Influence of density flow on treated water turbidity in a sedimentation basin with inclined plate settler

K. Takata and R. Kurose

ABSTRACT

The removal efficiency of particulate matter from a sedimentation basin with an inclined plate settler in drinking water treatment facilities is sometimes reduced by density flow caused by temperature increases in the raw water. In this study, the structure of the density flow and its prevention are investigated by means of three-dimensional computational fluid dynamics (CFD). The results of CFD show that upward velocity is uniform and normal operations are performed before the increase in inlet water temperatures. After the onset of a temperature increase in the raw water, the upward flow velocity on the inclined plate settler increases, especially in the upstream zone of the plate. This velocity increment has a strong correlation with increase in turbidity as a result of the overflow of particulate matter. The effects of the installation of baffle plates on the inclined plate settler to reduce turbidity were explored. The CFD results using baffle plates show a significant decrease in upward velocity on the inclined plate settler. This suggests that baffle plates are effective in suppressing the overflow of particulate matter. To verify the prediction by CFD, baffle plates were installed in a drinking water treatment facility. The results show that the turbidity of treated water was reduced by the proposed procedure.

Key words | baffle plate, CFD, density flow, inclined plate, sedimentation basin, turbidity

K. Takata (corresponding author)
Department of Mechanical Engineering,
National Institute of Technology, Kure College,
2-2-11, Agaminami,
Kure,
Hiroshima 737-8506,
Japan
E-mail: *k-takata@kure-nct.ac.jp*

R. Kurose
Department of Mechanical Engineering and Science,
Kyoto University,
Kyoto daigaku-Katsura,
Nishikyo-ku,
Kyoto 615-8540,
Japan

INTRODUCTION

The sedimentation basin is a water treatment facility used in many industrial fields. Various measures and improvements have been made to reduce their installed area and enhance their solid–liquid separation performance. In drinking water production facilities in particular, an inclined plate settler is often used in water treatment plants as a solid–liquid separator to increase sedimentation performance. The performance of sedimentation basins is susceptible to temperature differences because of a very slow upward velocity. The removal efficiency of particulate matter from these basins is decreased by the overflow of coagulation matter with the treated water. This is sometimes caused in summer daytime by a temperature increase of raw water compared with the temperature of water in the sedimentation basin. A temperature difference of only 1 °C is sufficient to cause such a decrease in efficiency (Goula *et al.* 2008a, 2008b). This phenomenon is considered to be caused by density flow, which occurs as a result of the temperature difference between the inlet water and the sedimentation basin. Typical density-driven flow occurs when the inflow to the sedimentation basin of higher-temperature raw water exposed to solar radiation increases flow velocity fluctuations. This prevents normal operational performance and decreases treated water quality.

The research on these density flows and carryover has had a long history. Many research reports have been written (Adams & Rodi 1990; Lyn *et al.* 1992; Zhou *et al.* 1992), starting with the pioneering research on horizontal flow sedimentation basins by Camp (1946).

Recently, with the development of computer analysis code for fluid flow, various studies using computational fluid dynamics (CFD) have been conducted to clarify flow structure and improve solid–liquid separation performance

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(Tarpagkou *et al.* 2013; Das *et al.* 2015). There have also been several reports focusing on optimizing the baffle plate, which enhances sedimentation velocity, and its verification (Krebs *et al.* 1995; Mohanarangam & Stephens 2009; Heydari & Bajestan 2013; Razmi *et al.* 2013; Xanthos *et al.* 2013; Lutfy *et al.* 2015). In particular, the installation of baffle plates at the basin inlet has been examined for increasing sedimentation velocity, and for increasing inlet flow velocity to reduce the effect of temperature differences between the inlet water and the basin water (Goula *et al.* 2008a, 2008b). The influence of temperature differences on sedimentation performance for particles of various diameters has also been studied (Goula *et al.* 2008a, 2008b). However, the research on density flow has mainly addressed horizontal flow sedimentation or circular sedimentation basins without an inclined plate, for wastewater and water purification facilities.

The effects of an inclined plate (lamella clarifier) on flow in a settling basin have been examined by the CFD method for small-scale water purification treatment (Tarpagkou & Pantokratoras 2014). Although important results on sedimentation ponds have been reported as described above, no research has been done to address the mechanism of density flow in large-scale water purification plants using the inclined plate settler. Addressing this knowledge gap is the object of this study.

In the present study, we aim to elucidate the transient phenomena of density flow in a sedimentation basin resulting from temperature fluctuations in raw water flowing into the basin. The CFD method was used for this elucidation. We also aim to clarify the cause of particulate matter carryover from the sedimentation basin when an inclined plate settler is used in a large-scale water purification plant in Japan. In addition, a method to prevent carryover was investigated by CFD, and the effectiveness of the proposed method was tested by applying the method to a commercial facility.

