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The Modified Primary Swirl Sedimentation Tanks in Waste Liquids Treatment Plant: Liquid Viscosity Effect

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Abstract: This paper discusses design, evaluation, and application for the use of swirl/vortex technologies as liquid purification system. A study was performed using modified swirl sedimentation tanks. The vortex separators containing baffle have been studied under laboratory conditions at hydraulic load from 21 to 64 [$m^3/(m^2 \cdot h)$]. Analyzed disperser phases were municipal water and glycerol solutions of varying concentration. The pressure drop and the efficiency of purification of liquid stream were analyzed. The suspended particles of different diameters were successfully removed from liquid with the application of swirl chambers of proposed constructions. It was found that damming of liquid in the tank increases alongside liquid stream at the inlet and depends on the tank construction. The efficiency of the sedimentation tanks increases alongside the diameters of solid particles and decrease in the liquid flow rate. The best construction proved to be the one where baffle is located in the middle of in- and outlet due to the highest efficiency of the purification liquid stream for solid particles of the smallest diameter. The proposed solution is an alternative to the constructions of heavy fraction separators.

Introduction

Sedimentation of particles dispersed in a fluid is a fundamental phenomenon in separation process as it allows to separate solids from suspension. It is characterized by notable practical importance because of its uncomplicated parameters of process that can lead to a wide range of applications. Some of them are treatment of industrial and domestic wastewater, chemical or food industry (Green and Perry 2008, Bajcar et al. 2010, Błażejewski 2015, Shah et al. 2019, Piazza 2020). Development of sedimentation research brings the field of sedimentation engineering. It concludes identification of the problem, solution planning, analysis and research and finally remediation and purification or removing of undesirable effects of sedimentation (MacArthur et al. 2007, Błażejewski 2015, Huang et al. 2018). One of the reasons of this research is to obtain appliance with high efficiency at low costs, that can be used in purification systems and treatment plants. The environmental case is brought by developing and industrialized nations, where number of contaminants entering water is growing constantly and it is caused by human activity. The solution is to develop more effective and lower-cost methods of water purification (Shannon et al. 2008, Ochowiak et al. 2017, Jurczak et al. 2018). New methods and devices also need to become efficient without endangering human health or environment (Shannon et al. 2008, Kundzewicz et al. 2014, Młyński et al. 2016).

Improvement of water purification process can be performed by separators or settling tanks. Just over fifty years ago, there were only three types of sedimentation tanks used in sewage works practice – a tank with longitudinal flow, circular or square tank. The last two were characterized by radial, vertical or upward flow from a central inlet. These days we can distinguish a lot more types of settling tanks. More and more novelty constructions are developed by many companies, so the description can be supported by commercial materials. There are sand and/or oil separators depending on what kind of material is needed to be separated. Considering construction types there are coalescence or lamella separators and hydrodynamic, horizontal or vertical (vortex) settling tanks (Wavin 2015, Ecol-Unicon 2018, Nixor 2018, Pur Aqua System 2018, Szulc 2018, Shah et al. 2019). Each type of settling tank (separator) has its own specific features and has different application that depends on watershed size, the amount of suspended solids in wastewater or separator's sensitivity. Lamella separators are used in dividing out petroleum derivatives. They use flotation and sedimentation phenomenon. They also can separate solids with greater size or other floating substances. Furthermore, coalescence tanks have watertight concrete (or PE-HD) body or a separated reservoir chamber and they also separate mostly petroleum derivatives. Oil and water dividing is proceed due to the phenomenon of gravitational separation, which is enhanced by the phenomenon of coalescence (Ecol-Unicon 2018, Szulc 2018). Hydrodynamic settling tanks are used at small gross covered area with wastewater flow containing a lot amount of sand. Their construction uses drainage catch pit, usually made of polyethylene that effects on blocking out smaller particles inside the vertical part (EcoBlue 2013, Wavin 2015). Horizontal tanks are simple constructed devices made of modular reinforced concrete retention tanks or can be installed as separate chambers with pre-treatment system. Liquid purification occurs as the effect of holding the sewers conditions of slower flow rate. They can operate as a single device or be a part of pre-treatment system. Horizontal settling tanks can be used in overrun areas, like roads or car parkings (Ecol--Unicon 2016, Nixor 2018, Pur Aqua System 2018). Relatively new type of separator is swirl settling tank, where despite of gravity force presence, there is also a centrifugal force. They are characterized by high efficiency of suspension separation at high hydraulic load. In addition, they have smaller sizes than other types of settling tank, and with circular, narrow body comes gross covered area arrangement, which is an advantage. Directional deflector or tangential placement of inlet port affects the rotary movement of liquid inside the device. The purpose of swirling flow is to gain longer way for particles to precipitate with relatively small tank construction need (Ecol--Unicon 2016, Ecol-Unicon 2018, Pur Aqua System 2018). As we can see, there is a tendency to develop constructions that already exist and to obtain new ones to provide higher efficiency of water purification.

