National Conference with International Participation
ENGINEERING MECHANICS 2007
Svratka, Czech Republic, May 14 – 17, 2007

THE INFLUENCE OF THE AGITATION INTENSITY ON FILTRATION RUNS DURING WATER TREATMENT

M. Pivokonský*, L. Pivokonská*, M. Švec*

Summary: *The aim of this contribution is to investigate aggregation efficiencies when high (G= 260 s^{-1}) and low (G= 60 s^{-1}) intensity agitation is applied for a treatment of surface water with high content of humic substances in a pilot size operation. It was established that high intensity agitation represented by a fluid layer of granular material (FLGM) can be more effective for an aggregation agitation than low intensity agitation with the help of the perforated baffles (PB). The FLGM improves performance of the filters because the filtration runs in the technological arrangement with FLGM took longer periods compared with low intensity agitation.*

Introduction

The aggregation agitation influences the properties of aggregates being formed which, in turn, decisively influence their separation capabilities. In water treatment technology the movement of liquid is caused by agitation either by hydraulic or mechanical means at which the aggregating particles are subjected to the action of adhesive forces (affecting their combining) and tangential, shear forces (preventing their combining). Mutual ratio of the magnitudes of these forces is a factor determining kinetics of the aggregation process. In addition, it also influences resultant size and inner structure of the aggregates formed, i.e. the properties of aggregates that are important from their separation point of view. Generally, the influence of mutual ratio of the two forces on the structure of aggregates formed can be described as follows: when the colliding particles affect one another by great adhesion forces and when the tangential forces are small, then the particles join one another at the point of their first contact. As a result, sizeable voluminous aggregates of a geometrically loose, widely branched spaciously extended net structure are formed. Such aggregates contain large quantities of voids that are filled with entrapped water. The ultimate aggregates are large, having low density and are very fragile with a tendency to fragment. In contrast, when the colliding particle affect one another by small adhesion forces and tangential forces are great bit smaller than the critical ones, the colliding particles during their combining slide along each other until they occupy geometrically the most favourable and energetically the most stable position. As a result smaller aggregates of a compact and relatively arranged structure, more resistant to fragmentation are formed. Such aggregates have a smaller volume of voids and hence contain a smaller volume of entrapped water. Consequently, their density is higher. Similar situation occurs when the colliding particles are affected by great adhesion forces and exposed to action of great tangential forces because great tangential forces weaken the effect of great adhesive forces. When the tangential forces affecting the colliding particles are considerably greater than the adhesive forces, the aggregation of particles does not occur or occurs to a very limited extent only.

* Martin Pivokonský, Lenka Pivokonská, Martin Švec: Ústav pro hydrodynamiku AV ČR, v.v.i.; Pod Paťankou 5; 166 12 Praha 6; tel.: +420.233 109 011, fax: +420.224 333 361; e-mail: pivo@ih.cas.cz; pivokonska@ih.cas.cz; svec@ih.cas.cz

From foregoing it follows that the magnitude of adhesive forces is well defined by chemical composition of particles of impurities and by the degree of their destabilisation. As the magnitude of tangential forces is expressed by the velocity gradient G, the resulting properties of aggregates, namely their size and form, are influenced by its magnitude and since the aggregation of particles proceeds gradually, also by the period of its application. Therefore, both these parameters define the hydrodynamic conditions of aggregation agitation and are considered to be the basic design data for the device in which aggregation agitation takes place.

The mean velocity gradient $\overline{G}$ is calculated from the relationship derived by Camp and Stein (1943)

$$\overline{G} = \sqrt{\frac{P}{V\eta}} \tag{1}$$

where P represents power input to the water, V is agitated volume of water and η stands for dynamic viscosity.

