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STUDY THE EFFECT OF TEMPERATURE ON RECTANGULAR SEDIMENTATION TANKS PERFORMANCE

BADANIE WPŁYWU TEMPERATURY NA FUNKCJONOWANIE PROSTOKĄTNYCH ZBIORNIKÓW SEDYMENTACYJNYCH

Sedimentation is the process of separating solids from the liquid stream. In the present case, FLUENT Computational fluid dynamics (CFD) software was used to form an understanding of a periodic dysfunction at a drinking water production plants at a site in Hrinova in Slovakia. The structure involved is a horizontal sedimentation tanks, supplied with surface water taken from the nearby reservoir. Numerical simulations, together with experimental measurements, have been performed on laboratory and full-scale plants in order to gain a better understanding of the physical phenomena (temperature effects on settling velocity) occurring in settling tanks. The following dysfunction was observed on the structure in question. In summer, during the hottest time of the day, a cloud of flocs would sometimes rise to the surface, appearing in the surface of the settling tank. The cloud then progressed slowly to the outer zone of the tank, where a proportion of the total suspended solids would overflow, impairing the quality of the treated water. The phenomenon was easily linked to large-scale external temperature swings, sometimes rising as high as 27°C in the shade during the daytime. In this study we find that the changes in temperature on settling tanks play an important role on the performance of settling tanks. The paper shows how CFD can be helpful in order to improve the design of existing water treatment plants and the process efficiency.

Sedymentacja to proces rozdzielania ciała stałego od strumienia cieczy. W rozpatrywanym przypadku zastosowano oprogramowanie Komputerowej mechaniki płynów FLUENT (ang. Computational fluid dynamics, CFD) w celu zrozumienia okresowych zaburzeń pracy stacji uzdatniania wody w miejscowości Hrinova, Słowacja. Omawiana struktura to poziome zbiorniki sedymentacyjne zasilane wodami powierzchniowymi z pobliskiego zbiornika. Przeprowadzono symulacje numeryczne wraz z pomiarami eksperymentalnymi w warunkach laboratoryjnych w ramach całego zakładu w celu lepszego zrozumienia zjawisk fizycznych (wpływu temperatury na prędkość osiadania) zachodzących w zbiornikach sedymentacyjnych. W omawianych procesach zaobserwowano następujące zaburzenia. Latem, w najgorętszej porze dnia kłaczki zawiesin niekiedy pojawiały się na powierzchni zbiornika sedymentacyjnego. Następnie zawiesina powoli przemieszczała się *do zewnętrznej strefy zbiornika, gdzie następowało przepełnienie zawiesin, powodujące pogorszenie jakości uzdatnianej wody. Zjawisko zostało szybko połączone z występującymi dużymi wahaniami temperatury zewnętrznej, wzrastającej niekiedy nawet do 27°C w cieniu w ciągu dnia. W niniejszym badaniu wykazano, że zmiany temperatury w zbiornikach sedymentacyjnych są ważnym czynnikiem mającym wpływ na ich funkcjonowanie. Niniejsza praca wykazuje ponadto, jak pomocne może być oprogramowanie CFD w konstrukcji stacji uzdatniania wody oraz jak może wpłynąć na wydajność procesu.*

1. Introduction

Design of sedimentation tanks for water treatment processes are often based on the surface overflow rate (Q/A, where Q is the flow rate and A is the clarifier surface area) of the tank. This design variable is predicated on the assumption of uniform unidirectional flow through the tank**. Dick (1982), Ghawi and Kris (2007 A), and Ghawi and Kris (2007 B)** though, showed that many full-scale sedimentation tanks do not follow ideal flow behavior because suspended solids removal in a sedimentation tank was often not a function of the overflow rate. Because of uncertainties in the hydrodynamics of sedimentation tanks, designers typically use safety factors to account for this nonideal flow behavior (**Abdel-Gawad and McCorquodale, 1984).**

Non-ideal flow behavior can be the result of the following **(DeVantier and Larock, 1987; Wells and LaLiberte ,1998):** 1. Inlet and outlet geometry, 2. Inflow jet turbulence, 3. Dead zones in the tank, 4. Resuspension of settled solids, and 5. Density currents caused by suspended solids and temperature differentials within the tank.

Recently, Computational fluid dynamics (CFD) software has become easy to use, fast and user-friendly. This new generation software offers an inexpensive means of testing and optimizing hydraulic operation of both existing constructions and those under design.