The aim of the study

In the literature there are many articles describing sedimentation tanks working in the water-solid particle and water-polluting liquid systems, but there is a paucity of literature on the purification of high-viscosity liquid streams (Wang et al. 2014). The goal of this work was to construct and analyze selected modified designs of swirl sedimentation tank in terms of purifying Newtonian liquids from solid contamination with density greater than the liquid's, also in relation to liquid's viscosity. Modifications of the settling tank pertained to variable location of applied baffle inside the device and two different locations of inlet pipe also. The studies included analysis of dependencies of separator efficiency and liquid damming on the hydraulic load. Two constructions with the highest efficiency of separation heavy contamination and possibly lowest liquid damming level were distinguished by comparison all obtained and analyzed swirl settling tanks, also with conventional type of swirl settling tank that exists on the market.

Experimental set-up

Fig. 1 shows the block scheme of studied laboratory installation including essential equipment and actions for separation process. A few most important elements were: Ebara Optima MA rotary water pump, HK-4CC rotameter (Kytola), heavy solid fraction feeder, sedimentation tank and filter (Retsch sieve). The weight of solid contaminants before addition to water flow and those caught after leaving the tank was measured by digital laboratory scale PS 210/C/2 (Radwag) with an accuracy of ±0.001 g. Solid contaminants with density greater than liquids' were quartz and feldspar grains. They were characterized by well-sorted sizes and well-rounded shape, which makes them an appropriate experimental material. They were easily divided using a set of sieves and the sieve shaker "Retsch AS 200". Performed sieve analysis brought fractions of solid particles with average diameters: 0.125, 0.175, 0.25 mm and those above were considered as a waste.

The construction of settling tank had similar features like diameter of tank and diameters of ports, as previous designs characterized in earlier papers (Ochowiak et al. 2017, Ochowiak et al. 2017, Ochowiak et al. 2018). Settling tank analyzed in this paper outstood with installed longitudinal baffle hung on variable height and location in regard to tank's axle. Basically, inside diameter of the device was 0.19 m (D), its height – 0.69 m (H), location of inlet and outlet ports in cross point with tank wall were constant and had a value of 0.415 m (h_w), distance from symmetry of tank to the baffle was 0 or 0.055 m (l_b), inner diameter of inlet and outlet ports were even and they equaled 0.03 m (d), the inlet port submersion levels (h_p) were 0.2 and 0.3 m. Baffle location height (h_b) values were: 0.34, 0.30 and 0.26 m. Only one constructional variation is characterized by baffle location at 0.18 m height, and it is caused by previous research to show correctness of decision about determined baffle placement.

In order to gain clarity of obtained results the constructions were numbered. The analysis was performed on twelve