Equations (2) and (3) provide the calculation of the power input P for the basins agitated by the hydraulic and mechanical means, respectively

$$P = \rho g \Delta H Q \tag{2}$$

$$P = \sqrt{\frac{f A_p v_r^3}{2\nu V}} = Eu \rho n^3 d^5 \tag{3}$$

where ρ is density of liquid, g gravity constant, ΔH loss of head, Q rate of flow, f resistance factor of the stirrer, A_p area of stirrer blades perpendicular to movement, v_r relative velocity of stirrer blades to liquid, ν kinematic viscosity, Eu Euler's number (power factor) adjusted for the conditions of mixing, n a number of revolutions of the stirrer and d stirrer diameter.

Intensity of agitation and distribution of velocity field in an agitated volume depend on an ultimate size of the aggregates required, which is determined by a method used for their separation. The rapid (high intensity) agitation, i.e. with velocity gradient $G > 100$ s^{-1}, results in a formation of micro-aggregates. The slow (low intensity) agitation, i.e. $G < 80$ s^{-1}, enables a formation of macro-aggregates from the micro-aggregates formed during the preceding phase of rapid agitation. The slow agitation has its justification as the second phase only when formation of large and readily settleable aggregates is achieved at and is applied only after completion of the formation of aggregates in the phase of rapid agitation. This has been verified in the following literature (Polášek and van Durren, 1978; Mutl et al., 2006; Pivokonská and Pivokonský, 2006).

Methods

The experimental work was carried out at the Mezibori waterworks (near the town Litvinov, Czech Rep.), treating water from the impounding Flaje reservoir. This reservoir is characterised by a relatively stable water quality and stable temperature over a long period time, which ensures reproducibility of the pilot plant operations and hence the results obtained.

The basic technological parameters (dosages of alkalisation and destabilisation reagents) were determined by the jar tests, evaluated in accordance with the methodology described in Polasek and Mutl (1996). A variable speed eight-paddle stirrer LMK 8-04 (EJP company, Czech Republic), and 2-litre jars were used for jar testing. The procedure consisted of a 1

minute rapid agitation (G = 400 s^{-1}), 15 minutes of slow agitation (G = 70 s^{-1}) and 60 minutes of settling.

The pilot plant tests were carried out with a plant consisting of a FLGM reactor – high intensity agitation, PB reactor – low intensity agitation, and rapid gravity sand filter (RGF), see Fig.1. The FLGM and PB reactors consisted of a 3000 mm long Umaplex tubes of an inner diameter d = 90 mm. The FLGM reactor was charged with silica sand of granularity d_s = 0.40 - 0.50 mm. The sand depth corresponded to L_0 = 1500 mm. The FLMG expansion ratio E attained approximately 1.75. The mean velocity gradient produced was G = 260 s^{-1} (high intensity agitation) and a retention period in the fluidised layer corresponded to T = 170 s. The 15 perforated baffles each with 12 holes (d = 8 mm) were installed in the PB reactor. The mean velocity gradient produced was G = 60 s^{-1} (low intensity agitation) and a retention period in the PB reactor corresponded to T = 170 s. The velocity gradients were calculated using a head loss measured by head probe (P_0). The rapid gravity filter consisted of a 2500 mm long Umaplex tube of an inner diameter d = 125 mm with the probes (P_1-P_6) for measurement of head loss (14) along the depth and flow regulator (11) installed in the filtrate discharge pipe. The filter was charged with silica sand of a granularity d = 0.8 - 1.25 mm to a filter bed depth L_F = 1100 mm. During the pilot plant operation several filtration runs of the RG filter were evaluated at a filtration velocity v_f = 3.0, 6.0 and 9.0 m.h^{-1}. The backwashing of RGF is carried out using tap water (12).

