Effects of influent temperature variation on floc blanket behavior and effluent water quality

Wasantha Illangasinghe, Jagath Manatunge, Niranjanie Ratnayake and Niranjali Jayasuriya

ABSTRACT

The temperature of the water in clarifier tanks has been shown to have a significant influence on floc blanket stability. The objective of this research was to determine the effects of variations in the influent temperature on a floc blanket using laboratory and field experiments and to assess whether the cohesivity of the blanket expressed as the sludge cohesion coefficient (*SCC*) can be used to interpret the effect of temperature variations. Effluent turbidity exhibited a strong positive correlation with inflow temperature during the increasing temperature phase and a strong negative correlation during the temperature recession phase. An increment of 2 °C in the influent temperature caused the effluent turbidity to increase by 1 NTU. The *SCC* of the blanket exhibited a significant relationship with the influent temperature. The optimum blanket cohesivity (*SCC* of 0.7 mm/sec) was observed at a temperature of 23.2 °C, above which the cohesivity decreased. At higher temperatures, frequent particle collisions owing to high inertial forces cause particle motion with the upward flow and increase the effluent turbidity. No correlation between *SCC* and blanket settling velocity was observed.

Key words | clarifier, cohesivity, effluent turbidity, floc blanket, influent temperature

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HIGHLIGHTS

- Water/wastewater treatment plant operators often observe disturbances in floc. blankets and thinning of upper layers during certain hours of the day when the ambient temperature remains the highest leading to a decrease of suspended solid removal efficiency.
- The objective of this research was to find the effect of influent temperature variations on a floc blanket.
- The experiments showed that the effluent turbidity had a strong positive correlation with inflow temperature during the temperature increasing phase and a strong negative correlation during the temperature recession phase.
- An increment of 2 °C in influent temperature caused the effluent turbidity to increase by 1 NTU.
- At increased temperature, frequent particle collisions due to high inertial forces cause particle motion with the upward flow and increase the effluent turbidity.

INTRODUCTION

The temperature of the water in clarifier tanks varies with changes in ambient meteorological conditions. Water/wastewater treatment plant operators often observe disturbances in floc blankets and thinning of the upper layers at certain times of day with the highest ambient temperature. This decreases the efficiency of

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suspended solid removal, affecting the clarifier's effluent quality.

The temperature has a significant influence on the settling of cohesive sediments (Lau 1994). Surface cooling during winter and inflows of warm water to the tanks during summer are considered to be the dominant factors affecting the overall hydrodynamics in secondary settling tanks (Ekama *et al.* 1997). Head *et al.* (1997) developed a mathematical model to simulate the floc blanket and found that the concentration of the blanket changes in response to variations in throughput, solid loading in the clarifier, and temperature. Head *et al.*'s model predicts that the floc blanket is affected by ambient temperature variations. At low temperatures in winter, the blanket is easily washed out at a given upward velocity, producing treated water with high turbidity. However, at higher temperatures, the same upward velocity can produce good-quality treated water in summer.

Experimental investigations indicated that there is a strong correlation between clarifier stability and temperature gradients. Temperature-induced vertical convective currents were observed in uncovered tanks as a result of surface cooling. A temperature inversion of 1 °C was noted between the surface and bottom of the tank during the winter season, which produced vertical convective currents two orders of magnitude greater than the tank overflow rate and reduced the particle settling rate (Wells & LaLiberte 1998).

Temperature differences between the bulk tank water and the inflow also significantly affect the mixing characteristics and may result in density gradients inside the tank, causing stratification and poor mixing (Mahmood *et al.* 2005). Formation of temperature-driven density currents was observed in activated sludge secondary clarifiers, even with a temperature difference as small as 0.2 °C between the influent and the tank contents. The type of density current, surface or bottom, depends on whether the influent is warmer or cooler than the tank contents. The current formation was found to be independent of the concentration of suspended solids in the influent suspension. The depth of the current was inversely related to the temperature difference (Taebi-Harandy & Schroeder 2000).