OBSERVATION OF DENSITY FLOW

Investigation and observation of physical density flow were conducted in the treatment facility by measuring water temperature in the sedimentation basin and the turbidity of treated water. Observation was done in a drinking water treatment facility in Hyogo Prefecture, Japan, with a daily treatment capacity of 40,000 m^3 per one operation line. Figure 1 shows the measured inlet raw water temperature and treated water turbidity, and Figure 2 shows the temperature distribution in the sedimentation basin. The red numbers show temperatures higher than those at 11:00 AM. The relationships between the measured and observation results are summarized as follows:

(1) Treated water turbidity had a nearly constant value when the temperature of the inlet water to the basin was constant during the morning.
(2) Coagulated matter flowed through the inclined plate settler from about 2:00 PM, and a proportion of the turbid matter was collected in a trough with the treated water. The remaining coagulated matter was suspended in the clarified zone – the upper part of the inclined plate settler.

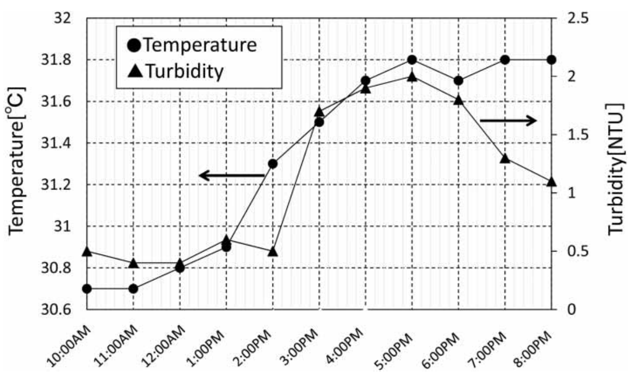

Figure 1 | Measured temperature and treated water turbidity.

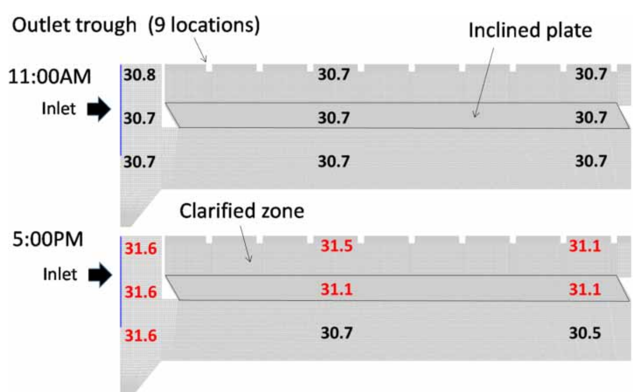

Figure 2 | Measured temperature distributions (°C) in the sedimentation basin at 11:00 AM and 5:00 PM.

(3) Large amounts of coagulated matter floated from the inclined plate settler and flowed horizontally upstream to downstream inside the clarified zone.
(4) A part of the coagulated matter was collected together with treated water from all collecting troughs, and the remaining matter flowed downstream in the clarified zone.
(5) Coagulated matter not collected by the trough flowed downstream. The clarifier zone was covered by coagulated matter.
(6) The temperature of the upstream zone near the water surface increased, and the maximum temperature difference in the basin was measured to be 1.1 °C. It was clear that the overflow of coagulated matter was substantial when the temperature difference in the basin was large.
(7) The coagulated matter flowing in the clarified zone began settling around 5:00 PM, and normal operating conditions appeared to resume.

The observation results suggest that the cause of the degrading of water quality is the enhancement of flow velocity caused by the temperature difference between inflow water and the basin interior.

NUMERICAL SIMULATION OF DENSITY FLOW

Governing equations and simulation model

Detailed velocity and temperature distributions in the sedimentation basin are necessary for clarifying the mechanism of density flow. The measurement of velocity is one approach. However, the sedimentation basin is designed to maintain a uniformly slow speed to settle small coagulated matter. Therefore, accurate measurement of small velocity fluctuations in the basin is difficult. Given this situation, CFD was considered an effective tool to clarify such flow fields. In our study, the structure of the density flow was elucidated by obtaining detailed velocity and temperature distributions through CFD. The CFD approach enables transient velocity and temperature distributions to be obtained in the analysis region, and is effective in examining the structure of the density flow. The equations governing momentum and energy for an incompressible Newtonian fluid are the Navier–Stokes equations with the Boussinesq approximation, and the transport equations of energy (temperature T), turbulent energy k, and turbulent dispersion rate ε in Cartesian coordinates as follows.