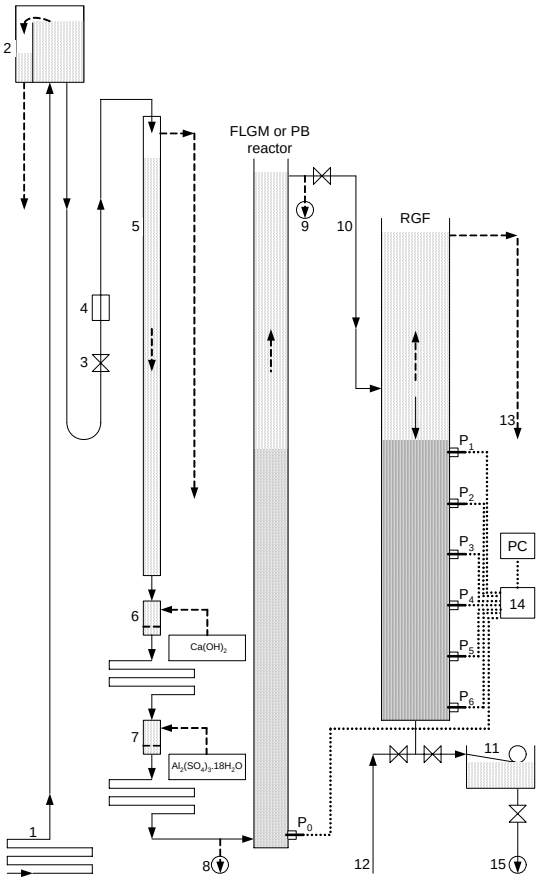

Fig. 1. Diagram of the pilot plant

The raw water is fed at maximum flow from raw water main (1) to a head tank. From the head tank raw water gravitates via a pipe fitted with flow regulator (3) and flow-meter (4) to a flow regulating system which is connected with the FLGM reactor. Flow regulating system enables stable flow rate (required to compensate for increasing head loss caused by formation of a cover layer on the grains of media) and automatic re-start of the plant in case of accidental raw water cut off. The feed pipe, just before connecting to the FLGM reactor, is provided with the facilities for injection of an alkalisation reagent /lime water/ (6), a destabilization reagent /aluminium sulphate/ (7) and a tube for sampling of the dosed water (8). Because the FLGM reactor was operated in aggregation mode in all cases of measurements, the facilities for injection of both reagent and its homogenisation with the raw water were placed at the inlet into long pipe installed before reactor. The water from the FLGM reactor gravitates through a pipe (10) with a tube for sampling of the flocculated suspension into the RGF. The filtration velocity is regulated using a flow regulator (11) installed in the filtrate discharge pipe. In the outlet from flow regulator there is placed the final sampling tube (15).

Data characterising the state of the agitation reactors (head loss H_R, depth of granular layer L_0, L_E, time of retention T) and filtration (head loss H_F and duration of filtration run T_F) were used as the operational parameters. The duration of filtration runs T_F was limited either on

exhausting the pressure head H_F, or exceeding the maximum allowed *Al* concentration in tap water (c_{Al} = 0.20 mg.l^{-1}). For the purpose of verifying reproducibility of the results obtained, three series of the pilot plant tests were carried out.

The efficiency of the water treatment process was determined by:

1. a direct comparison of water quality indicators: content of metal component of destabilising reagent Al, chemical oxygen demand COD_{Mn}, dissolved organic carbon DOC, pH value, alkalinity and temperature;
2. determining separation efficiency φ of Al and DOC, according to the relationship

$$\varphi = 1 - \frac{C_F}{C_0} \tag{4}$$

where C_0 is the initial concentration of Al or DOC used and C_F is the final value in treated water.

The effect of agitation was evaluated by the degree of aggregation α and determined in crucial stages of formation of suspension. It is calculated according to the relationship

$$\alpha_A = \frac{C_0 - C_F}{C_0} \tag{5}$$

where C_0 is the concentration of monitored indicator (Al, DOC) at the point of testing and C_F is the concentration of the monitored indicator determined in the sample after its treatment by centrifugation under defined conditions.