The effects of temperature on settling velocities and sedimentation in general have been largely recognized and debated. **Hazen (1904)** suggested that particles settle faster as the water becomes warmer. He stated that "a given sedimentation basin will do twice as much work in summer as in winter." This is maybe a bold statement, but the influence of temperature differentials in the settling tank performance have been demonstrated by several researches. In this respect, **Wells and LaLiberte (1998)** suggested that in the presence of temperature gradients in the settling tanks, such as during periods of winter cooling, the temperature effects are important and should be included in the modeling of the settling tank. The atmospheric cooling process was earlier studied by **Larsen (1977)**; he suggested that the cooled-denser water sinks and is replaced by rising warmer water. He also suggested the removal efficiency of a tank may vary over the year with a minimum during the winter season when cooling rates are at a maximum. Similar effects were observed by **Kinnear (2004). Kinnear (2004)** found that the excess effluent suspended solids increases as the air temperature decreases.

McCorquodale (1977) showed that a diurnal variation in the influent of the order of ± 0.2°C may produce short circuiting in sedimentation tanks. **Larsen (1977)** showed that the direction of the density current in settling tank may be defined by the difference between the inflow and ambient fluid temperature. A cooler influent produces a bottom density current, while in the cases of a warmer influent the density current is along the surface. Studies done by **Zhou et al. (1994), and Wells and LaLiberte (1998)** support these findings. **Wells and LaLiberte (1998)** found that temperature differences affect the hydrodynamic of settling tank.

Another temperature-effect to take into consideration is probably the direct effect on the settling properties of the sludge. **Surucu and Cetin (1990)** suggested that the zone settling velocity decreases as the temperature of the tank increases.

Generally, many researchers have used CFD simulations to describe water temperatures variance in settling tanks for sewage water treatment. However, works in CFD modelling of sedimentation tanks for potable water treatment, rectangular sedimentation tanks, and have not been found in the literature. The following dysfunction was observed on the structure in question. In summer, during the hottest time of the day, a cloud of flocs would sometimes rise to the surface, appearing in the surface of the settling tank. The cloud then progressed slowly to the outer zone of the tank, where a proportion of the total suspended solids would overflow, impairing the quality of the treated water.

Non-ideal flow behavior as a result of temperature and suspended solids differentials in uncovered, rectangular sedimentation tank was studied in Hrinova Water Treatment plant in Slovakia.

The aim of this study was originally stated as to improve the operation and performance of Hrinova sedimentation tanks in Slovakia used in water treatment plants which have been identified as operating poorly, to be achieved by predicting the existing flow distribution settling velocity of the sedimentation tanks by means of Computational Fluid Dynamics (CFD) techniques. A CFD model has been developed to include the following factors: hydrodynamics, five types of settling, turbulence, and temperature changes with the atmosphere. CFD was used to investigate the temperature effects on settling velocity profiles at current and projected loadings for the settling tanks.

2. Experimental Methods

Experiments were conducted in Slovakia during the summer and winter at water treatment plants in Hrinova in Slovakia. In order to examine the effects of surface heating, study periods were chosen coinciding with summer weather conditions when surface heat losses would be significant. These conditions were most significant during the day (afternoon) hours when plant flow rates were high and summer heating was greatest.

All the tanks had an inlet perforated baffle and an effluent v-notch weir. Table 1 shows the settling tanks data. Table 2 shows the physical and hydraulic data during study periods.

In order to measure the temperature distributions in these tanks, thermistors at varying depths were attached to each tank. Each thermistor was attached to a computer data logger that recorded temperature continuously during the study periods. The study period for the sedimentation tanks was between 3 and 4 days in winter and summer in 2006 and 2007.

The data presented in this section was collected at the Hrinova WTP in winter and summer. This data shows the results of the procedure aimed to determining a correction factor for the zone settling velocities based on temperature difference.

Table 3 summarizes the different temperatures (T_s (summer temperature) and T_w (winter temperature) measured at Hrinova WTP.

Tab. 1. Settling tanks data.

Tab. 1. Dane dotyczące zbiorników sedymentacyjnych

Tank parameter	Value
Tank length (m)	30 m
Depth inlet baffle (m)	1.9 m
Tank depth (m)	3.9 m
Tank width (m)	4.5 m
No. of tanks	4

Tab. 2. Physical and hydraulic data during study periods.

Tab. 2. Dane fizyczne i hydrauliczne podczas okresów badawczych

Tank parameter	Value
Average flow rate	60 l/s
Sludge pumping rate	5 l/s
Average Inflow temperature	4°C in winter and 25°C in summer
Inflow suspended solids	25-50 mg/l
Detention time	3.6 hr
C_{min}	0.17 mg/l
M	0.002 N.s/m^2

Tab. 3. Measured temperature in winter (average) and summer (average) at Hrinova WTP

Tab. 3. Temperatura mierzona zimą (średnia) i latem (średnia) — Hrinova WTP

Sample at Summer Temperature (T_s)		Sample at Winter Temperature (T_w)	
Inlet temperature ^{0}C	**Outlet temperature ^{0}C**	**Inlet temperature^{0}C**	**Outlet temperature ^{0}C**
27.5	27.6	6.0	6.0
27.5	27.8	4.6	4.8
26.0	26.2	5.8	6.8
25.3	25.3	4.0	5.9
23.7	23.9	3.8	5.0
23.7	24.0	6.2	6.4
21.4	22.0	6.0	6.8
21.4	21.9	5.4	6.6

3. Computational Fluid Dynamics (CFD) Modelling

Several computer software programs have been developed for CFD modelling. In this study Fluent and the 2D k-ε turbulence model in the Environmental Engineering Module was used. During this study hydraulic CFD modelling began with the definition of tank geometry. Secondly fluid characteristics and boundary conditions were defined. The momentum balance including the turbulence model and continuity equations were then solved numerically for the tank using the finite volume method. Finally, the obtained solution was post-processed to be properly visualized.