Continuity:

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

Navier–Stokes:

$$\frac{\partial \rho U_i}{\partial t} = \frac{\partial U_j \rho U_i}{\partial x_j} - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu \frac{\partial U_i}{\partial x_j} - \rho u_i u_j\right] - \rho g_i \beta (T - T_0) \tag{2}$$

Turbulent energy k:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial U_i \rho k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\sigma_k}\left(\frac{\partial k}{\partial x_i}\right)\right] - G_s + G_T + \rho\,\varepsilon \tag{3}$$

Turbulent dispersion rate ϵ:

$$\frac{\partial \rho\,\varepsilon}{\partial t} + \frac{\partial U_i \rho\,\varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\sigma_\varepsilon}\left(\frac{\partial\,\varepsilon}{\partial x_i}\right)\right] + C_1 \frac{\varepsilon}{k}(G_s + G_T)(1 + C_3 R_f) - C_2 \frac{\rho \varepsilon^2}{k} \tag{4}$$

Energy (temperature) T:

$$\frac{\partial \rho C_p T}{\partial t} + \frac{\partial U_j \rho C_p T}{\partial x_j} = \frac{\partial}{\partial x_j}\left[K \frac{\partial T}{\partial x_j} - \rho C_p u_j t\right] \tag{5}$$

Here, U, u, T, and t represent mean velocity, fluctuated velocity, mean temperature, and fluctuated temperature, respectively. Also, μ, ρ, g, and β represent fluid viscosity, density, the force due to gravity, and the volumetric thermal expansion coefficient, respectively. C_p and K specify specific heat and thermal conductivity. The numerical values of these physical properties of water used here are $\mu = 8.0\text{E-4}\,\text{Pas}$, $\rho = 995\ \text{kg/m}^3$, $g = 9.8\ \text{m/s}^2$, $\beta = 3.0\text{E-4}\ \text{K}^{-1}$, $C_p = 4.178\ \text{kJ/(kg K)}$, and $K = 0.61\text{W/(m K)}$. In this model, the Reynolds stress term and constants in Equations (2) and (5) are assumed as follows:

$$\rho\, u_i u_j = \frac{2}{3} k\, \rho \delta_{ij} - \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_j}\right), \tag{6}$$

$$u_i t = -\frac{K_t}{\rho\, C_p} \frac{\partial T}{\partial x_j}, \quad K_t = \frac{\mu_t C_p}{P_{rt}}, \tag{7}$$

where K_t is turbulent diffusion conductivity and μ_t is the eddy viscosity of the fluid, which is defined as

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}. \tag{8}$$

In this model, the turbulent Prandtl number $P_{rt} = 0.9$ was used. The terms G_s, G_t and R_f in Equations (3) and (4) are defined as follows:

$$G_s = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j}, \tag{9}$$

$$G_T = g_i \beta \frac{\mu_t}{\sigma_t} \frac{\partial U_i}{\partial x_i}, \tag{10}$$

$$R_f = \frac{G_T}{G_s + G_T}. \tag{11}$$

The following numerical values were used for the parameters in Equations (3), (4), (8), and (10):

$$\sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3, \quad \sigma_t = 0.9, \quad C_1 = 1.44, \quad C_2 = 1.68, \quad C_3 = 0.00, \quad C_\mu = 0.09$$

Equations (1)–(5) were solved using analysis code for fluid flow (NuFD/Front Flow Red).

Figure 3 shows the analysis model used for the simulation. The model is three-dimensional, with the same scale as that of the commercial plant, having dimensions of 25 m in length, 5 m in depth, and 5 m in width. The three-dimensional mesh consists of $373 \times 50 \times 88 =$ 1,641,200 meshes. The positions of the inlet and outlet were set the same as that in the physical facility.

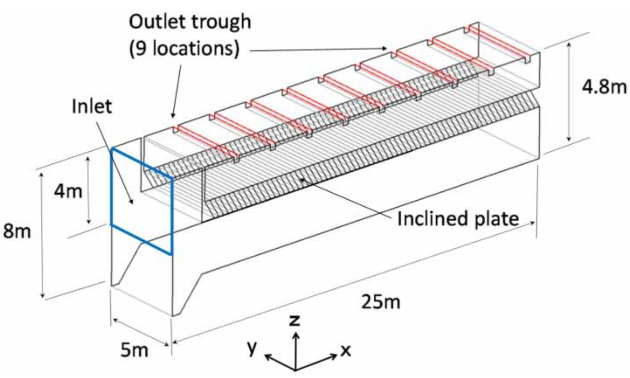

Figure 3 | Calculation model of the sedimentation basin for CFD.

Boundary and inlet conditions

The purpose of CFD was to describe transient flow caused by the change in inlet water temperature. In this simulation, the measured temperature at 1:00 PM was used to represent the water temperature under normal operating conditions, thereby obtaining the steady-state flow field. The flow field between the onset of density flow at 1:00 PM and its termination at 8:00 PM was calculated by applying the measured temperature shown in Table 1 as the inlet water temperature. This temperature was given hourly in stepwise fashion, and 7 hours of transient phenomena were calculated by computer.