Density and size of formed aggregates were determined by a test of aggregation, which enables separation of the formed aggregates into the four basic categories: non-aggregate particles (*NA*), primary particles (*PR*), micro-particles (*MI*) and macro-particles (*MA*). The particle distribution existing in the system at any given moment is evaluated by the test of aggregation that is based on sedimentometric analysis. The technologically significant categories of particles are determined according to the following relationships (Hereit et al., 1980)

$$MA = \frac{C_0 - C_5}{C_0} \qquad MI = \frac{C_5 - C_{60}}{C_0} \qquad PR = \frac{C_{60} - C_{60F}}{C_0} \qquad NA = \frac{C_{60F}}{C_0} \tag{6-9}$$

and therefore

$$MA + MI + PR + NA = 1 \tag{10}$$

where C_0, C_5 and C_{60} are the concentrations of the monitored parameter measured in the samples taken at the beginning of sedimentation, after 5, and after 60 minutes of sedimentation, respectively. C_{60F} is a concentration of the monitored parameter determined in the sample after its treatment by centrifugation under the defined conditions.

The methodology of sampling, analytical processing of the samples and evaluation of the results obtained can be found in the previous works (Hereit et al., 1980; Polašek and Mutl, 1996).

Results

A pilot plant was installed in the Mezibori waterworks treating water from the Fláje impounding reservoir. The planned output of this water treatment plant is 500 l.s^{-1}. One-step separation technology with the perforated baffle-type flocculation chamber is used as an agitation element. The aggregates formed are separated using primary filtration. The water

quality represents high concentration of organic matter of humic character (DOC = 7.4 mg.l^{-1}) and low alkalinity ($KNK_{4.5}$ = 0.16 mmol.l^{-1}).

The efficiency of destabilisation of impurities in the treatment of humic waters is, in general, reaction pH dependent. The typical jar test results obtained from optimisations of both aluminium sulphate dosage and reaction pH are shown in Figs. 2 and 3. The efficiency of destabilisation process expressed by residual Al concentration and DOC value, determined in centrifuged samples taken after sedimentation, does not vary much over the full range of the dosages applied. The highest destabilisation efficiencies represented by residual Al concentration value α_A(Al) = 0.94 and DOC value α_A(DOC) = 0.76 were reached at dosage varying over a narrow range from D = 0.021 to 0.026 mmol.l^{-1} and pH ranged between 5.8 and 6.2.

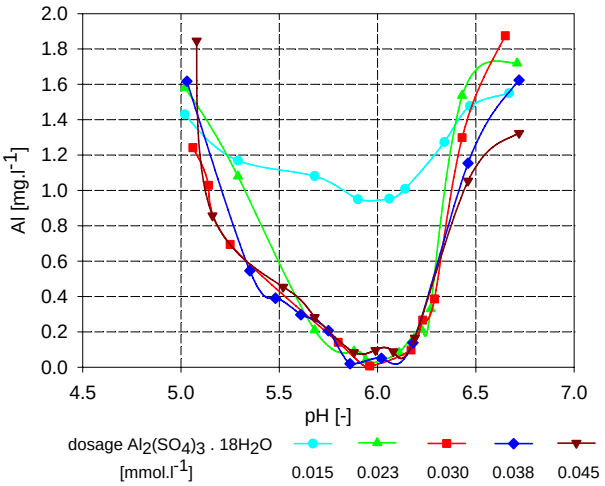

Fig. 2. Jar test optimisation of aluminium sulphate and reaction pH: residual Al

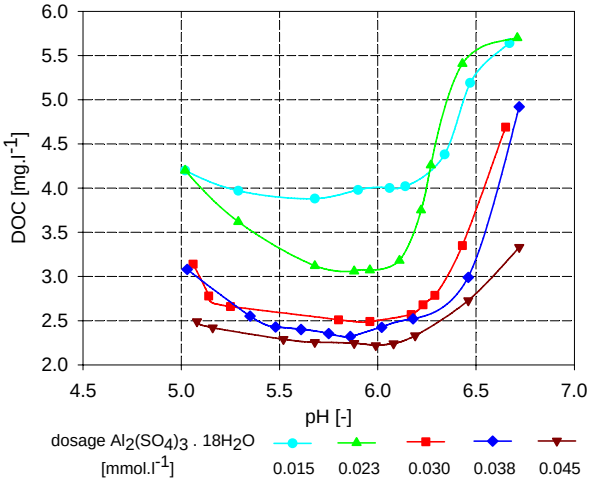

Fig. 3. Jar test optimisation of aluminium sulphate and reaction pH: residual DOC