3.1. Continuity and Momentum Equations

The two-dimensional (2D), axisymmetric flow of an incompressible fluid is governed by the continuity and the Navier- Stokes equations. Employing the Reynolds-averaging procedure, the turbulent stresses appearing in the transport equations are made proportional to the mean velocity gradients according to the Boussinesq eddy-viscosity hypothesis. The continuity, and momentum equations expressed in the coordinate system read**,** respectively

$$\frac{\partial}{\partial X}(U)+\frac{\partial}{\partial Y}(V)=0 \tag{1}$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{1}{\rho}\frac{\partial P}{\partial X}+\frac{\partial}{\partial X}\left(\mu_{eff}\frac{\partial U}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\mu_{eff}(\frac{\partial U}{\partial Y}\right) \tag{2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{1}{\rho}\frac{\partial P}{\partial Y}+\frac{\partial}{\partial X}\left(\mu_{eff}\frac{\partial V}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\mu_{eff}(\frac{\partial V}{\partial Y}\right)+g\frac{\rho_p-\rho_w}{\rho_w} \tag{3}$$

where U and V denote the time-averaged velocities in the X and Y direction, respectively; P = static pressure; ρ_w = density of clear water that serves as reference density; μ_{eff} = effective viscosity; and ρ_p = density of the particle.

3.2. *k-ε* Turbulence Model

The k-ε eddy-viscosity model **[see, e.g., Rodi (1993)]** determines the isotropic eddy viscosity μ_t as a function of the turbulent kinetic energy k and its dissipation rate ε by

$$\mu_{eff}=\mu+\mu_t$$

$$\mu_t=C_\mu\frac{k^2}{\varepsilon} \tag{4}$$

The distributions of k and ε are determined from the following model transport equations:

$$\frac{\partial k}{\partial t}+U\frac{\partial k}{\partial X}+V\frac{\partial k}{\partial Y}=\frac{\partial}{\partial X}\left(\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial Y}\right)+P_k+p_b-\varepsilon) \tag{5}$$

$$\frac{\partial \varepsilon}{\partial t}+U\frac{\partial \varepsilon}{\partial X}+V\frac{\partial \varepsilon}{\partial Y}=\frac{\partial}{\partial X}\left(\frac{\mu_{eff}}{\sigma_{\varepsilon}}\frac{\partial \varepsilon}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\frac{\mu_{eff}}{\sigma_{\varepsilon}}\frac{\partial \varepsilon}{\partial Y}\right)+C_1\frac{\varepsilon}{k}P_k-C_2\frac{\varepsilon^2}{k} \quad (6)$$

Where P_k represents the rate of production of turbulent kinetic energy resulting from the interaction of the turbulent stresses and velocity gradients, and

$$P_b=\frac{g}{\rho_w}\frac{\mu_{eff}}{\sigma_c}\frac{\partial(\rho_p-\rho_w)}{\partial Y}$$

represents the rate of production due to buoyancy effects. The empirical constants are given the standard values suggested by Rodi (1993); $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$. The value of the empirical constant σ_c associated with the buoyancy source term was found to depend on the flow situation considered. Test calculations have shown that the value of σ_c depends on whether P_b is a source term (i.e., in unstably stratified flows) or a sink term (i.e., in stably stratified flows). **Rodi (1993)** suggested that σ_c is in the range of 48-52 for stable stratification that prevails in ST and tends toward zero for unstable stratification.

3.3. Settling velocity

The settling process is modeled using the Karman-Kozeny equation (7)

$$V_s=\frac{(\rho_l-\rho_f)gE^3}{5S_0^2(1-E)\mu} \quad \text{for } \Phi<\Phi_g$$

$$V_s=\frac{\left[(1-E)(\rho_l-\rho_f)g+\left[\frac{(1-E)}{(1-E_g)}\right]^m\frac{\partial E}{\partial z}\right]E^3}{5S_0^2(1-E)\mu} \quad \text{for } \Phi\geq\Phi_g \quad (7)$$

where ρ_l and ρ_f are the liquid and floc densities, E is the porosity, $S_o = 6/dp$ is the specific surface area, dp is the particle diameter, μ is the fluid dynamic viscosity, Po is an empirical coefficient, and Φ and Φ_g are the solids and gel solid fraction respectively. **Kinnear (2002)** defined the gel concentration as the solids fraction at which flocs at a lower elevation provide mechanical support to flocs at a higher elevation.