Goula *et al.* (2008) used CFD (computational fluid dynamics) modeling adjusted using observations made at a full-scale treatment plant to assess the significance of influent temperature variations and found that a temperature difference of only 1 °C between the influent and bulk tank water was sufficient to induce density currents within the clarifier tank. When the influent temperature was increased, the tank contents exhibited a rising buoyant plume that changed the direction of the main circular current. This process kept the particles in suspension and led to a higher suspended solids concentration in the effluent, thus reducing the total settling efficiency. The temperature difference decreased as the warmer water continued flowing into the tank, and the current started to return to its original position, thus decreasing the suspended solids concentration. When the influent temperature increases with time (positive slope), the effluent turbidity increases. When the influent temperature decreases (negative slope) or is constant, the effluent turbidity remains constant.

The rate of particle destabilization, reduction of destabilized primary particles, and agglomeration varied with mixing intensity and temperature. Decreases in water temperature were found to impair the floc strength and floc formation efficiency, causing reductions in settling efficiency. However, the effect of temperature on floc formation and strength reduces with increased initial turbidity. A prolonged flocculation time at low temperatures breaks the flocs and reduces the settling efficiency (Joudah 2014).

Laboratory jar tests using a suspension of kaolin clay in tap water with three different coagulants at temperatures ranging between 6 and 29 °C showed that floc formation was slower at lower temperatures for all three coagulants. Floc breakage occurs with increases in shear rate. Breakage is greater at higher temperatures, leading to a reduction in floc size and weaker floc. At lower temperatures, floc-break is more reversible (Fitzpatrick *et al.* 2004).

As described above, the outcomes of both the mathematical model and the experimental studies indicate several reasons for the observed changes in the floc blanket with temperature variations. However, how temperature variations influence particle settling in a floc blanket of a water treatment plant that is susceptible to changes in temperature is not yet clearly understood. Therefore, the objective of this study was to determine the effects of influent temperature variations on a floc blanket and the effluent quality, and to assess the use of the sludge cohesion coefficient (*SCC*) for interpreting the temperature variations and behavior of a floc blanket.

The (*SCC*), a parameter established in the Water Treatment Hand Book, Degrémont (2007), is an appropriate indicator for characterizing floc blankets (Illangasinghe *et al.* 2016, 2019). In the present study, laboratory experiments conducted using synthetic sludge were used to establish the changes in blanket height and effluent turbidity with varying influent temperatures. The results of the laboratory experiment were then verified through subsequent field experiments conducted on a Pulsator® with upward flow clarification.

MATERIALS AND METHODS

Laboratory experiments

Experiment 1

Laboratory tests were conducted with a test setup using synthetic sludge samples.

The test apparatus was constructed using two acrylic columns (1,300 mm long with diameters of 100 mm (inner cylinder) and 250 mm (outer cylinder)), mounted on a metal stand of approximately 300 mm in height (Figure 1). A glass tube (10 mm diameter) with a funnel on top was mounted above the two cylinders using a steel frame. An inverted funnel (95 mm diameter) was fixed at the bottom of the glass tube. The lower funnel was held approximately