The pilot plant testing was aimed at evaluating the aggregation efficiency of the FLGM reactor (high intensity agitation) and PB reactor (low intensity agitation). The pilot plant arrangement was supplemented with a long pipe installed upstream of the reactors, where the destabilising particles aggregated into the primary-aggregates. The influence of varying dosage of aluminium sulphate on aggregation efficiency of FLMG and at pH = 5.9 regulated by dosing of lime water, was established using pilot plant testing. The maximum efficiencies were achieved for dosages varying over the same narrow range, which was achieved by the jar tests (D = 0.021 to 0.026 mmol.l^{-1}). For an aluminium sulphate dosage D = 0.023 mmol.l^{-1} (determined as the optimum dosage) the high degrees of aggregation α_A(Al) = 0.92 and 0.66 were achieved using FLMG and PB

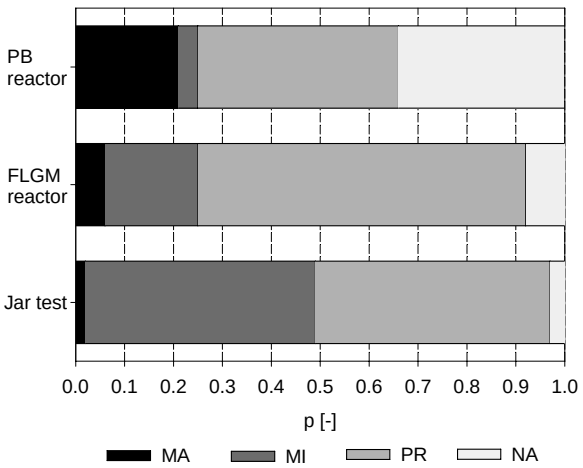

Fig. 4. Particle size distribution: jar test, FLGM, waterworks and pilot plant perforated baffles

reactors, respectively.

The efficiency of the FLGM on aggregation is demonstrated in Fig.4 depicting the portion of size fractions of the formed aggregates. A predominant portion of the formed aggregates is constituted by the primary-aggregates (p_{PR} = 0.67), which are favourable for the one-step separation by filtration. The relatively high portion of micro-aggregates (p_{MI} = 0.19) and low portion of non-aggregated particles (p_{NA} = 0.08) and macro-aggregates (p_{MA} = 0.06) were measured in the system using FLMG reactor as the agitation element. In contrast to it, the high portions of non-aggregated particles (p_{NA} = 0.34), primary-aggregates (p_{PR} = 0.41) and macro-aggregates (p_{MA} = 0.21), and very low portion of micro-aggregates (p_{MI} = 0.04) were measured during agitation using the PB reactor, see Fig.4.

Tab. 1. Comparison of operational performance and separation efficiencies of the pilot plant with FLGM and PB

	High intensity agitation				Low intensity agitation			
	FLGM reactor		RG filter - Outlet		PB reactor		RG filter - Outlet	
	Inlet	Outlet	v_f = 3 m.h^{-1}	v_f = 6 m.h^{-1}	Inlet	Outlet	v_f = 3 m.h^{-1}	v_f = 6 m.h^{-1}
Al [mg.l^{-1}]	1.32	1.30	0.05	0.07	1.32	1.32	0.08	0.08
DOC [mg.l^{-1}]	7.40	7.40	1.99	2.29	7.40	7.40	2.29	2.40
α_A(Al)[-]	---	0.92	---	---	0.66	---	---	---
φAl [-]	---	---	0.96	0.95	---	---	0.95	0.93
φDOC [-]	---	---	0.73	0.69	---	---	0.69	0.67
Time [h]	---	---	28.0	18.0	---	---	18.0	8.0
H [kPa]	---	---	2.10	2.90	---	---	2.30	1.60

