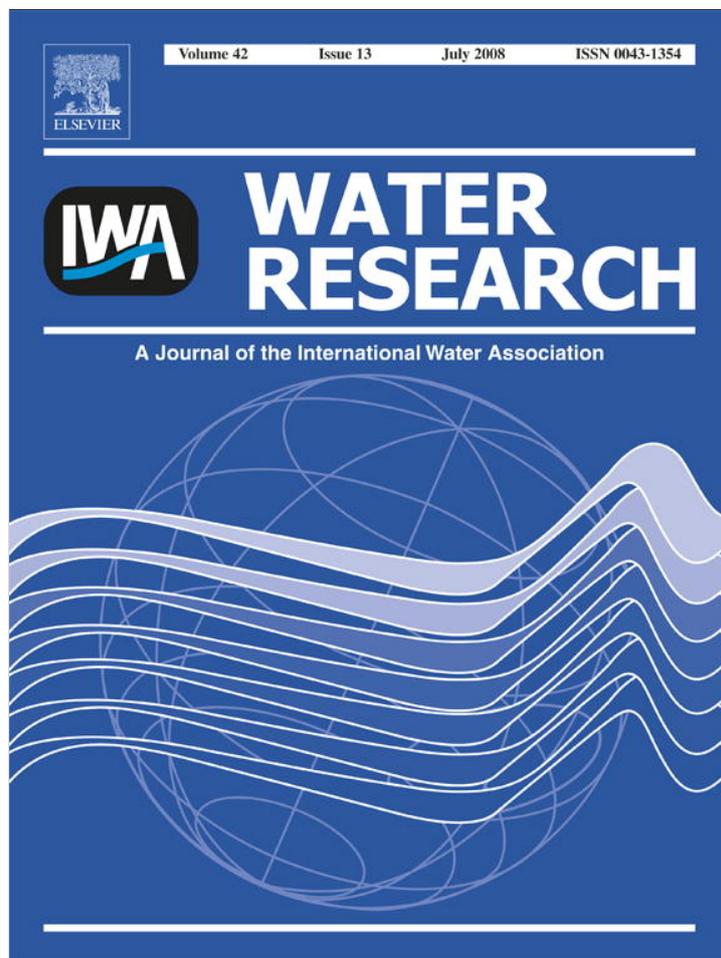


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# The effect of influent temperature variations in a sedimentation tank for potable water treatment— A computational fluid dynamics study

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## ABSTRACT

A computational fluid dynamics (CFD) model is used to assess the effect of influent temperature variation on solids settling in a sedimentation tank for potable water treatment. The model is based on the CFD code Fluent and exploits several specific aspects of the potable water application to derive a computational tool much more efficient than the corresponding tools employed to simulate primary and secondary wastewater settling tanks. The linearity of the particle conservation equations allows separate calculations for each particle size class, leading to the uncoupling of the CFD problem from a particular inlet particle size distribution. The usually unknown and difficult to be measured particle density is determined by matching the theoretical to the easily measured experimental total settling efficiency. The present model is adjusted against data from a real sedimentation tank and then it is used to assess the significance of influent temperature variation. It is found that a temperature difference of only 1 °C between influent and tank content is enough to induce a density current. When the influent temperature rises, the tank exhibits a rising buoyant plume that changes the direction of the main circular current. This process keeps the particles in suspension and leads to a higher effluent suspended solids concentration, thus, worse settling. As the warmer water keeps coming in, the temperature differential decreases, the current starts going back to its original position, and, thus, the suspended solids concentration decreases.

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## 1. Introduction

Settling by gravity is the most common and extensively applied treatment process for the removal of suspended solids from water and wastewater. Generally, the ability of sedimentation tanks to clarify water by letting suspended solids settle down as flocculated particles depends on two aspects: (a) the water flow pattern through the tank, which in turn is determined by the configuration of the tank and by

operational parameters (solids concentration, water flow rate and temperature) and (b) the settling characteristics of the particles as determined by their shape, size and interaction with the water through drag and buoyancy forces. Since the investment for settling tanks in treatment plants usually accounts for one-third of the total investment, the determination of the removal efficiency of a sedimentation tank has been the subject of numerous theoretical and experimental studies.

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From a hydraulic point of view, a distinction has to be made between primary and secondary settling tanks in terms of density effects. In secondary clarifiers, the solids-loaded influent has a higher density than the ambient water and, hence, plunges as a density jet to the bottom of the tank; this is the so-called density current. As a result, a secondary counter current is induced at the surface; even a three- or four-layered structure in the flow field can be experimentally observed (Bretschler et al., 1992; van Marle and Kranenburg, 1994). Such phenomena are less evident—if at all—in primary clarifiers where solids load is smaller. In the case of potable water treatment, the solid mass fraction is even smaller than in primary clarifiers.

Numerical modeling of sedimentation tanks has gained an advanced state of development in the past years. Much research has been done on secondary sedimentation tanks for wastewater treatment. McCorquodale et al. (1991) developed a model using a combination of finite element methods and finite difference methods. McCorquodale and Zhou (1993) investigated the effect of various solids and hydraulic loads on circular clarifier performance, whereas Zhou et al. (1994) linked the energy equation with the Navier–Stokes equations to simulate the effect of neutral density and warm water into a model clarifier. Krebs et al. (1995) used the Phoenix code to model different inlet arrangements and evaluated the effect of inlet baffle position and depth. Deininger et al. (1998) improved the Champion 3D numerical model and predicted the velocity and solids distribution in a circular secondary clarifier. Kim et al. (2005) have recently performed a numerical simulation in a 2-D rectangular coordinate and an experimental study to figure out the flow characteristics and concentration distribution of a large-scale rectangular final clarifier in wastewater treatment.