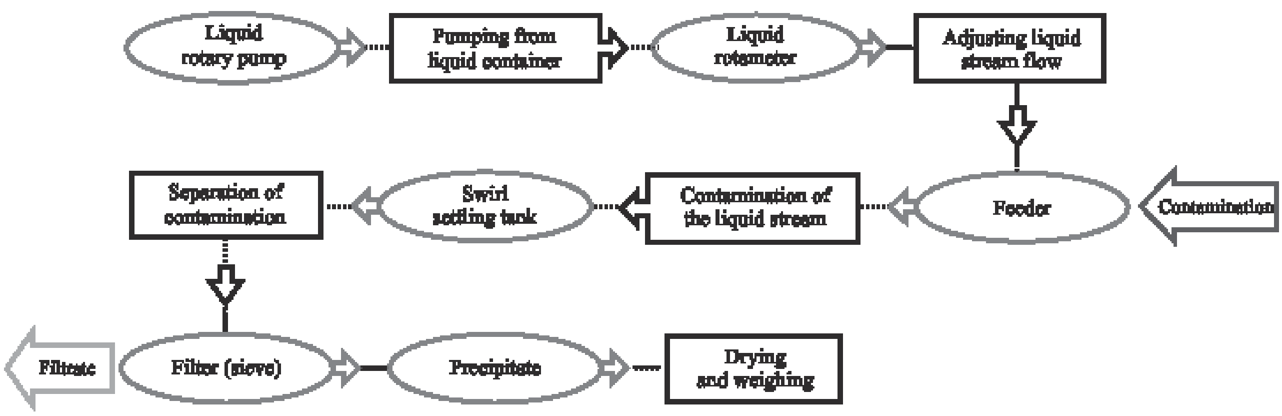

Fig. 1. Block scheme of solid particles separation system used in the analysis

modified swirl settling tanks. Table 1. presents studied apparatus with its constructional specifications. Constructions no. I–III and VII–IX characterized with amount 0.2 m of inlet port submersion level, those from no. IV to VI and no. X to XII had inlet port submerged on 0.3 m depth. All of I to VI had baffle moved 0.055 m relative to tank's axle towards outlet port, and in constructions from VII to XII baffle was located exactly in the middle of the separator. All constructed modified swirl settling tanks were described by the same amount of gross covered area arrangement, which was calculated from the formula for the area of the circle.

Settling tank inlet pipe was directed vertically download and was ended with the above-mentioned elbow bent at the horizontal angle of 45° and directed straight on tank's wall. Thickness of tank wall and baffle were equal 0.005 m. There was also characterized the gross covered area arrangement (*A*p). Fig. 2 presents sedimentation tank scheme. Pipeline at the escape of the tank led to simple sieve filter where heavy fraction that was not collected inside the separator was caught and weighed afterwards. This solution allowed to calculate the efficiency of separator according to standard percentage dependency of the contamination mass added to liquid stream (input) and the mass of contamination caught on the filter (outlet) (Green and Perry 2008, Królikowska 2011). A novelty about the analyzed settling tank is flat bottom of the tank in conjunction with baffle located vertically and in the upper part of the tank. Literature overview shows that each of mentioned elements was already used but not in one combination. For example, Shah and coworkers (2019) analyzed settling tank that had conical bottom head and central hatch pipe without baffle. In earlier papers attentiveness mostly was focused on horizontal long sand traps or cone-shaped sedimentation tanks (Lekang et al. 2001, Azzopardi and Sanaullah 2002, Królikowsk 2011, Ramin et al. 2014). Separation process conditions were determined. Water temperature was 20°C and its volumetric flow rate amounted from 0.6 to 1.8 m^3/h and was adjustable by valve. Water viscosity value reached 1 mPa·s and its density was 998 kg/m^3. Heavy fraction (HF) density equaled 2800 kg/m^3. Aqueous solution of glycerol was used with different concentrations of glycerol – 24, 41, 50, 55 and 59% w., therefore the solution's viscosity was in sequence: 2, 4, 6, 8 and 10 mPa·s. Its density value was contained in the range from 1051 to 1152 kg/m^3.

Experimental results and discussion.

Liquid damming analysis.

Almost every liquid depurative separator has to manage the pressure and hydraulic load caused by liquid stream. Both are depended on tank's construction type. Performed studies included measurement of height of water over outlet level that raised with flow rate escalating which for this analysis was included in from 0 to 1.8 m/s. Some of studied sedimentation tanks outstood with extreme values of liquid height level that depended on flow rate set up at the inlet to the tank. It is observed that the construction with topmost inlet port submersion level equaled 0.2 m and with the upmost location of baffle that is also relocated towards the inlet (construction no. III) has the lowest results in comparison to others swirl settling tanks for the highest flow rate values. Every construction shows significant increase of liquid level from the point where flow rate overruns 1 m/s.

