Modeling industrial thickener using computational fluid dynamics (CFD), a case study: Tailing thickener in the Sarcheshmeh copper mine

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ABSTRACT

Separation of particles from liquid in the large gravitational tanks is widely used in mining and industrial wastewaters treatment process. Thickener is key unit in the operational processes of hydrometallurgy and is used to separate solid from liquid. In this study, population balance models were combined with computational fluid dynamics (CFD) for modeling the tailing thickener. Parameters such as feed flow rate, flocculant dosage, inlet solid percent and feedwell were investigated. CFD was used to simulate the industrial tailing thickener with settled bed of 120 m diameter which is located in the Sarcheshmeh copper mine. Important factor of drag force that defines the rake torque of rotating paddles on the bed was also determined. Two phases turbulence model of Eulerian/Eulerian in accordance with turbulence model of k-e was used in the steady-state. Also population balance model consists of 15 groups of particle sizes with Luo and Lehr kernel was used for aggregation/breakage kernel. The simulation results showed good agreement with the operational data.

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1. Introduction

Thickener units are key operational processes in hydrometallurgy and are used to separate solids from liquid. Flocculants are often used to form a chain of solid particles and to create a larger aggregate to accelerate sedimentation in the thickener. The inlet slurry in the thickener is divided into two flows of upstream that contain clear water and downstream which is a bottom flow of the pulp with a high concentration. The upstream flow results from fluid gathering in the thickener [1]. Naturally the flow in the feedwell has a critical importance in the performance of the industrial thickener and this is due to the forming the particle aggregate in this area. Fluid flow in the feedwell has turbulence, and turbulent flow has a big impact in the mixing process of the flocculant with feed particles and aggregation process. In fact, the forming larger aggregates that have high density depend on the turbulent flow in the feedwell. In a study by White, the feed flow tangentially entered the feedwell and the modeling was compared with data from the pilot. Results indicated the use of an LDV measurement ability and image evaluation of the flow using the color tracer in the feedwell. Tangential inlet feed to the well without the blades showed that the feed moves with a turning inside into the walls of the feedwell. The single-phase and three-dimensional model was used to evaluate the system. Velocity field was obtained using k-ε or Reynolds turbulent model that would fit well with the experimental results [1]. Peloquin et al. used CFD for the feedwell in the bauxite thickener to show the effect of the particle size, flow rate and diameter of the wells on the flow pattern [2]. Nguyen et al. considered a sustainable two phase model of Eulerian/Eulerian with k-ε turbulent model for the continuous phase. The feedwell design has a great effect on the sediment settlement and the performance of the phase separation. The amount of the feed flow rate has a large impact on the behavior and distribution of the solids in the feedwell. The effect of feed flow rate on the speed, solid percentage and particle size of the feedwell were studied [3]. In the study by Owen, different approaches of how the solvent can be added in a spray, what impact it has on the performance of feedwell and also different conditions of the feeding were studied. The CFD was used to predict different spray rates, flocculant spray direction, and its absorbance in the feedwell. The best direction to inject the feed is upward and toward the wall of feedwell [4]. As the thickeners are the key units for fine particle aggregation in the slurry feed, investigating the effect of various factors on their performance is essential. CFDs model combined with the ability of population balance was used to investigate the process of aggregate growth and breakage or in other words, flocculation kinetics. The CFD–PB thickener model has been developed based on the knowledge of the physical principles and chemical processes that occur within the thickener feedwell. This was obtained using a wide range of
the laboratory and industrial pilot data [3]. On the other hand, a key component in the thickener operation is the motion of concentrated settled particles on the bottom of the thickener toward the outlet flow which is located in the center. The transmission is done by two or four rakes in the most common thickeners and the high-speed thickeners. Each arm of the rake can include a preservative and a number of the blades according to the size and type of activities of a thickener. Although many operational problems are caused by thickerener blades, very little information is available on the design and the performance of blades [5]. Warden et al. presented single-equation mathematical models for the rake blades and blade spins. In the study, sediment transport was investigated in a water treatment thickener and the effect of same rake blades was approximated using mathematical comparisons in a continuous circular flow. Warden et al. presented a mathematical model of the sediment discharge rate as a function of the rake speed, and the parameters of the blade such as angle, length and height. Their studies showed that at the same size of the blade, quick movement of outer blades has a high ability to move particles than the internal ones. If the rakes are designed based on the low power movement of outer blades has a high ability to move particles than the internal ones. If the rakes are designed based on the low power movement of outer blades has a high ability to move particles than the internal ones. If the rakes are designed based on the low power movement of outer blades has a high ability to move particles than the internal ones. If the rakes are designed based on the low power movement of outer blades has a high ability to move particles than the internal ones. If the rakes are designed based on the low power movement of outer blades has a high ability to move particles than the internal ones. If the rakes are designed based on the low power movement of outer blades has a high ability to move particles than the internal ones.