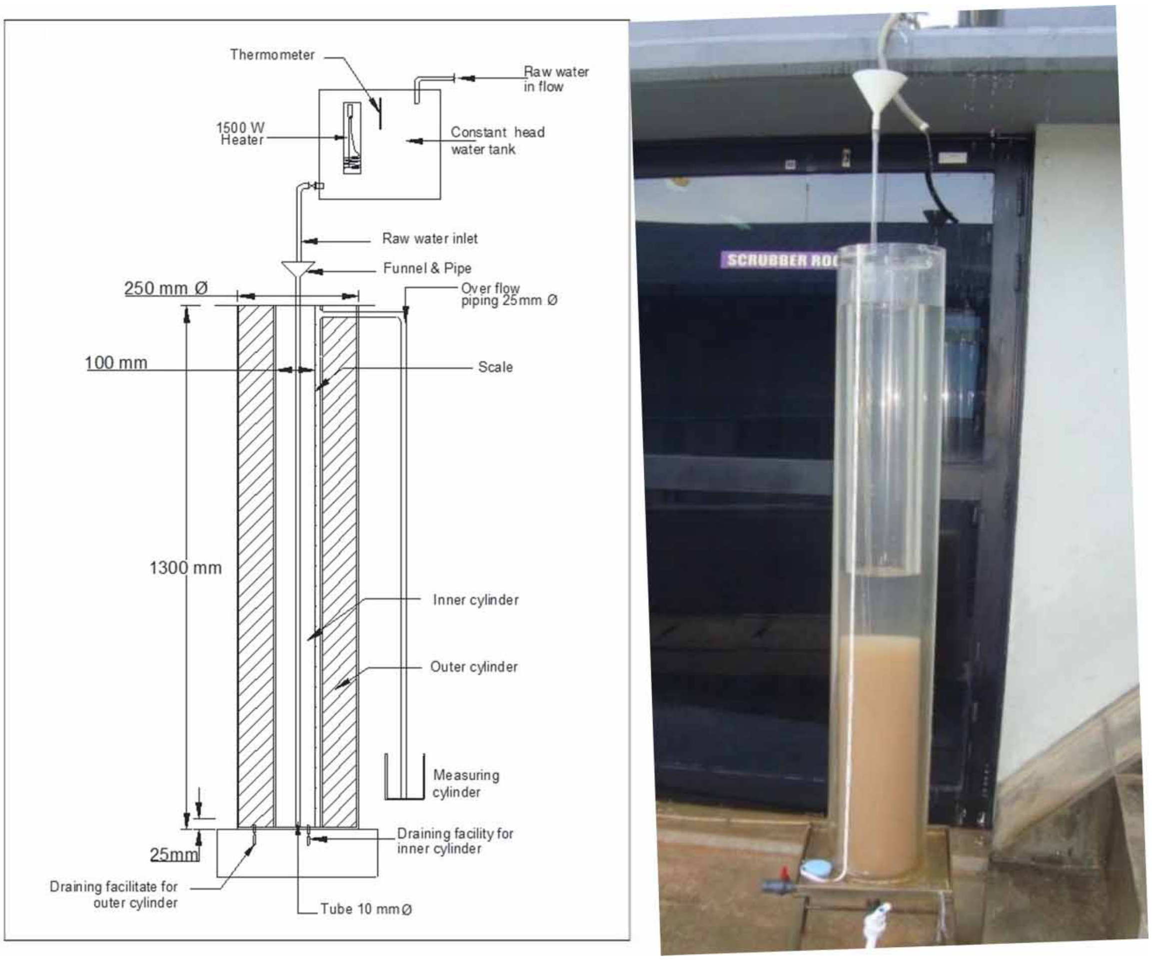

Figure 1 | Schematic diagram (left) and photograph (right) of the test apparatus.

25 mm above the bottom of the inner cylinder. Two taps were fitted at the bottom of the two cylinders to facilitate the draining of the cylinder content. An outlet pipe was fitted at the top of the inner cylinder to collect effluent samples

A stock solution was prepared by adding 10 g of bentonite clay powder to 1 L of tap water. The suspension was stirred well to ensure uniform mixing and then left for 24 h at room temperature to allow complete hydration of the particles. This synthetic turbid stock solution was then diluted with tap water to obtain the desired turbidity level for raw water.

Raw water with a turbidity of 800 NTU and a coagulant (PACl) dose of 90 mg/L was used for the experiments (Illangasinghe *et al.* 2019). Turbidity was measured using a HACH® Model 2100P portable turbidity meter (USA).