Below that value damming level remains low and sustainable. Basically, relation between the inlet and the baffle construction and location is crucial. The obtained results allow for the calculation of local resistance coefficient by dependency (Green and Perry 2008, Błażejewski 2015):

$$\xi = \frac{2 \cdot g \cdot \Delta h}{u^2} \qquad (1)$$

where: Δh is liquid damming [m], u – liquid flow rate [m/s] and g – gravitation constant [m/s^2]. Average values of local resistance coefficient of the chosen constructions are presented in Table 2.

In every settling tanks group it is observed that the highest resistance is made for the baffle located at 0.3 m height, which is the middle between the inlet and the outlet of the separator. The construction with the highest baffle position inside the tank characterized by the lowest values of local resistance coefficient.

Table 1. List of studied vortex separators constructional specifications

Settling tank's number	h_p [m]	h_b [m]	l_b [m]	Ap [m^2]
I	0.2	0.26	0.055	0.028
II		0.30		
III		0.34		
IV	0.3	0.26	0.055	
V		0.30		
VI		0.34		
VII	0.2	0.26	0	
VIII		0.30		
IX		0.34		
X	0.3	0.18	0	
XI		0.26		
XII		0.34		

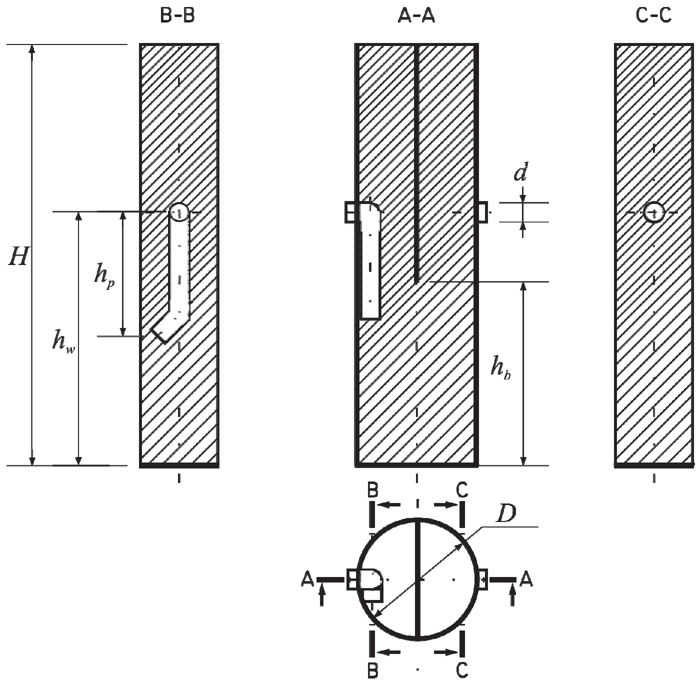

Fig. 2. Scheme of swirl separator in thirst-angle projection with cross-section view

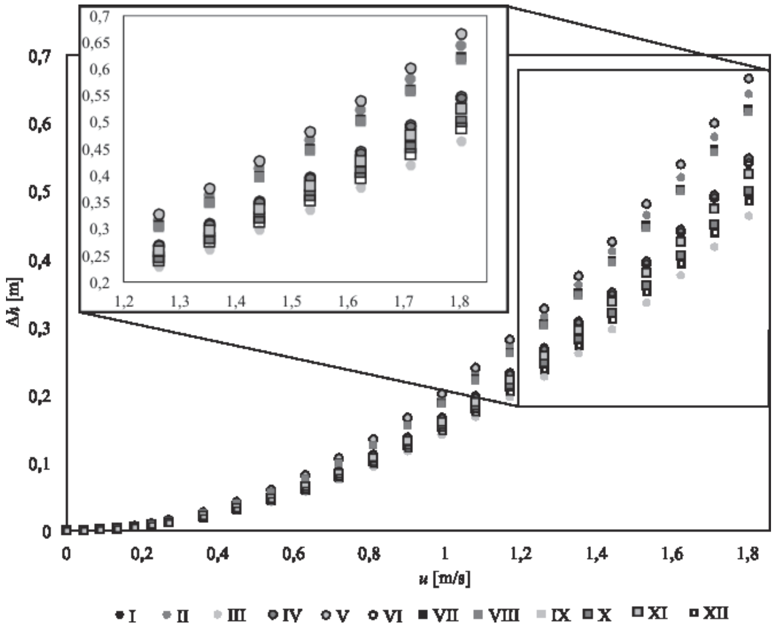

Fig. 3. Dependency of water damming height and inlet flow rate for analyzed swirl settling tanks