The dimensions of the analysis field are schematically shown in Figure 3. The basin was 25 m long, 5 m wide, and had a maximum depth of 8 m. Boundary conditions are schematically shown in Figure 4: in the inlet water region, depicted by the blue square on the left side of Figure 3, the inlet flow speed was set at 0.005 m/s, based on operating conditions. In the effluent region (trough), natural effluent conditions were stipulated. The water surface was set to the free-slip condition, and measured effluent water height between that surface and the overflow trough was specified. Velocity components were set to zero at the wall of the sedimentation basin, including the surface of the inclined plate settler.

Table 1 | Measured turbidity for cases with and without baffle plates

	Turbidity [NTU]		
Conditions/Time	**11:00 AM**	**5:00 PM**	
No baffle	0.3	2.7	
4 baffles	0.2	1.05	
8 baffles	0.2	0.6	
Target value	< 1.0		
	Turbidity [NTU]		
Date	**No baffle**	**4 baffles**	**8 baffles**
8th Aug.	2.4	0.65	0.45
9th Aug.	2.5	1.05	0.6
16th Aug.	1.85	0.6	0.35
18th Aug.	3.2	0.5	0.35

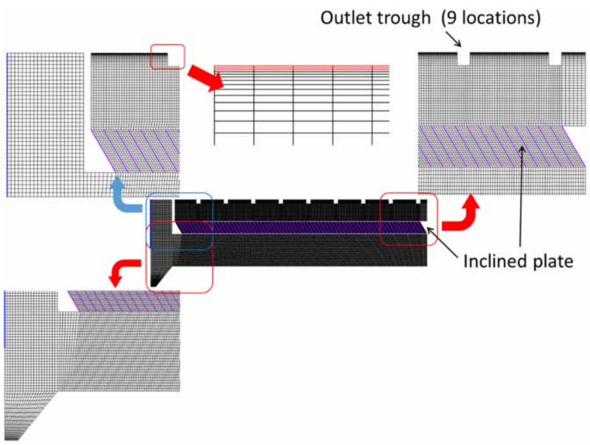

Figure 4 | Boundary conditions of CFD.

RESULTS AND DISCUSSION

Mechanism of the generation of density flow

Figure 5 shows transient velocity and temperature distributions along a basin cross-section under normal operating conditions, just prior to the generation of density flow. These results indicate that flow velocity was nearly uniform inside the inclined plate settler. However, for water temperature increases between 3:00 PM and 5:00 PM, a substantial velocity increment in the area upstream of the settler is indicated by the CFD results. This suggests that the deterioration in water quality was caused by the overflow of particulate matter, which was not only in the inlet raw water but also floated upward from the basin bottom. There was a strong relationship between the velocity increase resulting from temperature differences and degradation of water quality by overflowing coagulated matter.

Density-flow conditions were the most typical at around 5:00 PM, and then started to gradually change as a result of the decrease in temperature difference between inlet water and the basin interior. Around 8:00 PM, the maximum upward velocity at the inclined plate settler of the upstream zone declined, and the temperature distribution in the sedimentation basin appeared to shift to a stratified condition. This condition was expected to return to a uniform velocity distribution as in the normal condition by the time the lower-temperature water flowed into the basin. The transient temperature distributions produced by CFD show that the higher-temperature raw water flowed in the clarified zone in a downstream direction. When velocity fluctuation was substantial, at around 3:00 PM, higher temperatures in the left upper zone and lower temperatures in the right bottom zone formed in the basin. These CFD results were compared with measured ones. The measured temperatures also show the formation of a higher-temperature zone in the upper left zone and a lower-temperature zone in the lower