The sludge samples were carefully poured into the inner cylinder of the test apparatus, taking care not to break the flocs, and then left for 10 min to establish a sludge blanket. The outer cylinder was filled with clear water to maximize visibility. Water was added to the upper funnel at an inflow velocity of 2.94 mm/sec using a constant head tank. Water leaving the inverted lower funnel flowed upward through the sludge blanket. Variation of the blanket height using a calibrated scale fitted to the cylinder, effluent turbidity, and inflow temperature were recorded with time.

Experiment 2

Having established the blanket behavior with the introduction of a warm upward flow, experiment 2 was conducted to verify the results of experiment 1. The inflow velocity was set to 4.25 mm/sec. The blanket was allowed to stabilize at room temperature, after which the temperature of the inflow was increased from 23 to 44 °C. The temperature variation, blanket behavior, and effluent turbidity were recorded. The temperature of the effluent was also recorded during this experiment.

In both experiments, the inflow temperature was increased to a very high level to clearly capture the variation in blanket height and effluent turbidity.

Field experiments

The Kandy South water treatment plant in Sri Lanka uses upward flow sludge blanket clarification. Two Pulsator® units, each with a capacity of 16,000 m^3/day, operate as the clarifier. Coagulation and flocculation are created within the unit using a vacuum chamber and inflow pipes, which create an expansion mass and form a floc blanket. Three sampling points were chosen at the top, middle, and bottom of the blanket (at 1 m, 2 m, and 2.36 m, respectively, measured from the top of the water level in the tank).

Experiment 1

The quality of the raw water entering the Pulsator® unit, the floc blanket behavior, and the effluent quality were monitored for 7 h from 8.30 a.m. to 3.30 p.m.

Samples were drawn hourly from the three sampling points from 8.30 a.m. to 3.30 p.m. Hourly measurements of raw water quality (temperature, pH, and turbidity), effluent turbidity, and floc blanket height, and temperature were recorded. The sludge volume fraction (*SV*) of each sample was determined by following the procedure described by Illangasinghe *et al.* (2019).

Experiment 2

The second set of tests was conducted to find the floc blanket parameters, average settling velocity, and cohesivity using the settling test and the sludge cohesion test on samples extracted at 2.0 m and 2.36 m depths. The *SCC* of each sludge sample was calculated as described by Illangasinghe *et al.* (2019). As insufficient sludge was available at the top of the blanket (at 1 m depth), no tests were conducted at this depth. In addition, the inflow characteristics, blanket temperature, pH, and effluent turbidity were recorded at hourly intervals.

RESULTS AND DISCUSSION

Laboratory experiments

Figure 2 shows plots of the floc blanket height, inflow temperature, and effluent turbidity obtained in the laboratory experiments versus time.