3.4. Energy Equation

The following energy equation can be used to model the temperature field **(Zhou et al., 1994; Ekama et al., 1997):**

$$\rho\left(\frac{\partial T}{\partial t}+u_j\frac{\partial T}{\partial x_j}\right)=\frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i}-\rho\overline{u_iT'}\right) \quad (8)$$

where T and T' are respectively the mean and fluctuating component of the temperature, λ is molecular diffusivity.

The temperature effects are commonly included in the reference density and kinetic viscosity of the water by means of equations of state. The following expressions represent examples of such equations:

$$\rho_{ref} = [999.8396 + 18.224944*T - 0.00792221*T^2 - 55.4486*10^{-6} * T^3 + 14.97562*10^{-8} * T^4 - 39.32952*10^{-11} * T^5 + (0.802 - 0.002*T)*TDS]/[1 + 0.018159725*T] \quad (9)$$

$$\mu_{ref} = (2.414*10^{-5})*10^{\left[\frac{247.8}{T+133.15}\right]} \quad (10)$$

In Equations 9 and 10 T is the water temperature in °C, ρ_{ref} is the water reference density in g/L, TDS is the Total Dissolved Solids in g/L, and μ_{ref} is the water dynamic viscosity in Kg /m.s.

The opposite effect is presented in Equation 7 and Stokes' law. Stokes' law shows that the settling velocity of discrete particles is affected by the viscosity of the water, which depend on temperature. Equation 7 (**Kinnear, 2002**) shows a similar effect for the hindered and compression settling regimes

3.5. Boundary Conditions

The capacity of the settling tank was stated as 0.04 cm/s up-flow rate. The volumetric flow rate (60 l/s) was specified as a withdrawal at the outlet weir location. The inlet pipe opening was specified as fixed pressure region, where the flow rate was allowed to satisfy the material balance.

All the boundaries corresponding to concrete surfaces were modelled using the wall functions provided by Fluent, with a surface roughness parameter set to 0.5 mm. The free surface was simply modelled as a rigid frictionless surface. Thermal effects were included in the model. There are six parts to the boundary: the inflow, effluent outlet, outlet for the thickened sludge, the water surface, the bottom of the tank, and the rigid walls (Figure 1).

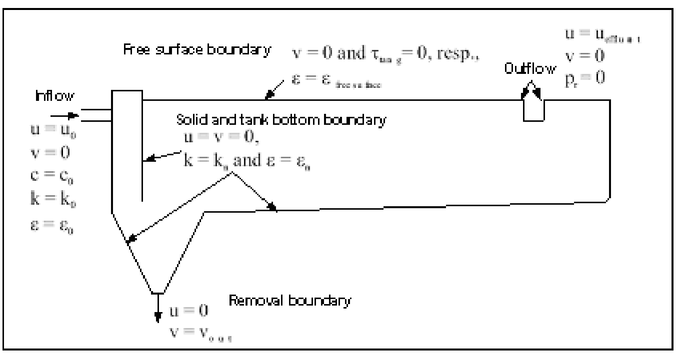

Fig. 1. Tank boundaries with specification of boundary conditions.

Rys. 1. Brzegi zbiornika z parametrami warunków dot. brzegów

4. Result and Dissection

4.1. Settling Velocity Correction Factor and CFD Model Predicted

The traditional discrete settling model proposed by the Stoke's law suggests that the settling velocity of discrete particles depends indirectly on the temperature of the fluid since the settling velocity is inversely proportional to the kinematic viscosity of the liquid. A similar relationship is presented in the compression rate model proposed by **Kinnear (2002)** in which the settling velocity is inversely proportion to the dynamic viscosity of the fluid. The model proposed by Stoke's law and **Kinnear (2002)** indicate that the settling velocity of discrete particles and the compression rate of the sludge are influenced by the temperature of the mixture.

In order to define a correction factor for the settling velocities based on temperature difference, the temperature effect on the zone settling velocity has to be determined.

Table 4 presents the settling velocities calculated by CFD at two different conditions: (a) zone settling velocity calculated at summer (field conditions) temperature, and (b) zone settling velocity calculated at a cooled temperature. This table also shows the temperature of the sample at the beginning and at the end of the calculation, suspended solids concentration, and the respective dynamic viscosity of the mixture calculated using CFD model.

Assuming the viscosity as the only variable in the models proposed by Stoke's law and **Kinnear (2002),** the settling velocity of discrete part and the compression rate of activated sludges can be expresses as:

$$V_S = \frac{K}{\mu} \tag{11}$$

where K is a constant independent of temperature but dependent on all other parameters affecting settling.