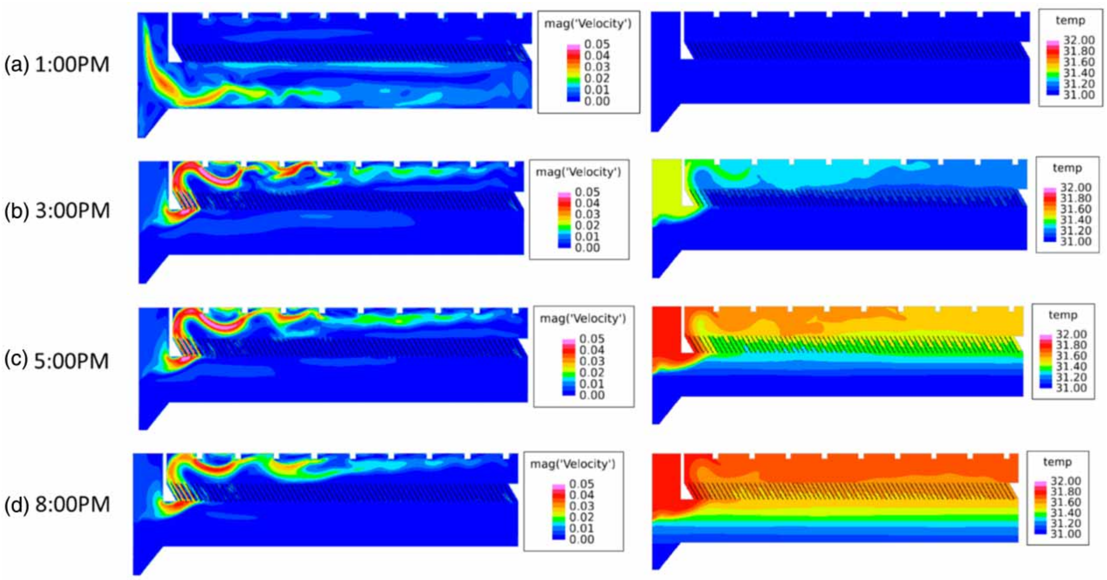

Figure 5 | Calculated transient velocity and temperature contours in the sedimentation basin.

right, almost identical to the CFD results. Thus, the prediction of density flow by CFD was accurate, and its extensive use is considered a possibility for investigating the prevention of density flow and improving water quality.

Prevention of density flow

To prevent the velocity increment caused by the generation of density flow in the upstream zone of the sedimentation basin, the effects of a baffle plate installation were investigated. The installation was in the clarified area, just above the inclined plate settler. In previous studies, the extension of the settler to near the collection trough and the relative reduction in the effects of density flow by increasing inlet flow velocity were investigated (Goula *et al.* 2008a). However, in our study, the installation of baffles was the most feasible method since the facility was under operation and the improvement had to be done during operation. The baffles can be installed easily from outside, and therefore it was suitable for the type of sedimentation basin studied, and thus baffle plates rather than settler extensions were investigated. Baffle plates are considered effective for reducing the velocity enhancement at the inclined plate settler and can also suppress the upstream-to-downstream flow in the clarified zone, caused by the density flow.

We predicted the flow field using CFD with different numbers of baffle plates and determined the effective installation to minimize the effect of density flow. The numbers of baffle plates selected were four and eight, and were installed with equal spacing (shown in Figure 6 as the calculation model). Different plate numbers were used to compare the influence of up-flow velocity at the inclined plate settler on treated water quality.

Figure 7 shows the calculated transient velocity and temperature distributions in the case of four baffle plates, and Figure 8 shows the distributions for eight plates. Figure 9 shows the average axial velocity distribution in the longitudinal direction at the center of the inclined plate settler. The results show a major change in the flow pattern in both cases, and the increment of up-flow velocity in the upstream region was reduced compared with that before installation of the baffle plates. Most notably, the use of eight baffle plates was more effective in reducing the up-flow velocity than four plates. The difference in maximum velocity in the upstream region between the eight-baffle-plate case and that without a baffle is approximately a factor of three. In the previous section, it was indicated that the cause of the deterioration in water quality was the overflow of coagulated matter with the treated water, as a result of the increased flow velocity caused by density flow. Based on the results described above, the baffle installation is effective in improving water quality because it reduced the up-flow velocity.

Verification

In agreement with the CFD results, the installation of baffle plates was effective in improving water quality. It was found that eight baffle plates were more effective in reducing the velocity than four plates. In the CFD calculations, we

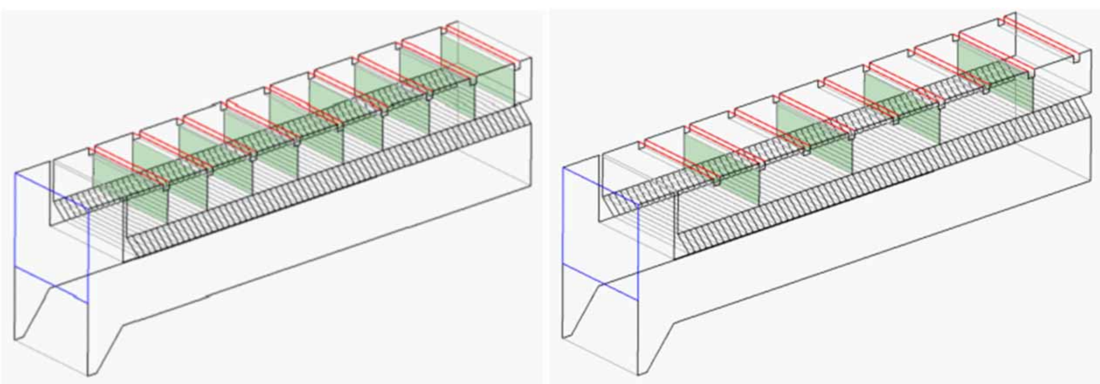

Figure 6 | Calculation model using baffle plates in two cases.