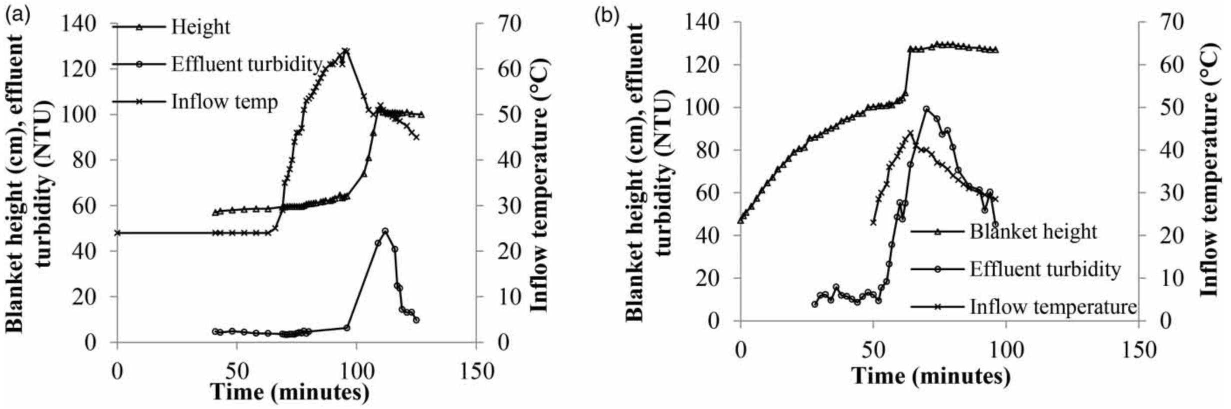

Figure 2 | Floc blanket height, effluent turbidity, and inflow temperature variation with time for experiments 1 (a) and 2 (b).

During experiment 1 (Figure 2(a)), the floc blanket was first established at an average height of 58 cm between 40 and 66 min after introducing the upward flow. After the floc blanket reached a plateau, the inflow temperature was increased. Owing to the temperature difference between the higher-temperature lower layers and the cooler upper layers, a rising buoyant plume was observed in the inner cylinder. After 10 min of inflow of heated water, the blanket started rising. The convective vertical mixing induced by the rising plume caused the blanket to rise gradually. The convective currents kept the particles in suspension, leading to a higher suspended solids concentration in the effluent. These observations were comparable to the observations reported by McCorquodale & Zhou (1992), Wells & LaLiberte (1998), Taebi-Harandy & Schroeder (2000), Mahmood *et al.* (2005), and Goula *et al.* (2008).

As the warmer water continued to enter the cylinder, the temperature differential decreased and the concentration of suspended solids in the effluent decreased. During the temperature decreasing phase, after switching off the heater and allowing the inflow temperature to decrease gradually to ambient temperature, the blanket formed at a higher level in the vessel and the effluent turbidity gradually reduced. The behavior of the blanket during the decreasing temperature phase was comparable to the findings of Goula *et al.* (2008).

Experiment 2 was carried out to verify the above observations (Figure 2(b)). The increase in the blanket height and the rapid increase in the effluent turbidity with increasing inflow temperature were confirmed in this experiment. Complete dispersal of the blanket was observed after 14 min and the blanket height reached the outlet level. No distinct interface between the blanket and clear water could be observed. When the warm water reached the upper layers of the cylinder, the temperature differential decreased and the blanket started to restabilize. A second plateau was observed at a higher level after heating of the inflow water was terminated. The effluent turbidity gradually decreased.

Goula *et al.* (2008) showed the relationship between sedimentation efficiency and the slope of influent temperature plotted versus time. When the influent temperature slope is positive, the density of the inflow water current is lower than the density of the water in the cylinder. Hence, buoyancy drives the water in the cylinder upwards preventing the deposition of particles. On the other hand, when the slope is negative, the temperature difference between the top and bottom layers is lower and the buoyancy effect diminishes, allowing the particles to settle back and reduce the effluent turbidity. This study confirms the above finding.

A detailed analysis of the blanket formation, response to temperature variations, and effluent quality was done using the results from experiment 2. Figure 3 shows the variation of the influent temperature and effluent turbidity with time during the increasing temperature and decreasing temperature phases. Figure 4 shows the variation of effluent turbidity with temperature.

It is noteworthy that the rate of change of effluent turbidity is different during the temperature increasing and