3. Results and discussion

A 120 m diameter thickener with 6 m high and its 9 m diameter feedwell with 1.5 m high were used for the modeling. Feed tube with 0.75 m diameter was used for feeding with density of 1168 kg/m³ and 22.5% as solid percent. The used computing mesh for the industrial thickener is shown in Fig. 1. Also, the particle size distribution in the population balance model for the industrial thickener is given in the Table 1.

Change in the feed flow rate was applied to achieve 40% of solid in the bottom flow of the thickener. Due to importance of the flow rate enhancement, only one lower flow velocity was studied on the plant performance. As a result, a good match was observed between data in the operational flow rate of 612 L/s and data obtained from modeling. Although the validation of models was done using pilot plant thickener data, it was also compared with operational

Fig. 1. Computing mesh for the industrial thickener.
enhancement in the trend of upward movement of the solid particles and destroying the chain of formed aggregates. As a result, water clarity is reduced in the output of the launder. As can be seen in Fig. 3, the input range of the feed flow rate between 600 and 750 L/s is appropriate for the thickener performance. To reach the operational sedimentation height, acting with input feed flow rate of 650 L/s and 22.5% as solid percentage is required.

As can be seen in Fig. 4, with increasing the feed flow rate, turbulence intensity increases, but the turbulence intensity in the industrial scale thickener is very low and has close linear trend with changes of the feed flow rate. At a constant input solid percent, there is almost no possibility for changes in the flow rate. More increasing the feed flow rate causes disorder in the flocculation process and consequently the height of settled bed increases. One way to rise up the flow rate and increase the input capacity is to reduce the concentration of solid in the thickener entry. As last study indicates, a change of the inlet solid percent with a constant flow rate results a change of the output concentration and the height of sediment bed [10]. Reduction of the inlet solid percent as be seen in Fig. 5 reduces the height of sediment bed and the outlet concentration. To achieve the solid percent of respective in the output, separation process could be done better by reducing the inlet solid percent and increasing the inlet flow rate. The flocculation process can be improved by reduction of input solid percent and as a result, the height of sediment bed decreases. In this situation, incoming force to the blades reduces and it will make control easier. Due to decrease in the torque, friction will reduce and the system becomes desirable. So in this case, the large turbulence intensity increases, but the turbulence intensity in the feedwell is one of the most important factors affected the flocculation process in a thickener. Turbulent flow is needed in the system to mix the flocculant with solid particles and particle aggregations. As discussed previously,

As can be seen in Figs. 2 and 3, by increasing the feed flow rate, bottom and launder flow increase [10]. It is essential to mention that excessive increase in the feed flow rate causes an increase in bed level even to the launder output. The level of settled sediment reaches the launder line at the flow rate higher than 1280 L/s which is shown in Fig. 3. Normally, the inlet solid percent of the feed is 22.5%. It is obvious that the amount of input solid increases as the flow rate increases. On the other hand, to achieve 40% of solid as the thickener output, the accumulation of the solid particles in the thickener gets higher and consequently the bed height is elevated. More increasing the bed height is not desirable because the height of sediment reaches to the border of the feedwell and consequently the feedwell lies within the settled bed. Hence, it influences on the flocculation process and causes that larger aggregates cannot be formed. It is not always undesirable to have the feedwell within the settled area in tailing thickener of the Sarcheshmeh copper mine. This phenomenon causes an enhancement in the trend of upward movement of the solid