For a fixed value of K in Equation 11, and two different temperatures T_1 and T_2, Equation 11 can be rearranged as:

$$V_{ST_1}\mu_{T_1} = V_{ST_2}\mu_{T_2} = K \tag{12}$$

where Vs_{T1} and Vs_{T2} are the settling velocities at temperatures T_1 and T_2 respectively, and μ_{T1} and μ_{T2} are the dynamic viscosities of the mixtures at temperatures T_1 and T_2 respectively. Figure 2 displays graphically the value of the relationship Vs_{T2} / Vs_{T1} and μ_{T2} / μ_{T1} for the data presented in Table 4 at temperatures T_s (summer temperature) and T_w (winter temperature).

Tab. 4 Settling velocity and dynamic viscosities for summer and winter temperature.

Tab. 4. Prędkość osiadania oraz lepkość dynamiczna dla temperatur letnich i zimowych

CFD Calculated at summer temperature				
SS mg/l	**Settling velocity m/h**	**Inlet temperature °C**	**Outlet temperature °C**	**Dynamic viscosity kg/m.s**
60	1.50	27.5	27.5	8.5e-04
50	1.70	27.5	27.5	8.6e-04
25	1.83	26.0	26.0	8.7e-04
15	2.52	25.4	25.4	8.8e-04
CFD Calculated at cooled temperature				
60	0.95	8	9.2	1.3e-03
50	1.05	6.6	6.8	1.35e-03
25	1.90	7.8	8.8	1.29e-03
15	2.70	7.0	8.9	1.30e-03

From Figure 2 can be observed that the numerical values of the ratios Vs_{T2} / Vs_{T1} and μ_{T2} / μ_{T1} are very close, suggesting that an easy correction in the zone settling velocity for different temperatures can be made with a correction factor based on the dynamic viscosity of the water at the two temperatures. Figure 3 shows an extended data set indicating the relationships between the ratios Vs_{T2} / Vs_{T1} and μ_{T2} / μ_{T1}.

Fitting a straight line to the data point presented in Figure 3 and using Equation 10 can find a correction factor for the settling velocities based on temperature

$$V_{ST_2} = V_{ST_1}\left(\frac{10^{\left[\frac{247.8}{T1+133.15}\right]}}{10^{\left[\frac{247.8}{T2+133.15}\right]}}\right) \tag{13}$$

Equation 13 can be applied to correct the settling velocities for difference in temperatures in whichever of the four types of sedimentation, i.e., unflocculated discrete settling, flocculated discrete settling, hindered (zone) settling and compression. Even though equation 13 can be used for a sensitivity analysis on the performance of the model for different seasons, e.g. summer and winter, there is no evidence that the settling properties can be accurately extrapolated from one season to another.

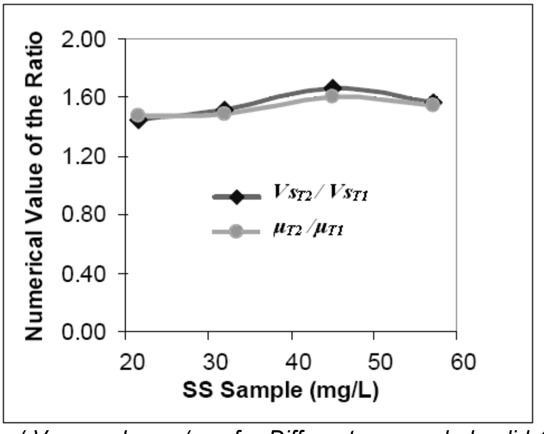

Fig. 2. *Ratios of Vs_{T2} / Vs_{T1} and μ_{T2} / μ_{T1} for Different suspended solid (SS) concentrations.*

Rys. 2. *Współczynniki Vs_{T2} / Vs_{T1} oraz μ_{T2} / μ_{T1} dla zawiesin (ang. suspended solid, SS) o różnym zagęszczeniu*

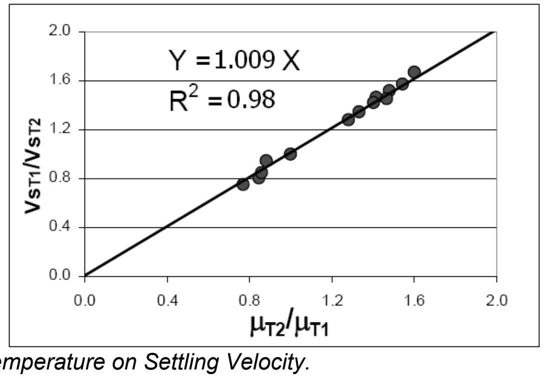

Fig. 3. *Effect of Temperature on Settling Velocity.*

Rys. 3. *Wpływ temperatury na prędkość osiadania*

Tab. 5. *Predicted ESS values for Different Temperature Variations*

Tab. 5. *Przewidywane wartości ESS dla różnych temperatur*

Influent temperature variation	**Heat exchange**	**Peak ESS (mg/l)**
+1 ^{O}C	Summer	36.24
-1 ^{O}C	Summer	16.25
0 ^{O}C	Summer	16.05
0 ^{O}C	Winter	33.65
+1 ^{O}C	Summer	23.90
-1 ^{O}C	Summer	41.19
0 ^{O}C	Summer	41.00
0 ^{O}C	Winter	21.19