With respect to primary sedimentation tanks, where the solids concentration is limited and discrete particle settling prevails, Stamou et al. (1989) simulated the flow using a 2D model in which the momentum and solid concentration equations were solved but not linked to account for buoyancy. Adams and Rodi (1990) used the same model as in 1989 and did extensive investigations on the inlet arrangements and the flow through curves. More advanced is the work of Lyn et al. (1992) that in addition to settling accounts also for flocculation, six different size classes with their respective velocities were considered. Frey (1993) used the VEST code to determine the flow pattern in a sedimentation tank, and the flow profiles were then used by the TRAPS code to determine particle tracks. Van der Walt (1998) used the 3D Flo++ code to determine the sensitivity of primary sedimentation tank behavior on a number of geometric, fluid and solids transport properties.

Van der Walt (1998) criticizing past CFD modeling efforts in the water industry pointed out that the power of CFD as a design tool has not been realized yet and gave several examples to highlight the improved insight that can be gained through the use of CFD techniques. Van der Walt and Haarhoff (2000) posed the question “is CFD a tool or a toy?” and concluded that CFD has reached the stage where it is no longer a toy, but can be used as a design tool to optimize several aspects of process tanks, including sedimentation tanks. Huggins et al. (2005) agreed with some of the well-

known advantages of using CFD modeling over laboratory physical models and found CFD models to be more flexible, faster to develop and less expensive than physical models. However, they did not expect CFD models to replace physical models, but to efficiently extend laboratory results to large scales and altered geometries.

Generally, the temperature of the water under treatment is another factor to consider in the operation of a sedimentation basin. Usually, a wastewater treatment plant has the highest flow demand in the summer, whereas when the water is colder, the flow in the plant is at its lowest. According to Wells and LaLiberte (1998), when the temperature decreases, the rate of settling becomes slower. The result is that as the water cools, the detention time in the sedimentation tanks must increase and usually the operator makes changes to the coagulant dosage to compensate for the decreased settling rate. Lau (1994) also mentioned that temperature has a significant influence on the settling of cohesive sediments, and, according to Stokes' law, settling velocities increase with temperature. Counterintuitively, experimental results for kaolinite clay and natural river sediments demonstrated that there was an increased deposition with large settling velocities when the temperature was lowered. This increased deposition was attributed to the effect of electrochemical forces on the properties of the flocs.

Density currents as described above originate from the presence of solids in the flow. However, a density difference between the incoming and ambient mixture may also emerge from differences in temperature (McCorquodale and Zhou, 1993). TeKippe and Cleasby (1968) gave an account of experiments that investigated the instabilities in peripheral feed model settling tanks for wastewater treatment. Large variations in the results of identical experiments were observed, especially at lower flow rates. Those experimenters felt this could be explained by the difference between tank temperature and the influent water temperature. Results were more reproducible when the tank temperature and influent water temperature were of the same value, which suggests a strong correlation between clarifier stability and temperature gradients in the tank. Ekama et al. (1997) compared various energy inputs and showed that surface cooling and wind can be dominant factors affecting the overall hydrodynamics in secondary settling tanks. According to full-scale observations of Wells and LaLiberte (1998), vertical mixing induced by surface cooling was able to keep the particles in suspension by the ensuing convective currents and differences of only 1 °C between surface and bottom temperatures seemed enough to induce a density current. Zhou and McCorquodale (1992) and Taebi-Harandy and Schroeder (2000) mentioned even temperature differences of only 0.2 °C. In addition, Mahmood et al. (2005), who evaluated the water mixing characteristics in distribution system storage tanks, mentioned that differences in the temperature between the bulk tank water and the inflow significantly affect the mixing characteristics and may result in density gradients inside the tank that cause stratification and poor mixing.

Generally, the influence of temperature in sedimentation tanks for potable water treatment was investigated neither systematically nor in detail. In addition, although many

researchers have used CFD simulations to study the effect of various parameters on sedimentation efficiency, most models presented in the literature have been restricted to secondary clarifiers for wastewater treatment. However, this kind of models is not so appropriate to predict the behavior of a sedimentation tank with low suspended solids concentration, such as that used for potable water. In the latter, the physical characteristics of the flocs may not be of equally high significance in the flow field of clarifiers for potable water, due to the much lower solids concentrations and the greater particle size distributions than those encountered in wastewater treatment.

In a previous work, a general CFD-based simulation strategy was developed to study the effect of adding a feed-flow control baffle on the efficiency of solids removal in a sedimentation tank for potable water treatment (Goula et al., 2008). In this study, the impact of influent temperature variation on the efficiency of solids removal within a sedimentation tank of a potable water treatment plant is evaluated using the CFD package FLUENT 6.2.16. The structure of the present work is the following: Section 2 presents the CFD-based simulation strategy developed according to specific features and conditions of the potable water treatment application. It describes the way of particle trajectories calculation, based on their small mass loading, whereas the influence of particle structure is discussed and a method for particle density calculation is developed. Section 3 presents the outcomes of simulations for monodisperse particles using four different temperature profiles inside the tank and discusses the influence of temperature gradients on the flow pattern and the solids distribution. Finally, conclusions drawn from this study are presented in Section 4.

## 2. Materials and methods

### 2.1. Sedimentation tank

A full-scale circular sedimentation tank was investigated, similar to those used in the potable water treatment plant of the city of Thessaloniki. The plant receives raw water from Aliakmon river and its maximum capacity is around  $150,000 \text{ m}^3 \text{ d}^{-1}$  with three tanks of equal dimensions operating in parallel. Each sedimentation tank, with a volume of  $2960 \text{ m}^3$ , is centre-fed with a peripheral weir. The bottom floors have a steep slope of  $12.5^\circ$  and a blade scraper pushes the sludge towards a central conical sludge hopper. Information about geometrical characteristics of the tank is provided in Fig. 1.