Table 2. Local resistance coefficient average values for analyzed swirl settling tanks

Settling tank's number	Local resistance coefficient ξ	Settling tank's number	Local resistance coefficient ξ
I	3.19	VII	3.72
II	3.87	VIII	3.74
III	2.79	IX	3.01
IV	3.30	X	3.02
V	4.01	XI	3.17
VI	3.27	XII	2.93

Possibly, the cause is relation between lower settling zone in separator where the liquid creates specific vortex currents and breaching them constructional type of baffle. Although, it is still unknown how that dependency can be measured.

Next parameter that characterizes constructed settling tanks is hydraulic load. It depends on intensity of inlet stream of liquid and structural type of separator. More specific, it is the gross covered area arrangement, which is tank's cross-section area. Equation 2 describes the form of hydraulic load:

$$Q_h = \frac{Q}{A_p} \quad (2)$$

where: Q_h is hydraulic load [m^3/(m^2·h)], Q – volumetric flow rate at the inlet of settling tank [m^3/h] and – tank's cross-section area [m^2]. It is accepted that hydraulic load for all constructions is in the range from 21.17 to 63.52 [m^3/(m^2·h)].

The importance of this parameter is connected to increasing water consumption and the amount of discharged sewage inflowing into a wastewater treatment plant. The consequence might be a hydraulic overload, which affects the efficiency of purifying devices by leaching the sludge and contamination out of purification system (Młyński et al. 2016).

Separating efficiency analysis

Replacing rectilinear motion in conventional storm overflows with rotational (swirl) movement combines the function of a flow rate regulator with the function of rainwater pre--treatment (i.e. removing suspended solids from rainwater, mainly mineral). The existence of vortex flow conditions results in the separation effect of solids, where settled particles are captured by the secondary liquid flow of lower currents and centrifugal force moves suspended solid to the boundary layer. The sedimentation and flotation processes take place in this zone. As a result of phase separation two streams are created: one with a lower solid phase concentration, discharged to the receiver and the other one directed to the following drain or to a sewage treatment plant (Królikowska 2011).

The analyzed construction whole exhibits high enough efficiency of heavy fraction separation from liquid compared to commercial solutions. However, there are significant differences between modified constructions caused by the choice of applying the baffle inside the tank.

The first step of efficiency analysis was focused on the distinction of these constructions of swirl settling tanks which characterized by the highest results of heavy fraction separation process in water stream (Fig. 4). Research brought out four constructions that reached over 70% separation efficiency for contamination with average diameter 0.125 mm and over 80% for 0.175 mm particles at the top value of hydraulic load that is 63.52 [m^3/(m^2·h)] – no. VII, VIII, IX and XI. Each one was equipped with baffle located in tank's axle. The most effective construction turned out to be no. VIII, where baffle's height position inside the tank was in the middle between separator's inlet and outlet.

Next point of research was to perform efficiency analysis of solid particles in a liquid with changing viscosity on a chosen settling tank no. VIII. The results are presented by the relation in Figure 5. The graph shows that when liquid's viscosity and hydraulic load value were rising the efficiency of separation was dropping. Still chosen separator construction maintained a separation efficiency values over 55%.