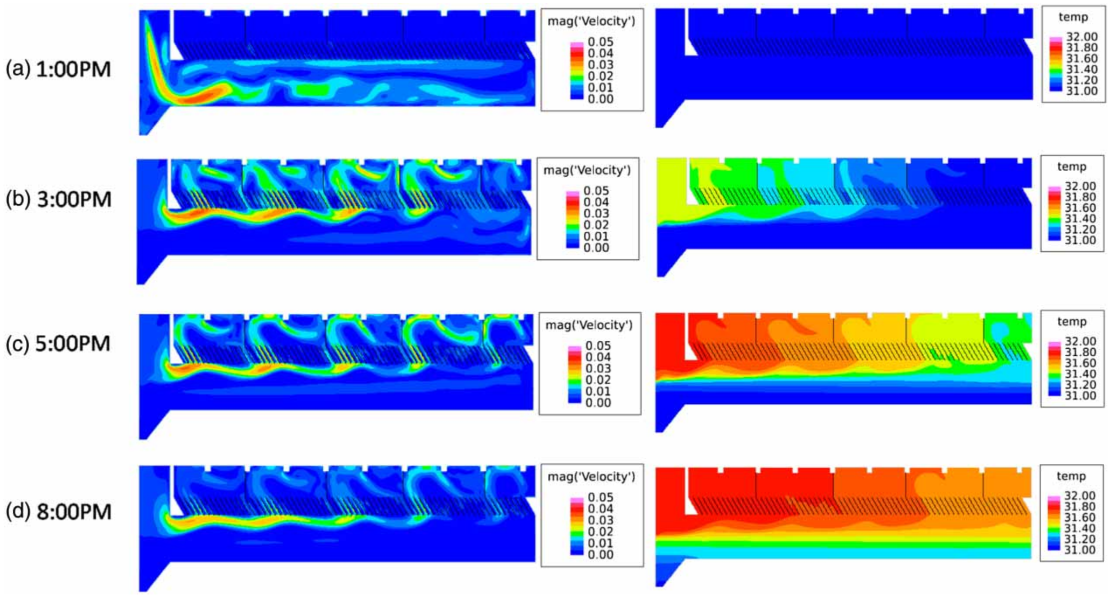

Figure 7 | Calculated velocity and temperature contours in the sedimentation basin using four baffle plates.

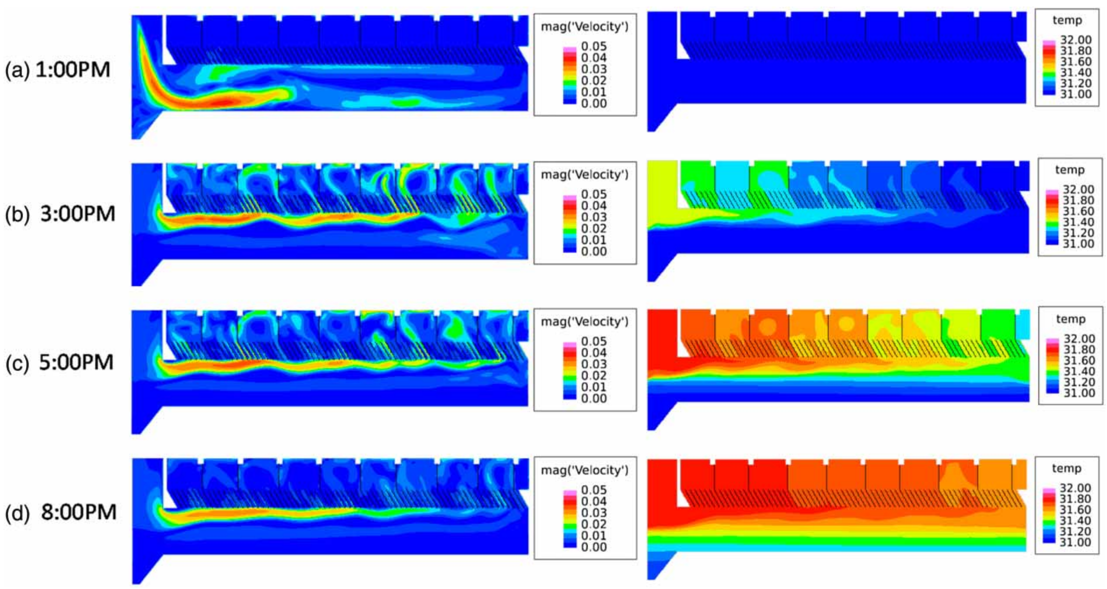

Figure 8 | Calculated transient velocity and temperature contours in the sedimentation basin using eight baffle plates.

assumed a homogeneous fluid without considering the behavior of the coagulated matter. Therefore, it was necessary to verify whether the results were applicable to a commercial treatment facility.

Verification was done at the same drinking water treatment facility mentioned earlier. In this part of the study, four and eight baffle plates were physically installed. Water turbidity without baffle plates was measured for comparison purposes.