During the pilot plant operation using the FLGM and PB reactors several filtration runs of the RG filter were evaluated at the filtration velocities v_f = 3 and 6 m.h^{-1}. The results characterising the course of typical filtration runs for all filtration velocities are summarized in Tab.1, and illustrated in Figs. 5-8. During operation using the FLGM and a filtration velocity v_f = 3 m.h^{-1}, the separation efficiency of the RG filter attained φAl = 0.96 and φDOC = 0.73, and the filtration runs ended approximately after 28 h operation also due to Al breakthrough at a very low filter head loss ΔH = 2.1 kPa.

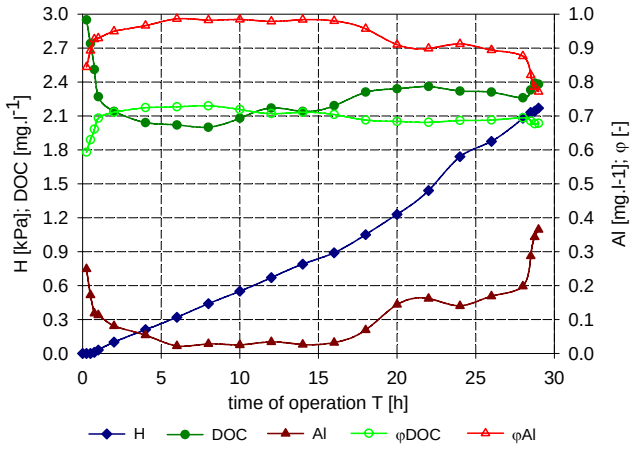

Fig. 5. Pilot plant operational performance with the FLGM during a filtration run (v_f = 3 m.h^{-1})

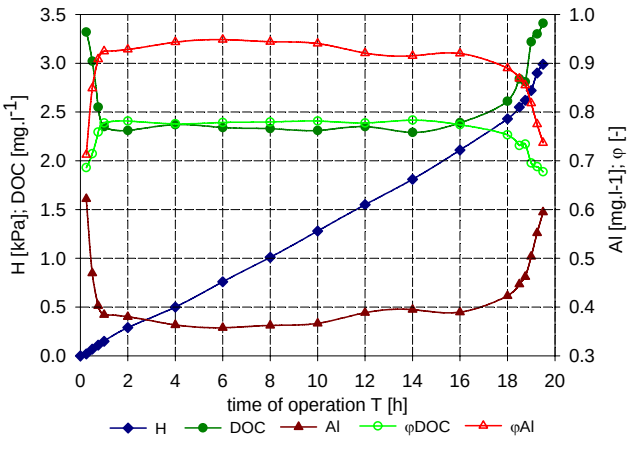

Fig. 6. Pilot plant operational performance with the FLGM during a filtration run (v_f = 6 m.h^{-1})

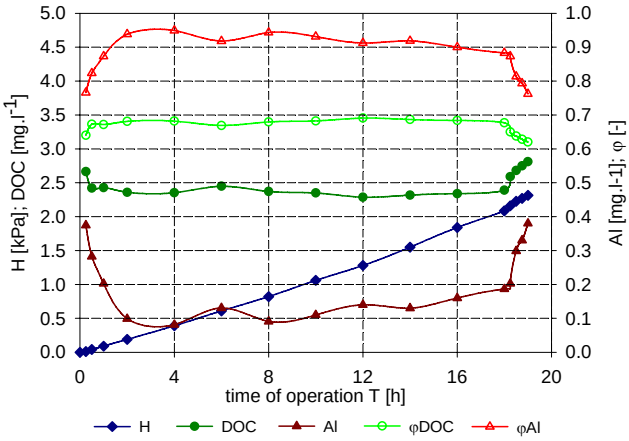

Fig. 7. Pilot plant operational performance with the PB during a filtration run (v_f = 3 m.h^{-1})