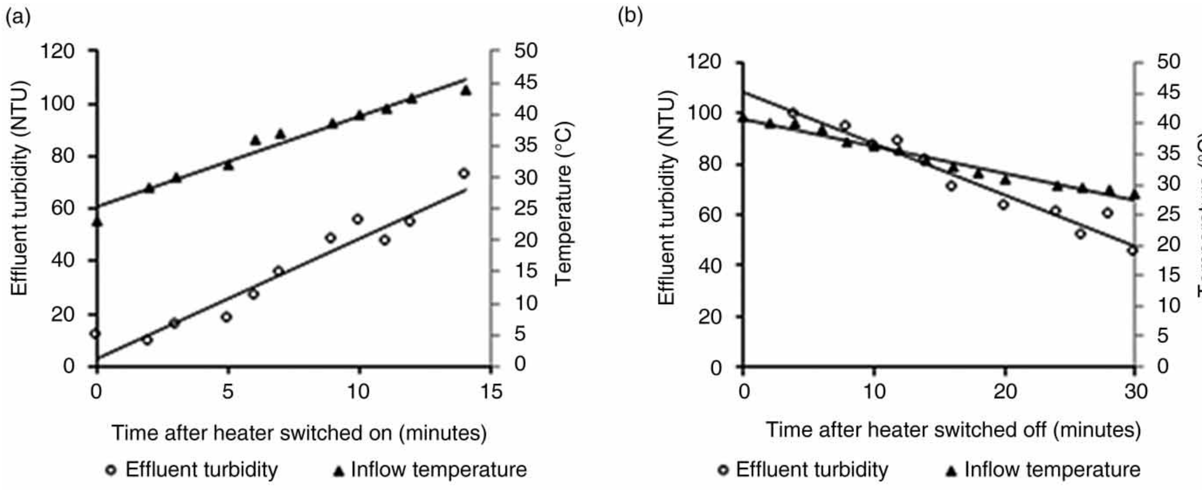

Figure 3 | Variation of influent temperature and turbidity with time: (a) temperature increasing phase and (b) temperature decreasing phase.

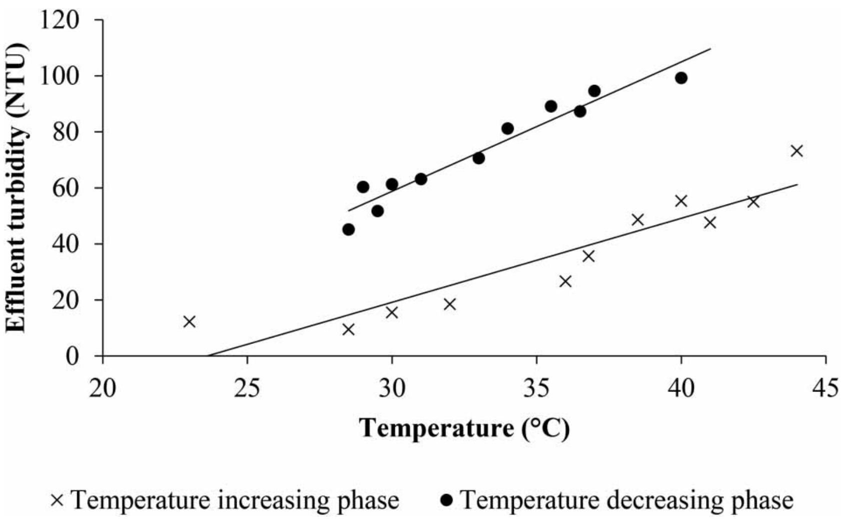

Figure 4 | Variation of effluent turbidity with temperature.

decreasing phases. The temperature variation during the recession phase is higher.

Statistical analysis of the variation of effluent turbidity with temperature shows a strong correlation between the two parameters in the temperature increasing ($R^2 = 0.86$, p-value $= 0.001$) and recession phases ($R^2 =$ of 0.94, p-value < 0.01)

Increasing effluent turbidity is associated with a large positive slope of the influent temperature with time. The rate of decrease in effluent turbidity in the temperature recession phase is 1.6 times higher than the rate of increase in effluent turbidity in the temperature increasing phase.

Field experiments

The results obtained from the field experiments also indicate a significant positive correlation between the temperature of the inflow raw water and the effluent turbidity with an R^2 of

0.7 (p-value <0.01) (Figure 5(a)). The raw water temperature variation during the test period was 2 °C. The effluent turbidity increased by 1 NTU. However, the temperature within the blanket varied by 1 °C. The effluent turbidity increased with the blanket temperature but no significant correlation was found (Figure 5(b)).