Table 1 shows measured turbidities for all cases. The turbidity with baffle plates was much lower than that of the no-baffle condition, thus demonstrating baffle effectiveness. These results indicate that velocity increases are suppressed by baffles and that coagulated matter carried

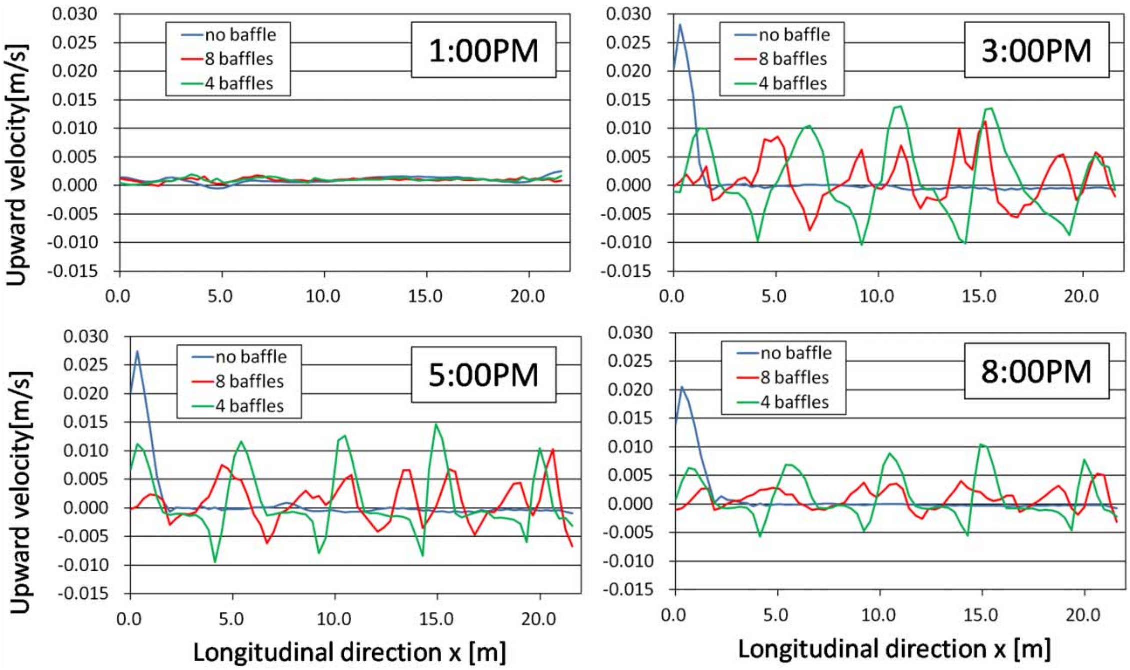

Figure 9 | Calculated average axial velocity distribution [m/s] in the longitudinal direction [m]. Graphs show distributions at 1:00, 3:00, 5:00, and 8:00 PM.

by the treated water is reduced. The results also confirmed that eight baffle plates were more effective in turbidity reduction than four plates.

Table 2 shows measured turbidity over time. Turbidity increased with time, and the rate of increase with no baffles was largest. Although turbidity increased when baffles were added, the magnitude of the increase was small compared with that of the no-baffle condition. This again shows that the installation of baffle plates is effective in enhancing water quality.

Figure 10 shows plots of measured turbidity at each collecting trough at approximately 4:00 PM on different days (for days as shown in Table 1), when the influence of density flow was considered strong. In the case with no baffle plate, turbidity at troughs in the upstream zone was greater than that in the downstream zone. This is attributed to the increased water treatment load in the former zone as a result of the generation of density flow. However, the case with eight baffle plates produced the least turbidity at each trough, and turbidity was less than the target value. Although turbidity in the upstream zone was also greater than that in the downstream zone, turbidity at each trough had a nearly uniform value. This shows that the treatment load was normalized by the effect of the baffle plate. All the above results indicate that the substantial increase in upward velocity, which exceeds the sedimentation velocity

Table 2 | Measured turbidity over time for cases with baffle plates and no baffle plates

	Turbidity [NTU]	
Time	**No baffle**	**8 baffles**
9:00 AM	0.3	0.2
2:00 PM	1.3	0.5
4:00 PM	2.7	0.6

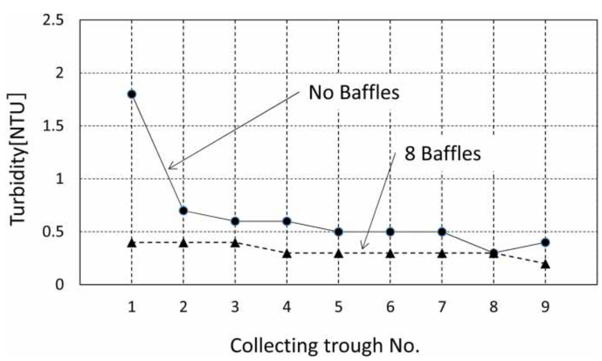

Figure 10 | Measured turbidity at each collecting trough. Circles show the case of no baffle plate, and triangles the case of eight baffle plates.

of coagulated matter, degrades water quality in the no-baffle case. In the case with baffles, the increase in upward velocity is restricted to less than the limiting velocity, thereby maintaining sedimentation capacity.