Samples of incoming suspension and effluent were taken and analyzed for particle size distribution using a laser diffraction analyzer (Mastersizer 2000, Malvern). Chief drawbacks of the laser diffraction technique are the assumption of sphericity of particles in the optical model and the required dilution step to avoid multiple scattering, because this is not taken into account by the optical model. The latter is checked by means of the obscuration level, which should be within a certain range. The possibility of misinterpreting the size distribution of open porous flocs by assuming them as compact spheres is well known in the literature, but at

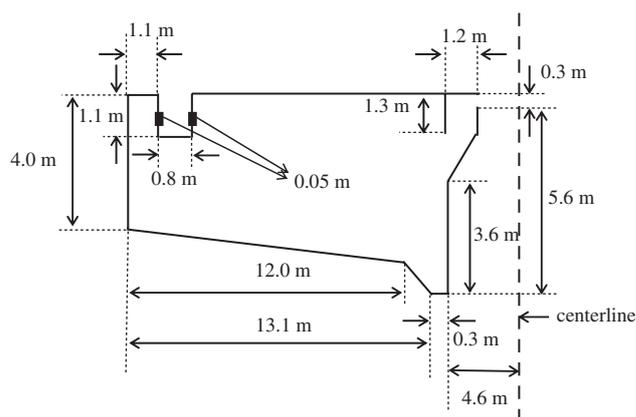


Fig. 1 – Schematic representation of the simulated sedimentation tank.

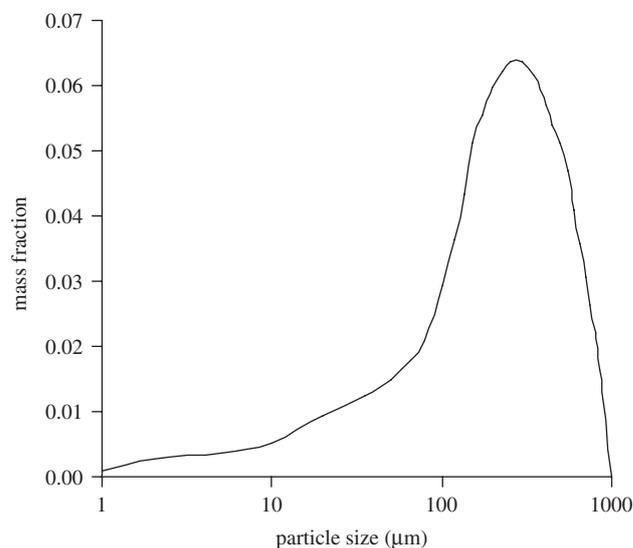
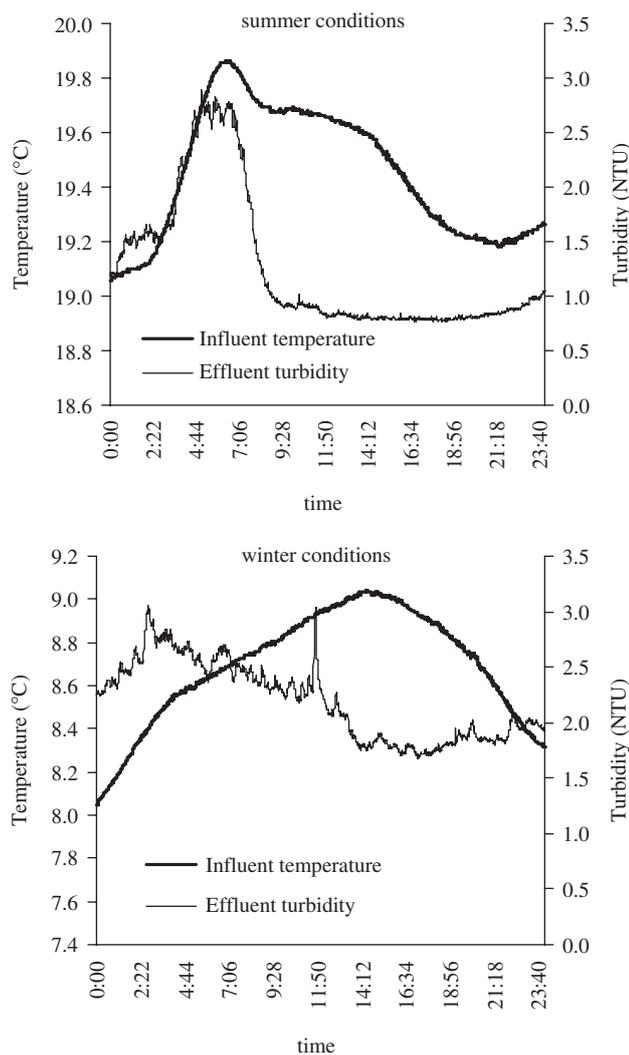


Fig. 2 – Particle size distribution in the influent of the simulated sedimentation tank.

present laser diffraction techniques are acceptable since there are no better alternatives (Nopens et al., 2005). Fig. 2 presents the measured particle size distribution in the influent of the sedimentation tank. The figure represents average values of three measurements conducted for the three sedimentation tanks of the plant. The repeatability expressed as the average standard deviation of the three measurements was 1.3%.

Experimental data concerning the effect of the influent temperature on the settling efficiency of the specific tank are presented in Fig. 3, which shows the variation in effluent turbidity as a function of influent temperature during a daily operation for winter and summer conditions. Inspection of this figure reveals some very interesting trends, typical for the daily operation of the water treatment plant examined here. Apart from the well-known differences of the effluent solid concentration between summer and winter in literature, there is a considerable variation of this concentration along a single day. This variation constitutes a problem to the



**Fig. 3 – Effect of influent temperature on effluent turbidity of the simulated sedimentation tank.**

overall efficiency of the water treatment plant. The present work aims to explain this variation. Careful observation of Fig. 3 reveals that increased effluent turbidity is associated with large positive slopes (with time) of the influent temperature. On the contrary, constant temperature (zero slopes) or negative temperature slopes seem to lead to a rather constant turbidity. In order to understand the observed correlation between the influent temperature slope and effluent turbidity, an artificial influent temperature slope is created by imposing a step temperature change to the influent temperature. This is achieved by running a transient problem with the influent temperature different from the initial tank temperature.