Through standard mathematical descriptions (Bandrowski et al. 2001, Błażejewski 2015) concerning solid particle falling phenomenon, the attempt to determine the connection between separation efficiency and Reynold's Number was made. The dependency was determined with settling velocity for solid particle u_s (eq. 3) and Reynold's Number (eq. 4) which included mentioned velocity, particle diameter d_s, liquid's density ρ_l and viscosity μ_l.

$$u_s = \frac{d_s^2 \cdot (\rho_s - \rho_l) \cdot g}{18 \cdot \mu_l} \quad (3)$$

$$\mathrm{Re}_s = \frac{u_s \cdot d_s \cdot \rho_l}{\mu_l} \quad (4)$$

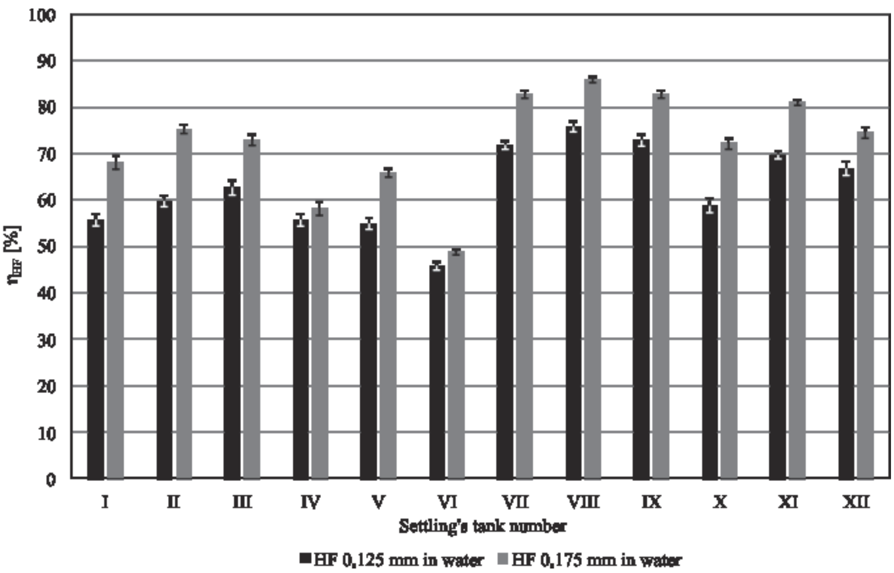

Fig. 4. Heavy fraction contamination separation efficiency in water for analyzed swirl settling tanks at hydraulic load Q_h = 63.52 [m^3/(m^2·h)]

The graph in Figure 6 presents dependence as power function of separation efficiency and Reynold's Number for falling solid particle for different hydraulic loads in the separator. Because of changing power index in equation it is difficult to unequivocally delineate correlation coefficient that would allow easily for commutation separation efficiency in dependence on hydraulic load in separator. Also the slope is not rising linearly. Generally, the performed analysis shows that the efficiency can be described as a following function:

$$\eta_{HF} = f\left(\rho_l, \rho_s, u_s, \mu_l, d_s, Q\right) \quad (5)$$

Research and theoretical consideration performed by Królikowska (2011) present separation efficiency as dependency of settling velocity of solid particle u_s, rainwater flow velocity u_i, overflow chamber height h, swirl chamber diameter D, inlet pipe diameter d, intensity of continuous load q, and inlet flow to the separator Q (eq. 2):

$$\eta_{HF} = f\left(\frac{u_s}{u_i}, \frac{h}{D}, \frac{D}{d}, \frac{q}{Q}\right) \quad (6)$$

The mentioned relation includes separator's profile, but does not contain liquid's viscosity influence. Another difference is application of overflow chamber, which is not a part of the analyzed modified swirl settling tanks in this paper.

Description of dependency of settling tank efficiency and liquid's viscosity or settling velocity (Reynolds number) according to construction solution is a rarity. Many papers correlate settling tank's level of separation to time or concentration (Bürger et al. 2013, Ramin et al. 2014). Because of great diverseness in settling tank's construction there is still no one all-purpose design model, so that leads to experimental research of every type of sedimentation separator based on sedimentation theoretical fundamentals (Błażejewski 2015).

