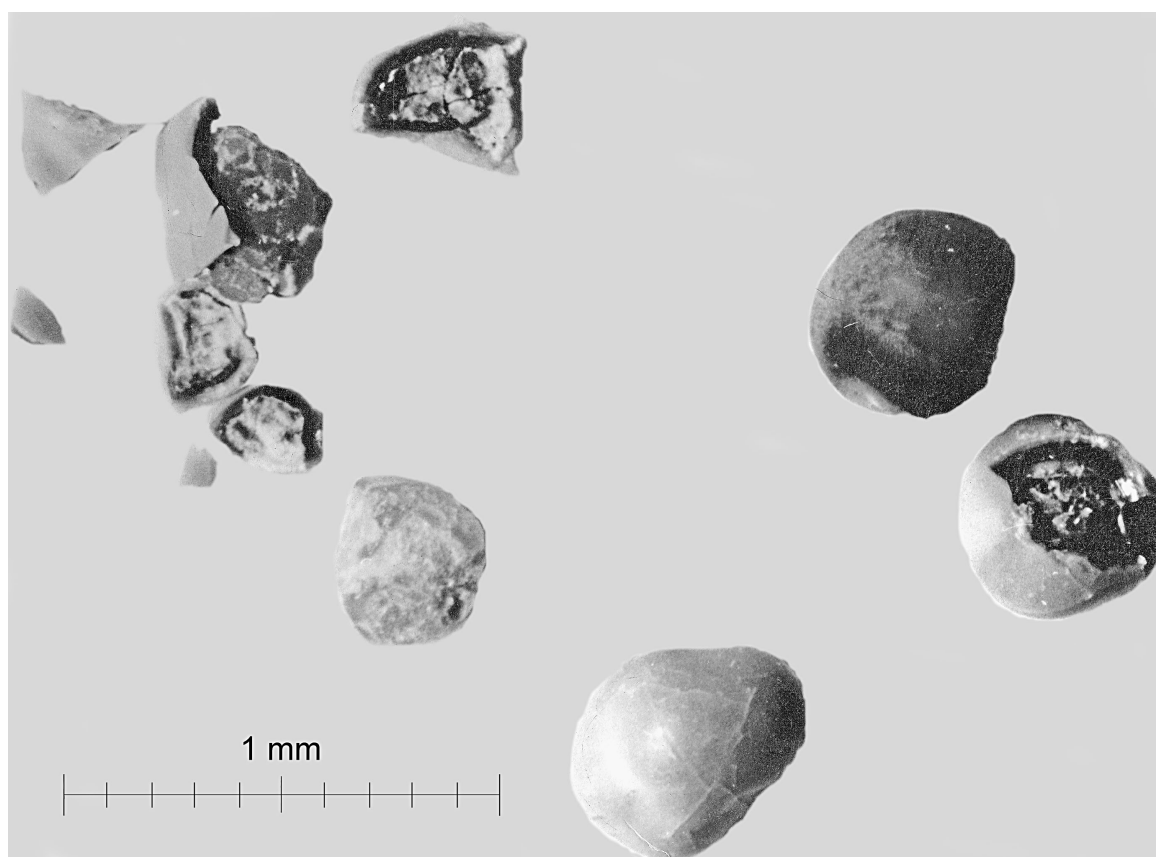


Fig. 8. Character of covered sand grains of fraction of 0.40–0.50 mm after 1650 hours of fluidized layer operation.

4. Conclusions

Based on the results obtained the following conclusions can be made:

- Waterworks suspension can be separated by the interception of destabilized particles on the fluidized layer grains in the form of a solid, water-free shell with density of 2450 kg m^{-3} . The non-intercepted particles combine with each other to form floc aggregates, which need to be separated in subsequent treatment stages (e.g. with rapid gravity sand filters).
- The highest efficiency of destabilization of impurities, enabled by the optimal dosage of the destabilization reagent, is one of the conditions for the achievement of highest separation efficiencies.
- The degree of aggregation of destabilized impurities at the moment of their contact with fluidized layer grains determines whether aggregation or separation ability of FLGM prevails. The highest separation efficiencies are achieved when the particles enter the layer immediately after dosing of the destabilization reagent, when they have not aggregated yet (the degree of aggregation is very low). On the contrary, the separation efficiency of the layer decreases with the increasing degree of aggregation at the moment of entering the FLGM.

- The separation efficiency of the layer also depends on the total equivalent surface area of the layer grains (porosity of the material is not considered in this paper). A comparison of the efficiencies for individual grain sizes showed that the minimal surface area at which the maximal separation efficiencies are achieved is approximately the same for all grain sizes (about 20 m²). Increasing the grain surface area above this minimal value does not further significantly change the separation efficiency.
- The separation efficiency is also significantly influenced by hydraulic conditions, especially the mean velocity gradient and retention time of flocculating suspension in the fluidized layer. We showed that the efficiency of separation of destabilized particles on the fluidized layer grains increases with an increasing $\bar{G}$.
- The efficiencies of separation on fluidized layer grains reached values of $\varphi_{Al} = 0.81$ ($D_{Al} = 1.55$ mg L⁻¹) and $\varphi_{TOC} = 0.31$ ($D_{Al} = 2.36$ mg L⁻¹).

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List of symbols

A	– cross-sectional area of the FLGM reactor [m ²],
C_0	– initial concentration of the parameter (Al, TOC) [mg L ⁻¹],
C_E	– concentration of the parameter determined in the sample after the separation on FLGM grains [mg L ⁻¹],
C_F	– concentration of the parameter determined in the sample after centrifugation under defined conditions (1467 x g, $t = 20$ min) [mg L ⁻¹],
d_{eqv}	– equivalent diameter of a fluidized layer grain [mm],
d_g	– diameter of a fluidized layer grain [mm],
E	– expansion ratio [–],
g	– gravitational acceleration [m s ⁻²],
$\bar{G}$	– mean velocity gradient [s ⁻¹],
L_0	– height of a stable layer [m],
L_E	– height of a fluidized layer in expansion [m],
ΔL_E	– change in height of a fluidized layer [m],
m	– weight of the granular medium [kg],
Δm	– change in weight of the granular medium [kg],
p	– pressure drop [Pa],
Δp	– change in pressure drop [Pa],
Q	– rate of flow [m ³ s ⁻¹],
S_{eqv}	– equivalent grain surface area [mm ²],
ΣS_{eqv}	– total grains surface area [m ²],
t	– retention time in a fluidized layer [s],
t_a	– aggregation time before inlet to the fluidized layer [s],
T	– water temperature [°C],

v_{cr}	– critical upflow velocity [m s ⁻¹],
v_{up}	– upflow velocity [m s ⁻¹],
V_{eqv}	– equivalent volume of grain [mm ³],
V_E	– volume of the fluidized layer in expansion [m ³],
V_P	– volume of pores between layer grains [m ³],
α_A	– degree of aggregation of the particulate impurities [–],
α_{Al}	– degree of aggregation expressed by Al-ion [–],
η_w	– dynamic viscosity of water [Pa s ⁻¹],
ρ_w	– density of water [kg m ⁻³],
ρ_g	– density of fluidized layer grains [kg m ⁻³],
φ_A	– separation efficiency [–],
φ_{Al}	– separation efficiency expressed by Al-ion [–],
φ_{TOC}	– separation efficiency expressed by total organic carbon [–],
ω_0	– void fraction of a stable layer [–],
ω_E	– void fraction of a fluidized layer in expansion [–].

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