## 2.2. Flow solver

The computational fluid dynamics code FLUENT 6.2.16 has been used to carry out the sedimentation tank simulations described in this article. The code predicts fluid flow by numerically solving the partial differential equations that

describe the conservation of mass and momentum. A grid is placed over the flow region of interest, and by applying the conservation of mass and momentum over each cell of the grid sequentially, discrete equations are derived. In the case of turbulent flows, the conservation equations are solved to obtain time-averaged information. The time averaging refers to the fast turbulent time scales and not to the macroscopic time scale of the process. Since the time-averaged equations contain additional terms, which represent the transport of mass and momentum by turbulence, turbulence models based on a combination of empiricism and theoretical considerations are introduced to calculate these quantities from details of the mean flow (Fluent Corporation, 2005).

The trajectories of individual particles through the continuum fluid using the Lagrangian approach are calculated by the discrete phase model of FLUENT. The particle mass loading in a sedimentation tank for potable water treatment is typically small and, therefore, it can be safely assumed that the presence of particles does not affect the flow field (one-way coupling). This means that the fluid mechanics problem can be solved in the absence of particles to find the steady-state flow field. Then computational particles, whose density and size can be assigned at will, are released from the inlet and tracked thereafter. The volume fraction of particles in the tank is of the order of  $10^{-4}$ . The turbulent coagulation is well known to be proportional to this volume fraction, so it can be ignored under the present conditions. Also, the coagulation due to differential settling can be neglected due to the relatively low settling velocities resulting from the low densities of the flocs. Hindering of the settling velocity is insignificant for these levels of solids volume fraction, as it can be shown by employing the corresponding theories (Berres et al. 2005). Moreover, Lyn et al. (1992), based on model observations, concluded that for conditions of relatively small particles concentrations in sedimentation tanks, the flocs coalescence does not affect the flow field and also the effects on the concentration field and the removal efficiency may be of secondary importance. Finally, particles in the size range relevant to primary separators do not suffer breakage (Wilkinson et al., 2000). The final system of particle conservation equations is a linear one, so the superposition principle can be invoked to estimate the total settling efficiency.

The inlet particle size range is divided in classes based on the discretization of the measured size distribution (Fig. 2) with the medium size of each class assumed as its characteristic (pivot). Then independent simulations are conducted for monodisperse particles in the feed using every time the individual pivot sizes. The overall settling efficiency can be estimated by adding appropriately the efficiency for each particle size.

Tracks are computed by integrating the drag, gravitational and inertial forces acting on particles in a Lagrangian frame of reference. The dispersion of particles due to turbulence is modeled using a stochastic discrete-particle approach. The trajectory equations for individual particles are integrated using the instantaneous fluid velocity along the particle path during the integration. By computing the trajectory in this manner for a sufficient number of representative particles,

the random effects of turbulence on particle dispersion may be accounted for.

### 2.3. The influence of particle structure

The settling velocity of an aggregate depends on its structure both through its effective density and its drag coefficient. These variables must be independently estimated for the aggregate shapes instead of the settling velocity, because settling velocity cannot be directly entered to the Fluent code for the discrete multiphase flow model. This is possible for the Eulerian–Eulerian multiphase models for which empirical correlations for the settling velocity accounting for the finite solid volume fraction can be used (Takacs et al., 1991). As regards the drag coefficient of fractal aggregates, ample information can be found in the literature; from simulation of the flow inside reconstructed flocs using the Fluent code to purely empirical relations (Chu et al., 2005).

On the contrary, the effective density cannot be estimated at all. As the ratio of the resistance experienced by a floc to that of an equivalent solid sphere was found to vary between 0.85 and 0.95 and the settling velocity is not so sensitive to its effects, the resistance coefficient was fixed at 0.90 and the apparent density was then estimated at  $1066 \text{ kg m}^{-3}$  by requiring the final computed settling effectiveness to coincide with the measured settling effectiveness of 90% (Goula et al., 2008). This is a typical effective density value for the aggregates met in water treatment applications (Deininger et al., 1998).

### 2.4. Simulation

To limit computational power requirements, the circular settling tank was modeled in 2D axisymmetric geometry. The major assumption in the development of the model is that the flow field is the same for all angular positions; therefore, a 2D geometry can be used to properly simulate the general features of the hydrodynamic processes in the tank. As a first step, a mesh was generated across the sedimentation tank. A grid dependency study was performed to eliminate errors due to coarseness of the grid and also to determine the best compromise between simulation accuracy, numerical stability, convergence and computational time. In addition, the mesh density was chosen such that the grid was finest where velocity gradients are expected to be largest. The selected grid was comprised of 137,814 quadrilateral elements. Two other grids (one finer with 216,850 elements and one coarser with 11,170 elements) were also used to determine the effect of the overall grid resolution on predictions. While the predictions obtained using the coarse grid were found to be different from those resulting from the selected one, the difference between the predictions made by the selected and finer grids were insignificant. As a result, the solutions from the grid of 137,814 quadrilateral elements were considered to be grid independent.

The segregated solution algorithm was selected and the PISO procedure was used for the pressure–velocity coupling. The SST  $k-\omega$  turbulence model was used to account for turbulence, since this model is meant to describe better low Reynolds numbers flows such as the one inside our sedimen-

tation tank (Wilcox, 1998). Adams and Rodi (1990) pointed out that for real settling tanks the walls can be considered as being smooth due the prevailing low velocities and the correspondingly large viscous layer. Consequently, the standard wall functions as proposed by Launder and Spalding (1974) were used. The water-free surface was modeled as a fixed surface; this plane of symmetry was characterized by zero normal gradients for all variables.

As a first step, the fluid mechanics problem was solved in the absence of particles to find the steady-state flow field. The converged solution was defined as the solution for which the normalized residual for all variables was less than  $10^{-6}$ . In addition, convergence was checked from the outflow rate calculated at each iteration of the run. The convergence was achieved when the flow rate calculated to exit the tank no longer changed. Then the particles, whose density and size could be assigned at will, were released from the inlet and were tracked along their trajectories. Particles reaching the bottom were deemed trapped, whereas the rest were considered escaped. Particle tracking is fast and 25,000 particles could be tracked in less than 10 min once the flow field had been computed.