The effects of the influent temperature variations on the hydrodynamics and the performance of the settling tank were evaluated by simulating the Hrinova ST with an influent temperature difference of ± 1ºC, and two different inlet concentrations, i.e. 30 and 75 mg/L. The low ion was selected in order to simulate loading conditions similar to those found in Hrinova WTP. The simulations were set up for summer and winter conditions. Table 5 shows the general data used in the simulations. Table 5 also shows the peak ESS found during the simulations. The values presented in Table 5 represent two specific sets of data for the City Hrinova. These values were obtained from the WTP laboratories, the winter data corresponds to Winter/2006 and 2007, and the summer data corresponds to Summer/2006 and 2007.

The values of the peak ESS presented in Table 5 indicate that the influent temperature variations have an important effect on the performance of the SST.

Figure 4 shows the temperature changes in the ST with the warmer influent for the summer conditions. This figure shows that the surface heat exchange warms up the surface water. Since this is a stable stratification gradient there is little mixing between the surface and the inner layers. This figure also shows the incoming water plume traveling near the bottom until it rises close to the end wall. A study presented by **Wells and LaLiberte (1998)** showed similar results to those presented herein.

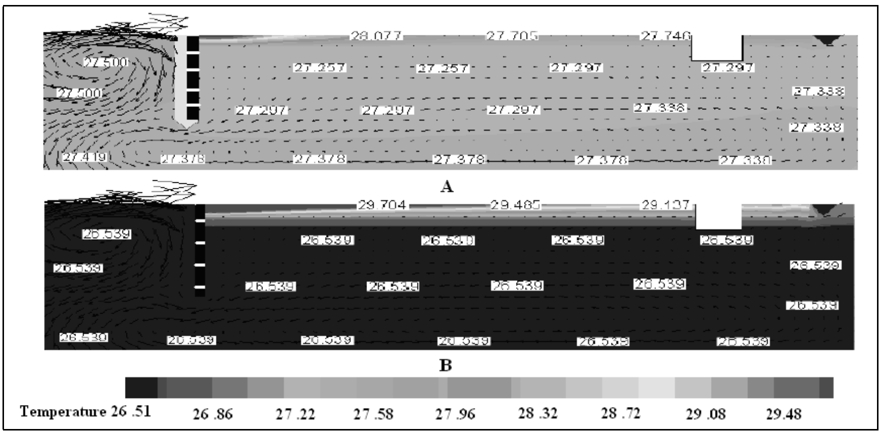

Fig. 4. Effect of Influent Temperature Variation on the Internal Temperature Distribution a) time 120 min, b) 220 min. at ΔT= +1ºC, SS= 75 mg/L

Rys.4. Skutki wpływu zmiany temperatury na wewnętrzny rozkład temperatury a) czas 120 min, b) 220 min przy ΔT= +1ºC, SS= 75 mg/L

The case with the cooler influent shows a rise of the Effluent Suspended Solid (ESS) when the cooler water enters the settling zone, but the rise is much smaller than the case with the warmer influent. In this case the cooler influent makes the inflow even denser which strengthen the density current. This effect is dissipated as the cooler water keeps entering and the difference in temperatures decreases. The generation of a stable stratification of the vertical density gradients seems to suppress the turbulence in the vertical direction and to damp the diffusion of the suspended solids.

The simulations with the lower Suspended Solid (SS) (30 mg/L) and the warmer influent (ΔT= +1ºC) shows a different flow pattern. In this case the ST shows a rising buoyant plume that changes the direction of the density current, i.e. previous to the change in temperature the density current rotates counterclockwise and then it changes to a clockwise rotation. The warmer influent impacts the baffle and is deflected downward. Immediately after passing below the baffle the flow shows a strong rising plume which reaches the surface and develops a surface density current. The surface density current travels at the surface, impacts the end wall and is deflected downward, and then is recirculated as an underflow current. As the temperature in the tank becomes more uniform, the counter flow becomes weaker, eventually returning to the counterclockwise density current dominated by the suspended solids. This flow pattern can be observed in Figure 6 Similar results to results to those presented herein have been presented by **McCorquodle (1977),** in studies conducted with physical models and full scale facilities and also by **Zhou et al. (1994)** in numerical simulations.

In Figure 8, there is a stable density interface between the cooler fluid at the bottom and the warmer fluid at the top. Little mixing is observed between these two layer, and the cooler water is withdrawn from the tank through the hopper. A similar stable-sharp interface is observed at the top of the tank between the surface water and the cooler water below it.