The influent turbidity and the composition of the floc blanket measured using the SV fraction did not have a significant impact on the effluent turbidity. To interpret the floc blanket behavior and changes in the blanket settling velocity with temperature variation during experiment 2, the cohesivity and the settling velocity of the Pulsator® floc blanket were calculated with increasing temperature. The variation of the *SCC* with inflow temperature is shown in Figure 6(a).

The optimum blanket cohesivity was observed at a temperature of 23.2 °C and an *SCC* of 0.7 mm/sec, after which the cohesivity decreases with increasing temperature. Particle movement in a suspension is due to hydrodynamic forces counteracted by viscous forces. As reported by Kotlyar *et al.* (1998), particle movement in a liquid–solid suspension occurs as a result of the dissipation of energy by viscous or turbulent conditions. The cohesivity of the blanket increases owing to short-range cohesive forces, resulting in an increase in the *SCC* (Illangasinghe *et al.* 2019). At optimum cohesivity, viscous forces are dominant

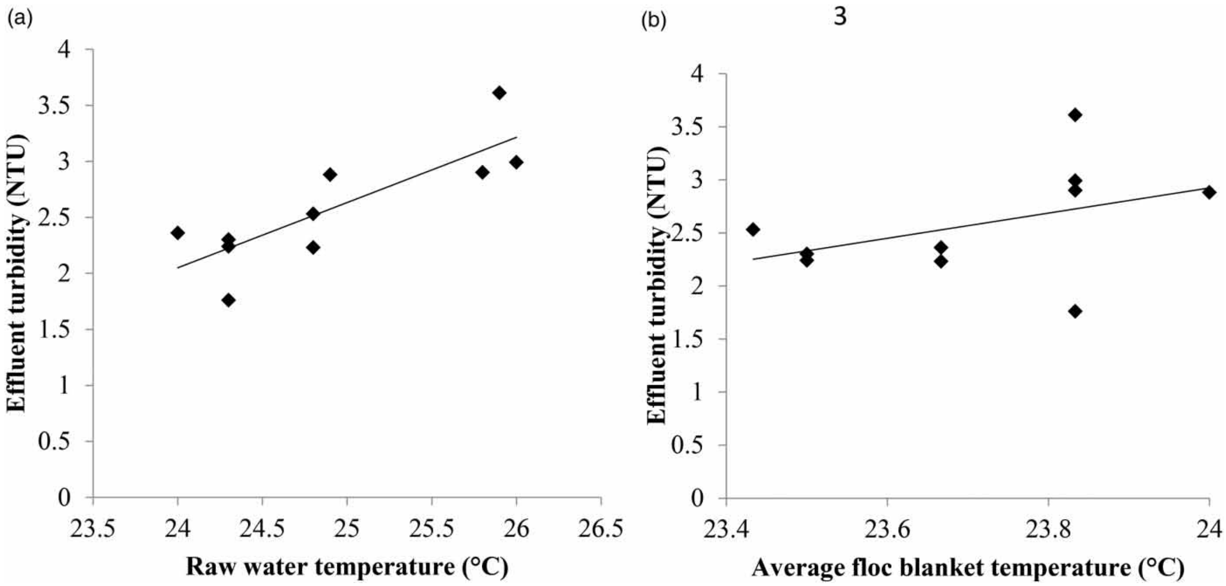

Figure 5 | Variation of effluent turbidity with (a) inflow temperature and (b) blanket temperature.