The number of particles was selected after many trials in order to combine the solution accuracy with short computing time for convergence. As the number of particles increased from 2000 to 25,000, the number of iterations needed for the model to converge decreased, whereas an even higher number did not yield any significant improvement. Therefore, a number of 25,000 particles were selected as a suitable one. Convergence was checked from the particle number balance calculated at each iteration of the run. Convergence was achieved when the percentage of particles calculated to exit the tank no longer changed.

The settling tank was simulated for a specific set of conditions used in the Thessaloniki treatment plant for which the particle size distribution at the inlet and the total settling efficiency have been experimentally measured. The inlet was specified as a plug flow of water at  $0.085 \text{ m s}^{-1}$ , whereas the inlet turbulence intensity was set at 4.5%. The outlet was specified as a constant pressure outlet with a turbulence intensity of 6.0%. The water flow rate was  $0.6 \text{ m}^3 \text{ s}^{-1}$ . Based on this rate, the inlet flow rate of particles was estimated at  $0.15 \text{ kg s}^{-1}$  using a measured solids concentration of  $250 \text{ mg L}^{-1}$ , whereas the primary particle density was  $1066 \text{ kg m}^{-3}$ .

To test the effect of influent temperature variation on the hydrodynamics and the performance of the sedimentation tank, the tank was simulated with an influent temperature difference of  $1^\circ\text{C}$ . A temperature model is used. This model is formed by five components: simulation of the influent water temperature, an advection–diffusion equation for the transport of heat in the tank, surface heat exchange, effects of temperature on density and molecular viscosity, and effects of temperature on the settling properties. The temperature of the incoming water is treated as an advective (open) boundary condition. The value of the influent temperature is incorporated in the tank and is then transported using an advection–diffusion partial differential equation. The heat exchange through solids boundaries and the surface heat exchange are neglected.

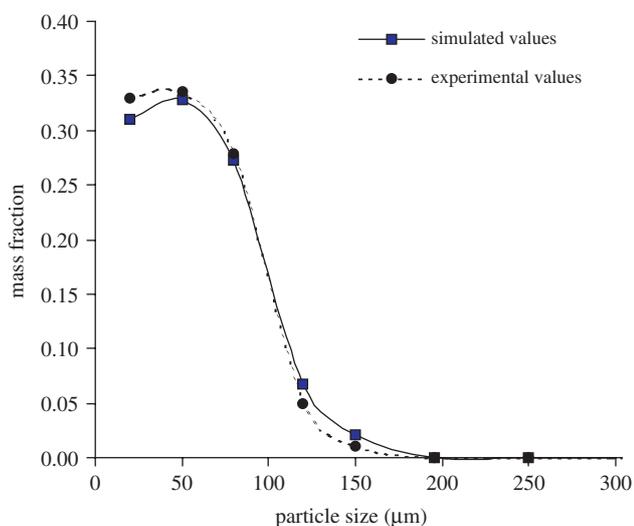
### 3. Results and discussion

#### 3.1. Model validity

As far as the CFD model validity is concerned, Fig. 4 presents a comparison between the experimentally measured and the simulated values of the floc size distribution in the effluent of the tank with a uniform temperature profile. Apparently, there is a good agreement between measured and predicted values. Despite this agreement, the proposed model has an important drawback. The theoretical settling efficiency tends to non-zero (in fact, relatively large) values as the particles size tends to zero. This is due to the combined effect of convection (fluid velocity towards the bottom of the tank), turbulent diffusivity (which is independent of the particle size) and the perfect sink boundary conditions. In practice, it is expected that the settling efficiency decreases as particle size decreases, going to a zero (or close to zero) value for Brownian particles. Although this inconsistency is not exhibited in the case studied here due to the relatively large particle sizes of the feed, it must be considered for the sake of completeness of the simulation procedure. The easiest way to accommodate the realistic behavior of a decreasing settling efficiency as particles size decreases is by incorporating a particle size-dependent trapping probability in the Lagrangian code. Nevertheless, even without the aforementioned improvement, the present CFD model provides a good overall description of the system behavior.

#### 3.2. Flow pattern

Fig. 5 shows the temperature changes in the sedimentation tank with a warmer influent by 1 °C. At 1800 s of simulation time, there is a stable interface between the cooler fluid at the bottom and the warmer fluid at the top. At 7000 s, little mixing is observed between these two layers and the cooler water is



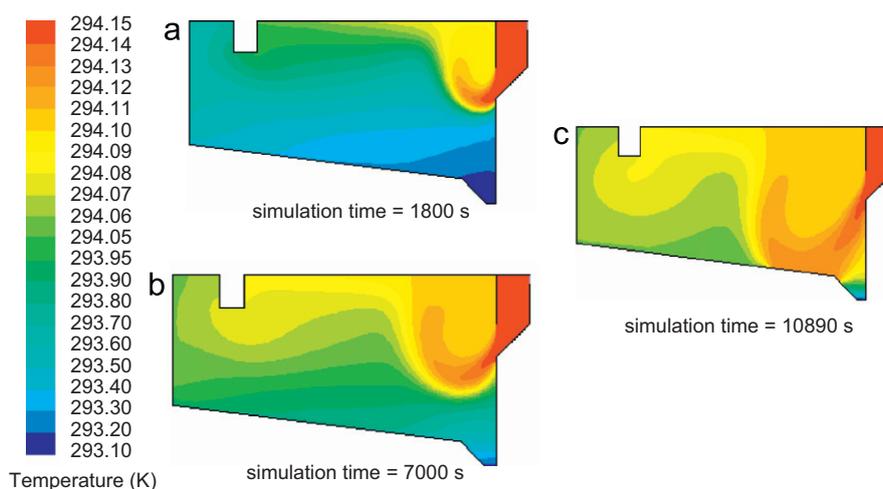
**Fig. 4 – Simulated and experimental particle size distribution in the effluent of the simulated sedimentation tank with the uniform temperature profile.**

stratified at the lower part of the tank, whereas at 10,890 s the temperature becomes more uniform.