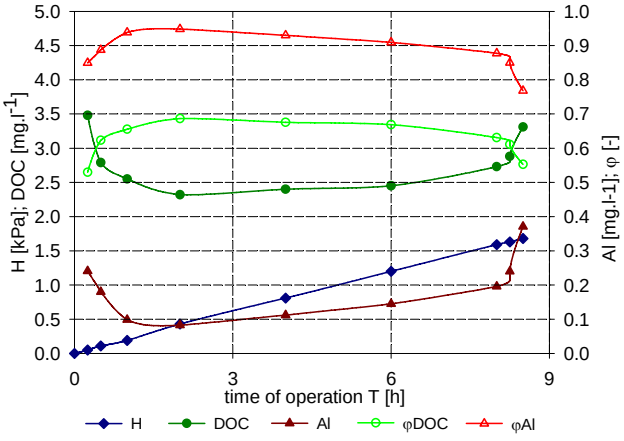

Fig. 8. Pilot plant operational performance with the PB during a filtration run (v_f = 6 m.h^{-1})

For the parallel tests carried out with a substantially higher velocity v_f = 6 m.h^{-1}, the total separation efficiencies of the pilot plant after filtration were φAl = 0.95 and φDOC = 0.69, and the filtration runs were characterised by a short time of duration and its runs ended approximately after 19 h operation also due to Al breakthrough at the relatively low filter head losses ΔH = 2.9 kPa.

In contrast to it, the filtration runs using the PB reactor ended approximately after 18 (v_f = 3 m.h^{-1}) and 8 (v_f = 6 m.h^{-1}) hours of operation due to Al breakthrough at the relatively low filter head losses ΔH = 2.3 kPa (v_f = 3 m.h^{-1}) and 1.6 kPa (v_f = 6 m.h^{-1}). For all tests carried out with the PB ractor, the total separation efficiencies of the pilot plant after filtration were φAl = 0.95 and 0.93, and φDOC = 0.69 and 0.67, respectively.

Conclusion

Based on the results obtained the following conclusions can be made

- The high portion of primary-aggregates (p_{PR} = 0.67) and micro-aggregates (p_{MI} = 0.19), and low portion of non-aggregated particles (p_{NA} = 0.08) and macro-aggregates (p_{MA} = 0.06) were measured in the system using the FLMG reactor as an agitation element. In contrast to it, the high portions of non-aggregated particles (p_{NA} = 0.34), primary-aggregates (p_{PR} = 0.41) and macro-aggregates (p_{MA} = 0.21), and very low portion of micro-aggregates (p_{MI} = 0.04) were measured during agitation using the PB reactor.
- The filtration runs ended after 28 h (v_f = 3 m.h^{-1}), 19 h (v_f = 6 m.h^{-1}) operation also due to Al breakthrough at very low filter head loss ΔH = 2.1 kPa (v_f = 3 m.h^{-1}), 2.7 kPa (v_f = 6 m.h^{-1}), using the FLGM as a agitation element.
- The filtration runs of the pilot plant with PB reactor ended after 18 (v_f = 3 m.h^{-1}) and 8 (v_f = 6 m.h^{-1}) hours of operation due to Al breakthrough at the relatively low filter head losses ΔH = 2.3 kPa (v_f = 3 m.h^{-1}) and 1.6 kPa (v_f = 6 m.h^{-1}).

Acknowledgement

The research project has been funded by the Grant Agency CR under the projects No. 103/07/0295 and 103/07/1016 and the Institutional Research Plan No. AV0Z20600510.

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