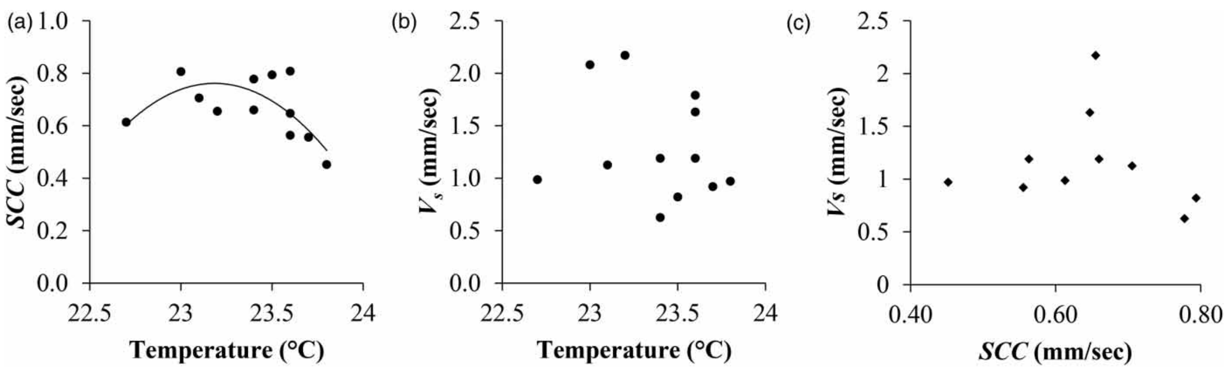

Figure 6 | Variation of (a) cohesivity (*SCC*) and (b) blanket settling velocity (V_s) with temperature and (c) variation of blanket settling velocity (V_s) with cohesivity (*SCC*).

in the blanket, enabling the clustering of particles as a result of particle–particle attractions caused by short-range cohesive forces (Bhatty 1986; Subbarao 2010). Inertial forces increase with increasing temperature. Particles move rapidly and hydrodynamic forces overcome cohesive forces, dislodging the clusters. The turbulent conditions created by larger and faster-settling clusters lead to the destruction and formation of smaller sub-clusters or separate particles and consequently the *SCC* decreases.

The variation of the particle settling velocity with temperature and with *SCC* is shown in Figure 6(b) and 6(c). Our experimental results show a blanket settling velocity range of 0.82 to 2.08 mm/sec. A relationship between influent temperature and V_s could not be established.

The increase in effluent turbidity is thought to be caused by temperature-induced density currents, causing the particles to remain in suspension and thus hindering the settling (McCorquodale & Zhou 1992; Wells & LaLiberte 1998; Taebi-Harandy & Schroeder 2000; Mahmood *et al.* 2005). An alternative explanation is that floc formation, as well as floc breakage, happens in response to changes in the shear rate (Fitzpatrick *et al.* 2004). Particles are considered to be subjected to frequent drafting, kissing, and tumbling (D-K-T) at high Reynolds numbers ($Re > 1$) (Zaidi *et al.* 2015).

The results of this work show that increasing the influent temperature reduces the viscosity and cohesive forces, causing increased disentanglement of particle clusters. Frequent particle collisions, forcing particles to move independently, cause the particles to move with the upward flow and increase the effluent turbidity.

CONCLUSION

The laboratory and field experiments conducted in this study show that there is a strong relationship between influent temperature variation and effluent quality. The results of our laboratory tests showed that settling efficiency improves at a faster rate in the temperature recession phase. Full-scale plant observations revealed that a 2 °C increase in the influent temperature causes the effluent turbidity to increase by 1 NTU.

The *SCC* of the blanket has a significant relationship with the influent temperature. The optimum blanket cohesivity of 0.7 mm/sec was observed at a temperature of 23.2 °C, above which the cohesivity decreases. Increasing the temperature leads to a decrease in the blanket cohesivity, which affects the clustering of floc particles. At higher temperatures, frequent collisions owing to higher inertial forces cause particles to move with the upward flow and increase the effluent turbidity. A correlation could not be established between *SCC* and blanket settling velocity.

Plant operators should thus pay attention to the sensitivity of the blanket to ambient temperature variations. The operational parameters of the different types of clarifier units, such as inflow velocity, pulsation time, and height, should be adjusted according to changes in temperature to obtain the desired effluent quality.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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