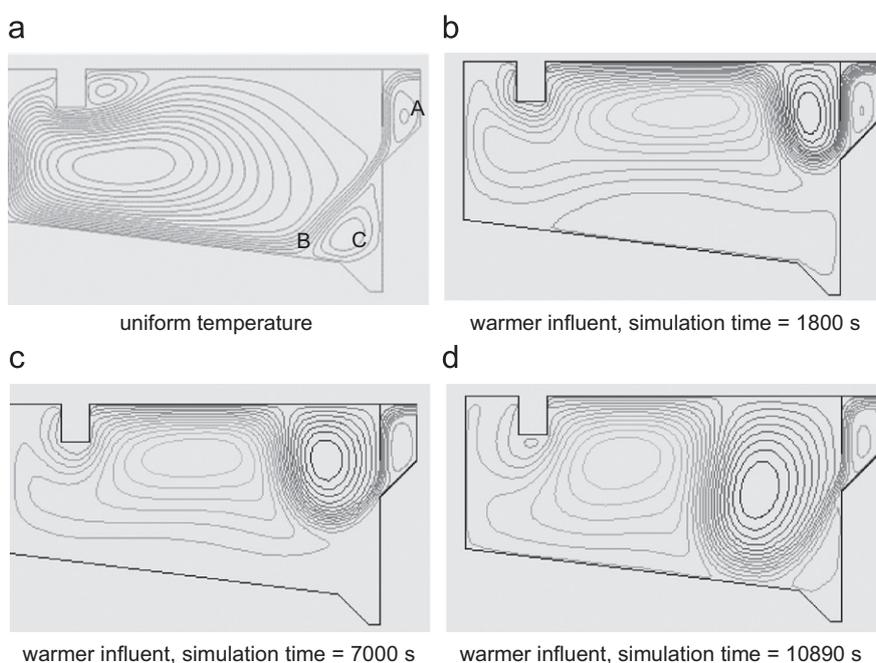
Fig. 6 presents the predicted streamlines for each temperature profile. The displayed simulations refer to particles of 250 µm. In the case of uniform temperature (Fig. 6a), the flow pattern is characterized by a large recirculation region spanning a large part of the tank from top to bottom. Three smaller recirculation regions are also found; two at the top of the tank near the entry and exit points of the liquid stream and one at the bottom right-hand side of the tank just above the cavity, where the sludge gathers before leaving the tank. As it can be seen in Fig. 6a, the influent, after impinging on the standard flow control baffle at point A, is deflected downwards to the tank bottom. The flow splits at point B on the bottom of the tank, producing a recirculation eddy at C. The above-mentioned observations are in agreement with the findings of Zhou and McCorquodale (1992), who studied numerically the velocity and solids distribution in a clarifier.

As it can be seen in Fig. 6b, when the influent temperature rises, the tank shows a rising buoyant plume that changes the direction of the circular current, i.e. previous to the change in temperature the circulation is clockwise and then it changes to a counterclockwise rotation. The warmer influent impacts the center well and is deflected downward. Immediately after passing below the well, the flow shows a strong rising plume that reaches the surface, impacts the end wall, is deflected downward and then is recirculated as an underflow current. As the warmer water keeps coming in, the temperature differential decreases, the counter flow becomes weaker and the current starts going back to its original position. This observation is similar to that reported by Kim et al. (2003), who concluded that the thermal density flow and concentration density flow have a similar structure in the initial unsteady state, while the thermal density flow will be changed to a non-stratified neutral condition in a steady state.

The formation of temperature-driven currents was also reported by Taebi-Harandy and Schroeder (2000), who concluded that the depth of these currents was inversely related to the difference between temperatures of the influent and tank contents. Moreover, the formation of this temperature-driven current was found to be independent of the amount of suspended solids in the entering suspension, and the current type, surface or bottom, was dependent on whether the influent was warmer or cooler than the tank contents. According to Wells and LaLiberte (1998), in the case of secondary clarifiers with higher suspended solids concentration in the influent, the warmer influent does not produce a change in the direction of the density current, but it temporally strengthens it and produces a rise in the effluent suspended solids concentration. In that case, when the influent temperature rises, the suspended solids probably keep the warmer, but still denser inflow, close to the bottom and when the current reaches the end of the clarifier and most of the solids have settled out, the plume rises reinforced by the vertical acceleration of the buoyant effect of the warmer water. This process results in a strengthening of the density current and a higher effluent suspended solids concentration. As the warmer water keeps coming in, the temperature differential decreases and the density current



**Fig. 5 – Effect of influent temperature variation on internal temperature distribution.**



**Fig. 6 – Effect of influent temperature variation on calculated streamlines. (a) Uniform temperature, (b) warmer influent, simulation time = 1800 s; (c) warmer influent, simulation time = 7000 s; (d) warmer influent, simulation time = 10,890 s.**