The results presented in figures 5 and 6 indicate that the performance of the ST strongly decreases under the influence of the surface cooling process presented during winter conditions. These results agree with the findings of **Larsen (1977), Wells and LaLiberte (1998) and Kinnear (2004)** who found that the removal efficiency of settling tanks may vary over the year with a minimum during the winter season.

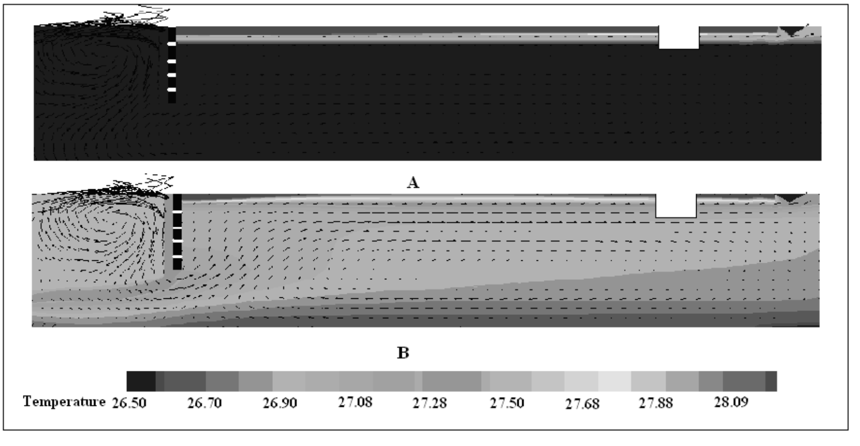

Fig. 5. Effect of Influent Temperature Variation on the Internal Temperature Distribution a) 120 min, b) 220 min. at ΔT= +1°C, SS= 30 mg/L

Rys.5. Skutki wpływu zmiany temperatury na wewnętrzny rozkład temperatury a) 120 min, b) 220 min przy ΔT= +1°C, SS= 30 mg/L

When the surface water becomes cooler it develops an unstable stratification density gradient promoting the mixing with the lower layers. As the cooler-denser water coming from the surface penetrates the tank, the counter clockwise density current carries the denser water towards the inlet region, where it impacts the baffle and is deflected downward. This denser plume mixes with the warmer influent, warming up and travelling with the bottom density current. This cycle creates a radial density gradient that promotes positive vorticity in the settling zone reinforcing the strength of the density current and increasing the suspended solids carrying capacity of the upward current. Close to the ST outlet, the current towards the effluent weirs obligates the surface denser water to pass below the baffle creating a density gradient in the opposite direction to the main gradient developed in the settling zone, this condition creates a small eddy that rotates in the opposite direction to the main density current. This eddy is apparently counteracting the upward flow of suspended solids, but its effect is too local and small to avoid the high ESS at the outlet.

Figure 6 shows the unstable temperature stratification that develops under the surface cooling process. The effect presented herein might have been exaggerated for the relative warm influent for "winter" conditions, i.e., 26.5ºC. To evaluate the conditions for a cooler influent, the test was repeated using a constant influent temperature equal to 11.0ºC. Figure 7 shows the temperature field pattern for this influent temperature; this figure shows the same pattern observed in Figure 6. In this case the peak ESS was 27.15 mg/L, 10 mg/L higher than the "summer" conditions, which supports the statements about the effects of the surface cooling process presented in the previous paragraphs.

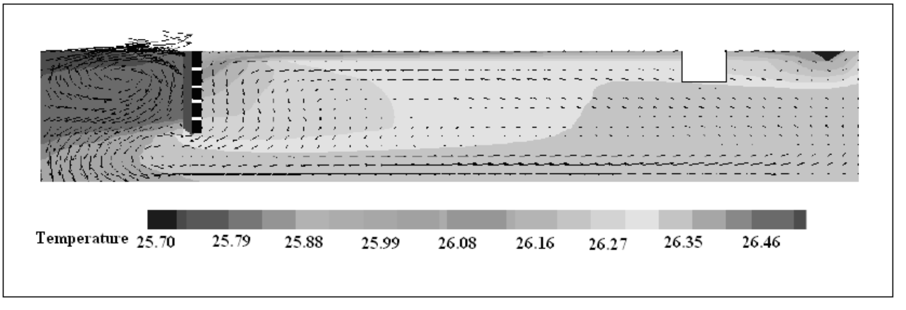

Fig. 6. Temperature Stratification under the Effect of a Surface Cooling Process for an Influent Temperature Equal to 26.5ºC

Rys.6. Stratyfikacja temperatury pod wpływem procesu schładzania powierzchni przy temperaturze wpływu równej 26,5ºC

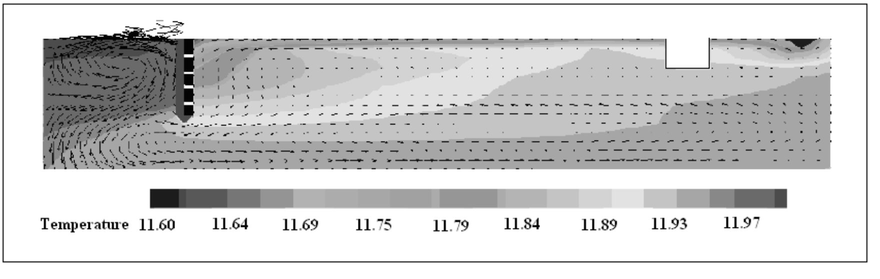

Fig. 7. Temperature Stratification under the Effect of a Surface Cooling Process for an Influent Temperature Equal to 11.0ºC.