CONCLUSIONS

The structure of density flow in a sedimentation basin with an inclined plate settler was described by CFD. A method that could be used for the prevention of this flow was investigated. The results are summarized as follows:

(1) A transient density-flow structure in the sedimentation basin, from onset to settlement, was predicted by CFD. Treated water degradation was suggested to be attributable to the overflow of impurities from the collecting trough. This overflow was suggested by an increase in upward velocity caused by temperature differences between the inlet water and the sedimentation basin.
(2) CFD indicates that installation of baffle plates in the clarifier zone is effective in suppressing the upward velocity. A physical investigation of the most effective baffle plate installation and the impact of the baffle plates on water quality was carried out by measuring turbidity at a commercial treatment plant.
(3) The use of CFD is effective not only for predicting transport phenomena but also for designing and improving water treatment facilities. Because such facilities are so large that implementation of physical experiments is difficult, CFD can provide an effective alternative research procedure.

REFERENCES

Adams, E. W. & Rodi, W. 1990 Modelling flow and mixing in sedimentation tanks. *J. Hydraul. Eng.* **116** (7), 895–911.

Camp, T. R. 1946 Sedimentation and design of settling tanks. *ASCE Trans.* **111**, 895–958.

Das, S., Bai, H., Wu, C., Kao, J. H., Barney, B., Kidd, M. & Kuettel, M. 2015 Improving the performance of industrial clarifiers using three-dimensional computational fluid dynamics. *Engineering Applications of Computational Fluid Mechanics* **10** (1), 130–144.

Goula, A. M., Kostoglou, M., Karapantsios, T. D. & Zouboulis, A. I. 2008a A CFD methodology for the design of sedimentation tanks in potable water treatment. *Chem. Eng. J.* **140**, 110–121.

Goula, A. M., Kostoglou, M., Karapantsios, T. D. & Zouboulis, A. I. 2008b The effect of influent temperature variations in a sedimentation tank for potable water treatment – a computational fluid dynamics study. *Water Research* **42**, 3405–3414.

Heydari, M. M. & Bajestan, M. S. 2013 The effect angle of baffle on the performance of settling basin. *World Appl. Sci. J.* **21** (6), 829–837.

Krebs, P., Vischer, D. & Gujer, W. 1995 Inlet-structure design for final clarifiers. *J. Environ. Eng.* **121** (8), 558–564.

Lutfy, M., El-Nahhans, K. & Safwat, M. 2015 Performance optimization of rectangular settling tanks in small water treatment plants by numerical approach. In: *18th International. Water Technology Conference (IWEC18)*, International Water Technology Association, Sharm El Sheikh, Egypt, 12–14 March, pp. 385–396.

Lyn, D. A., Stamou, I. & Rodi, W. 1992 Density currents and shear-induced flocculation in sedimentation tanks. *J. Hydraul. Eng.* **118** (6), 849–867.

Mohanarangam, K. & Stephens, D. W. 2009 CFD modelling of floating and settling phases in settling tanks. In: *7th International Conference on CFD in the Minerals and Process Industries*, CSIRO, Melbourne, Australia, 9–11 December, pp. 1–7.

Razmi, A. M., Bakhtyar, R., Firoozabari, B. & Barry, D. A. 2013 Experiments and numerical modelling of baffle configuration effects on the performance of sedimentation tanks. *Can. J. Civil Eng.* **40** (2), 140–150.

Tarpagkou, R. & Pantokratoras, A. 2014 The influence of lamellar settler in sedimentation tanks for potable water treatment – a computational fluid dynamics study. *Powder Technology* **268**, 139–149.

Tarpagkou, R., Pantokratoras, A. & Papadakis, N. 2013 The influence on the flow field and performance of a sedimentation tank for potable water treatment due to low (winter) and high (summer) temperatures. In: *Proceedings of the 13th International Conference on Environmental Science and Technology (CEST2013)*, Athens, Greece, 5–7 September, paper 75.

Xanthos, S., Ramalingam, K., Beckmann, K., Deur, A. & Fillos, J. 2013 Final settling tank CFD modeling: realizing the potential of waste water treatment modeling. In: *Proceedings of the 13th International Conference of Environmental Science and Technology (CEST2013)*, Athens, Greece, 5–7 September, paper 590.

Zhou, S., McCorquodale, J. A. & Vitasovic, Z. 1992 Influence of density circular clarifiers with baffles. *J. Environ. Eng.* **8** (6), 829–847.

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