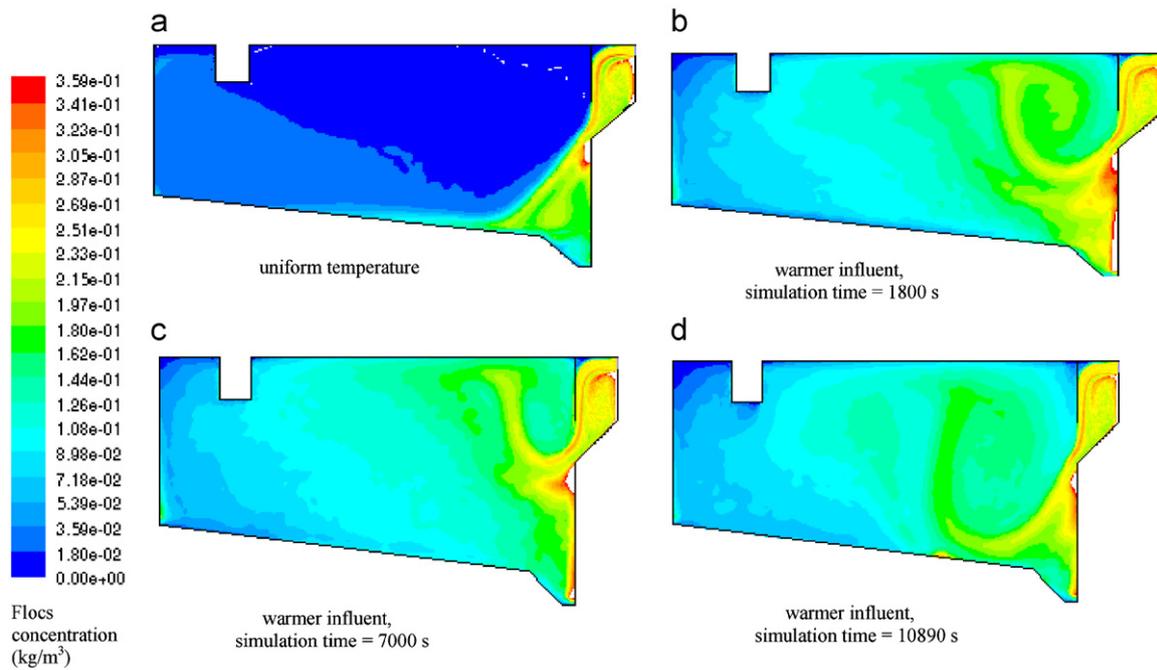
goes back to the original position with the corresponding decrease of the effluent solids concentration.

Thus, the effect of a warmer influent depends on the inflow solids concentration. If the concentration is low, as in the specific sedimentation tank for potable water treatment, the temperature becomes more important in determining the location of the interface and the water temperature difference defines the nature of the current, i.e. buoyant or sinking. A warmer influent results in a rising plume downstream of the center well and in a surface current in the settling zone. On the contrary, in secondary sedimentation tanks, the direction of the density current will be probably dominated by the gradient due to the suspended solids. A warmer inflow would travel near the bottom until it rises after the suspended solids have settled out. Moreover, the

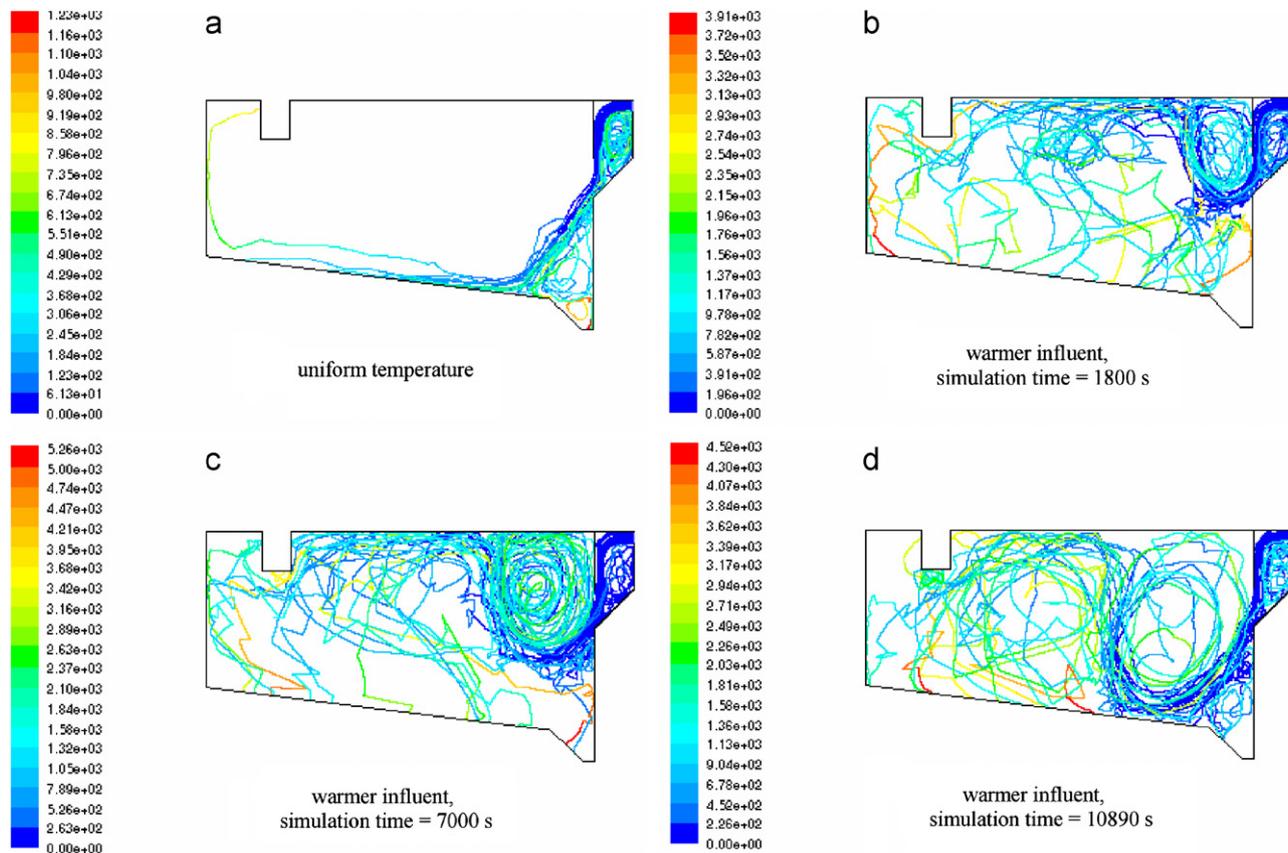
thermal currents may be more important in primary than in secondary sedimentation tanks. In secondary clarifiers it is necessary to consider the combination of thermal and suspended solids-induced density effects.