Rys. 7. Stratyfikacja temperatury pod wpływem procesu schładzania powierzchni przy temperaturze wpływu równej 11,0ºC

5. Conclusion

The major conclusions, general and specifics, obtained from this research are

- Temperature data from this study indicated that ideal, uniform flow often does not occur in sedimentation tanks when subject to winter cooling and summer heating. The degree of non-uniformity is a complex function of inflow conditions (temperature, suspended solids, flow rate, tank geometry, and inlet baffle design) and meteorological conditions. Hence, design approaches for sedimentation tanks should consider how inflow conditions and meteorological conditions (temperature) impact tank hydraulics.
- The water temperature affects the settling velocities via the fluid viscosity. The Stokes' Law relationship was shown to adequately describe the effect of temperature on a selected floc. This relationship can be applied to correct the settling velocities for difference in temperatures in whichever of the all types of sedimentation settling processes, i.e., unflocculated discrete settling, flocculated discrete settling.
- The changes in temperature on sedimentation tanks play an important role in the performance of settling tanks. A warmer inflow produces a transient strengthening of the density current which results in a higher ESS; the creation of an unstable stratification density gradient in the vertical direction magnifies this effect. A cooler inflow also results in a strengthening of the density current, but in this case the stable vertical density gradient seems to suppress the turbulence in the vertical direction and to damp the diffusion of the suspended solids.

The changes in temperature on settling tanks play an important role on the performance of settling tanks.

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References

[1] Abdel-Gawad, S. M. & McCorquodale, J. A. Hydrodynamics of Circular primary clarifiers. Canadian J. Civil Engr. ,11, 299-307, 1984.

[2] DeVantier, B.A. & Larock, B.E. Modelling sediment-induced density currents in sedimentation basins, Journal of hydraulic engineering, 113(1), 80-94, 1987.

[3] Dick, R. I. Sedimentation Since Camp, J Society of Civil Engrs, 68, 199-235, 1982.

[4] Ekama G.A., Barnard J.L., Günthert F.W., Krebs P., McCorquodale J.A., Parker D.S. & Wahlberg E.J., Secondary settling tanks: theory, modelling and operation. IAWQ Scientific and Technical Report No. 6, 1997.

[5] Ghawi A. Hadi & Jozef Kris. Design and Optimization of Sedimentation Tank in Slovakia with CFD Modeling. 10th International Symposium on Water Management and Hydraulic Engineering 2007 with special emphasis on the impact of hydraulic engineering construction on the environment 4 – 9 September 2007. Šibenik , Croatia. 2007a.

[6] Ghawi A. Hadi, & Jozef Kris. A Numerical Model of Flow in Sedimentation Tanks in Slovakia" Third International PhD Symposium in Engineering 25-26 October 2007, Hungary University of Pollack Mihály Faculty of Engineering Pécs, Hungary. 2007b.

[7] Hazen A. On sedimentation. Trans. ASCE, 53, pp. 45-71, 1904.

[8] Kinnear D. J. Biological Solids Sedimentation: A Model Incorporating Fundamental Settling Parameters. Ph.D. Thesis, University of Utah, 2002.

[9] Kinnear, D.J., Littleton Englewood Wastewater Treatment Facility, Personal communication, 2004.

[10] Larsen P., On the hydraulics of rectangular settling basins, Report No. 1001, Department of Water Research Engineering, Lund Institute of Technology, Lund, Sweden, 1977.

[11] McCorquodale, J.A, Temperature profiles in primary settling tanks. IRI Report University of Windsor, 1977.

[12] Rodi, W., Turbulence Models and their application in hydraulics – a state-of-the-art review 3rd ed, IAHR Monograph Series, A.A. Balkema, Rotterdam, 1993.

[13] Surucu, G., & Cetin F.D., Effects of temperature, pH, and D.O. concentration on settleability of activated sludge. Environmental Technology, 11, pp. 205-212, 1990.

[14] Wells S.A. & LaLiberte D.M. Winter temperature gradients in circular clarifiers. Wat. Environ. Res., 70(7), pp. 1274-1279, 1998.

[15] Zhou S., McCorquodale J.A., & Godo A.M. Short circuiting and density interface in primary clarifiers, J. Hydr. Eng. 120 1060– 1080, 1994.