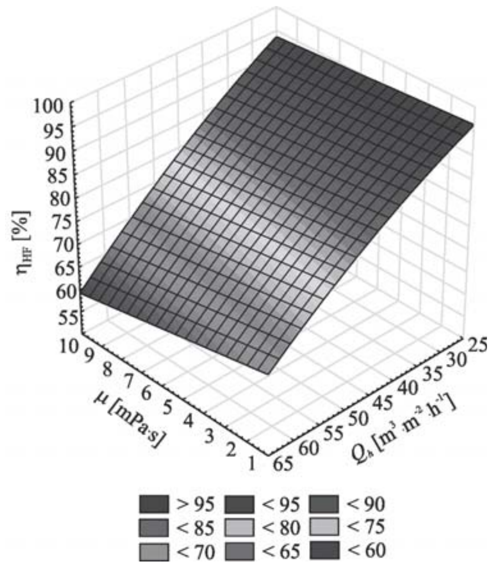

Fig. 5. Heavy fraction contamination separation efficiency dependent on hydraulic load and liquid's viscosity for settling tank no. VIII (h_p = 0.2 m, h_b = 0.3 m, l_b = 0)

Conclusions

The paper presented twelve constructions of swirl settling tanks with novelty constructional concepts, experimental tests of liquid damming and purification efficiency of solid pollutant in liquid stream. One construction (no. VIII) was chosen for the analysis of purification liquid stream with different viscosity. Modification concept was to obtain increasing efficiency of the devices, referring standard swirl sedimentation tanks. Research results allowed to formulate the following conclusions:

- damming of the liquid in swirl separator increases alongside hydraulic load and depends on the tank's construction and location of baffle;
- purification efficiency increases alongside the diameters of solid particles with density greater than liquid's density;
- chosen constructed swirl tanks (VII – IX) achieved high efficiency results that led to the next part of analysis with dependency of liquid's viscosity;

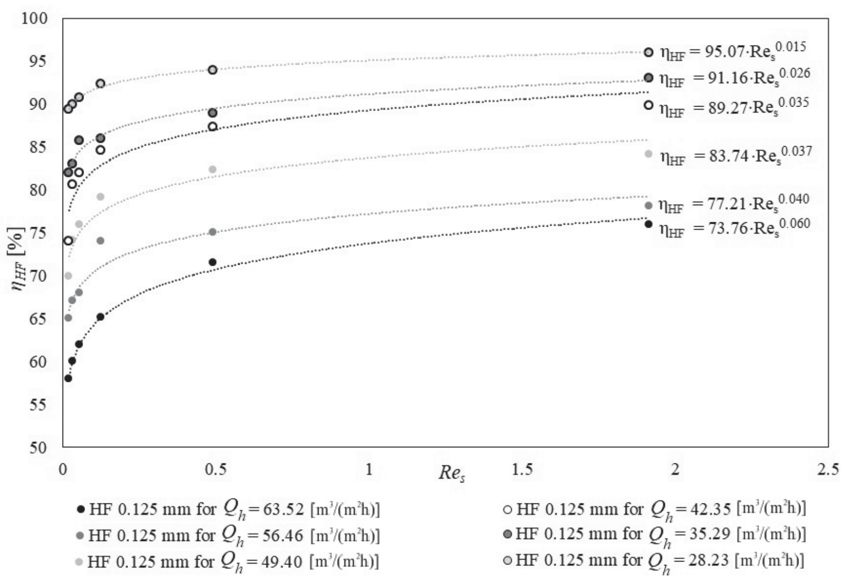

Fig. 6. Dependency of heavy fraction separation efficiency on Reynold's Number for solid particle falling and hydraulic load for settling tank no. VIII

- purification efficiency in separator no. VIII was dropping with increasing hydraulic load and rising viscosity of the liquid;
- the attempt of purification efficiency and research characteristic variables correlation was made, where standard relations of settling solid particle was cited.

The design, construction and experimental research of swirl settling separators may lead to improvement of efficiency of the removal of solid pollutants from rainwater stream and possibly to the reduction of the size of separators. The showed dependency of liquid stream viscosity and purification efficiency may be important in designing future separation devices, because of potential leak of substances used in cosmetics or pharmaceutical industry to the rainwater stream. Therefore, further studies of chosen constructions of swirl settling separator and liquids with different physical and chemical properties seem to be justified, especially from a perspective of rainwater treatment and environmental protection.

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