![Fig. 2. Flow rate of the launder and bottom of the thickener versus the feed flow rate, 22.5% as solid percent.](image1)

![Fig. 3. Height of settled bed versus the feed flow rate, 22.5% as solid percent.](image2)

![Fig. 4. Changes in the turbulence intensity with the feed flow rate in the thickener.](image3)
aggregate formation is extremely weak and studies showed that flocculation can be more effective in turbulent condition. The turbulence intensity for two types of the feedwell is demonstrated in Fig. 8. The results showed that turbulence intensity increases with increasing feed flow rate. Four horizontal cross sections were used to investigate the turbulence in the feedwell. These four cross sections include free level of the feedwell, half and one meter below the surface, and the common border of the thickener with the feedwell (the output of the feedwell). As can be seen, turbulence intensity increases from top to down. The turbulence in the feed entry is greater than the other parts of the feedwell. The values of turbulence intensity at the feed entry are larger in the type 1 than the type 2. The turbulence occurs mostly near the wall in the type 2.

As can be seen in Fig. 9, the turbulence intensity is higher in the second type of the feedwell and the turbulence level is higher at the higher flow rates. The turbulence intensity is greater near the entrance of the feed and the exit of the flow than other areas inside the feedwell. Fig. 8 resulted that turbulence is lower in the free surface than the other parts of the feedwell. However, turbulence is higher in the second type even at the free surface of the feedwell. At common borders of the feedwell with thickener, high turbulence intensity is observed due to the proximity of the flow tube to this area and the outgoing of the substances.

The aggregation process in the feedwell has a significant role in the rapid particles sedimentation inside the thickener. The feedwell design and optimization should be done in a way that the maximum level of mixing of the flocculant and particle is occurred in order to reduce the number of un-flocculated particles. As discussed before, turbulence has a significant impact on the initial aggregates formation. But excessive turbulence in the constant flocculant dosage results re-failure of the particles aggregation. For a constant flocculation dosage (1.47 g/t), the aggregate size increases with increasing the feed flow rate. However, for high feed flow rates, the diameter of the particles aggregate decreases again due to increase of solid percent and high turbulence intensity. The aggregates diameter is formed higher at the entrance of the feedwell due to the high turbulence intensity. The larger aggregate formation occurs near the wall for the second type of feedwell. For further comparison, the average aggregate diameter in the feedwell was calculated for each feed flow rate. The average aggregate diameter increases with increasing the feed flow rate for the first type of the feedwell which is shown in Fig. 10a. However, with excessive increasing the feed flow rate, the breakage of the particles aggregate increases and the average aggregate diameter decreases again due to high turbulence intensity and also rising of the input solid percent. In the second type of the feedwell, by increasing the input feed flow rate, the average aggregate size decreases. But higher than 800 L/s for feed flow rate, the average diameter of aggregate increases again. The maximum diameter of aggregates in the feedwell is shown in Fig. 10b. The larger particle aggregates is formed in the lower values of the feed flow rates for the first type of the feedwell. Meanwhile, enhancement in the input flow rate results forming the larger particle aggregates for the second type of the feedwell. For the flow rate of 612 L/s (the operational flow rate of the tailing thickeners in the Sarcheshmeh copper mine), the average and maximum aggregate diameters are 182.39 and 586.12 μm for the first type of feedwell; while for the second type, the average and maximum aggregate diameters are achieved 105.5 and 326.1 μm, respectively.