### 3.3. Solids distribution

The effect of the influent temperature variation is also displayed in Figs. 7 and 8 that show flocs concentration and pathlines colored by particle residence time, respectively, for particles of 250  $\mu\text{m}$ . As it can be seen, when the influent temperature rises (Figs. 7b and 8b), the tank shows a rising buoyant plume and the flow in the surface current is higher than the effluent flow due to the entrainment of the underflow current. This process keeps the particles in suspension



**Fig. 7 – Effect of influent temperature variation on flocs concentration (a number of cells have been blanked out. These near the walls have higher concentration than the scale maximum, whereas these inside the tank have negative values). (a) Uniform temperature; (b) warmer influent, simulation time = 1800 s; (c) warmer influent, simulation time = 7000 s; (d) warmer influent, simulation time = 10,890 s.**



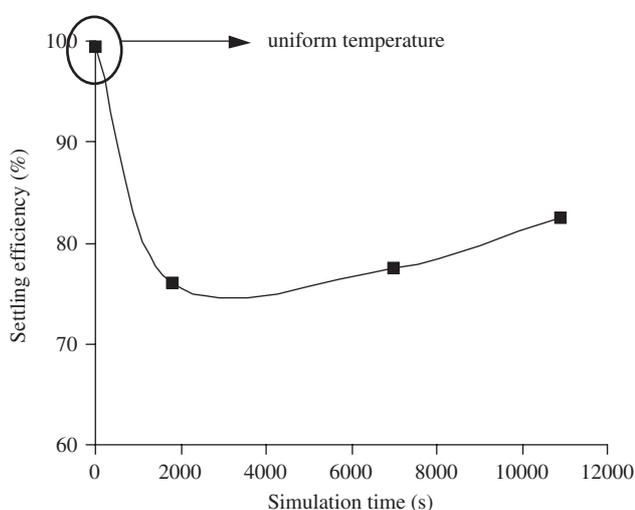
**Fig. 8 – Effect of influent temperature variation on flocs pathlines colored by residence time (s). (a) Uniform temperature; (b) warmer influent, simulation time = 1800 s; (c) warmer influent, simulation time = 7000 s; (d) warmer influent, simulation time = 10,890 s.**

by the resulting convective currents and leads to a higher effluent suspended solids concentration. As the warmer water keeps coming in (Figs. 7c, d, 8c and d), the temperature differential decreases, the current starts going back to the original position. and, thus, the suspended solids concentration decreases.

The effect of the temperature gradient on the settling efficiency is presented in Fig. 9 that shows the predicted percent of solids settled for particles of 250  $\mu\text{m}$  as a function of the simulation time. When the influent temperature rises, the percent solids removal efficiency initially decreases from 99.5% to 76.0%, but as the temperature differential decreases, the efficiency increases from 76.0% to 77.5% and then to 82.4%. Thus, the settling effectiveness is inversely related to the extent of the temperature differential in the tank.

The results of the CFD simulations performed here seem to confirm that there is a relationship between the slope of the influent temperature with time and the sedimentation efficiency. When a positive slope exists, the inflow stream is hotter than the rest of the water in the tank and so its density is lower and the buoyancy drives it upwards preventing the deposition of the dispersed particles in it. This phenomenon becomes stronger as the value of the slope increases. On the other hand, when the slope is negative, the inflow stream is colder than the rest of the tank water and sinks as soon as it enters the tank. Therefore, buoyancy does not oppose settling, and as a result the sedimentation efficiency is not affected by the temperature variation. In this work, simulations under indicative conditions were performed in order to illustrate qualitatively the above dependence. To obtain quantitative results, transient simulations must be performed under periodic (period of 1 day) influent temperature until the system reaches a stationary periodic steady state. Then, the computed periodic variation of the sedimentation efficiency can lead to quantitative relations for its dependence from the influent temperature variation.

In addition, as it can be seen in Fig. 3, the effluent turbidity generally presents higher values during the winter conditions. This observation agrees with the findings of Parker et al.



**Fig. 9 – Effect of influent temperature variation on settling efficiency for particles of 250  $\mu\text{m}$ .**

(2001), who found that the removal efficiency of settling tanks may vary over the year with the minimum during the winter season. This result may be attributed to the traditional discrete settling model proposed by the Stokes' law, which 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.

#### 4. Conclusions

This work deals with the development of a specialized strategy for the simulation of the treatment of potable water in sedimentation tanks. The strategy is based on the CFD code Fluent and on specific features and conditions met in practice for potable water treatment (low solids mass and volume fraction), which allow decoupling the fluid motion pattern from the particles motion. Alternative techniques as the Eulerian–Eulerian two fluid model and the Lagrangian Eulerian model with coupling between the fields can be used to give similar results but at much higher computational cost. This model is used to assess the effect of influent temperature variation on the hydrodynamics and the performance of a particular sedimentation tank using a temperature difference of 1  $^{\circ}\text{C}$  between influent and tank content.

The results show that when the influent temperature rises, the tank presents a rising buoyant plume that changes the direction of the circular current from a clockwise to a counterclockwise rotation. The flow in the surface current is then higher than the effluent flow, and, thus, the particles remain in suspension. This process leads to a decrease in the percent removal efficiency for the particles of 250  $\mu\text{m}$  from 99.5% to 76.0%. As the warmer water keeps coming in, the temperature differential decreases, the counter flow becomes weaker and the efficiency starts increasing. Thus, a temperature difference of only 1  $^{\circ}\text{C}$  is enough to induce a temperature-driven density current, which causes a non-uniform distribution of solids, and, therefore, a short-circuiting through the tank. The net results are a shortening of the detention time in the basin and a reduction of its solids removal efficiency. These outcomes confirm that there is a relationship between the slope of the influent temperature with time and the sedimentation efficiency.

In general, CFD provides new insight into the operation of a sedimentation tank for potable water treatment and can model its behavior accurately simulating not only internal changes (e.g. baffles, hopper shape, dividing walls) but also external changes (hydraulic load, temperature, wind). Thus, it is a design tool that integrates the physical behavior of the basin with its geometry.

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