A circular shelf with 0.5 m thickness was used inside the feedwell and 15 cm below the feed entrance and its influence on the thickener performance were investigated which is presented in Fig. 11. As can be seen in Fig. 12a, this shelf increases the average size of aggregates. Also the maximum aggregate size was increased in this case. Fig. 12b shows the changes in the maximum aggregate size with feed flow rate in the feedwell. Due to increase of the turbulence intensity and residence time when a shelf is used inside the feedwell, the particle size increases. The Changes in the
turbulence intensity at different feed flow rate are shown in Fig. 12c. The difference in the turbulence intensity and aggregate size in both cases is low at low flow rates. However, the more the flow rate, the more specific the effect of using a shelf becomes and the more the changes will be. The average turbulence intensity and the aggregate diameters are shown in Fig. 13 for the different areas of the first type of feedwell with shelf. As can be seen, changes are close when a shelf is added. This is due to the increased residence time and increased exit time of the feedwell.

3.2. Calculation of imposed forces on rake blades

There are long and short rakes for a tailing thickener. To calculate the forces on each rake blade, the drag force and the viscous force were calculated. The imposed forces on the rakes were
analyzed and investigated for different flows. The imposed forces on each blade are shown in Fig. 14a with their distances from the center of the thickener. The imposed forces on one side of the rake are shown in Fig. 14a. Since the two sides are symmetrical, the forces on the other side are the same. As can be seen, the imposed forces on the blades increase with increasing feed flow rate due to the increased solid sediment bed. The variation of the areas of the blades is the main reason of reduction in the force along the radius of the thickener. In the first seven blades, the area is greatly reduced. Change in the blade area is abrupt in 3 regions. As a result of this, there is a sudden drop in the force curve at three points. The force increases with increasing radius for the same blades. The great force increase in the last blade is the result of the increase in area. Due to the large decrease in the blade areas, the trend of force reduction is high in these blades. Fig. 14b shows the imposed force on the short rake blades.

To investigate the effect of output concentration of the bottom flow on the blade forces, four different concentrations were considered. As can be seen in Fig. 15, the imposed force on the blades was calculated for output concentrations of 40%, 45%, 50% and 55%. With increasing outlet concentration, the sediment bed shows more resistance against the movement and the imposed force on the blades increases. The force change is greater for the first blades due to the proximity to the output, while it is lower for the end blades. The change in the imposed forces on the blades is also greater for the short rake, as shown in Fig. 15b. With increasing
output concentration, more force will be imposed on the blades. The sudden change in the force, as mentioned, is due to a change in the blade area.

3.3. Calculation of torque

The imposed forces on the rake blades of the thickener achieved by CFD are applied to the rakes to calculate the internal forces of the rakes and the torque needed to spin the rakes. For this purpose, first short and long rakes are modeled separately in SAP2000 structural analysis software. Then, the imposed forces on the blades calculated by CFD analysis are allocated to them. Finally, the internal forces and the torque imposed on the thickener are calculated.

The studied thickener has two short and two long rakes. The long rakes are 59 m long and the short ones are 18 m long from the center of the thickener. All four rakes are attached to the center of the thickener. Due to excessive hardness of the shaft compared with the hardness of the rakes, the shaft can be considered as a rigid anchor for the rake. The structural system used to transfer the loads imposed on the rakes to the shaft is the three-dimensional truss system.

Two types of the loads are imposed to the rakes. The first one is the gravitational load which is due to the immersion weight of the rake, and the fluid column above. The next load imposed on the thickener is the load on the blades, which is mainly caused by the viscosity of the slurry down the thickener.

Figs. 14 and 15 show the changes in torque. The torque increases with increasing velocity. The trend of change in torque is too high at high flow rates. As can be seen, the torque highly increases after a flow rate of 750 L/s and the increasing trend will also be in the torque value. This is due to the high concentration of the sediment bed and the increase in the height of settled sedimentation. The torque imposed on the long rake is more than the one for the short rake and the rapid change in the torque is too high.

There is a possibility of rake deformation due to the gravitational force and the force caused by the formation of solid settled on the rake. The study of the rake deformation shows that an initial rise for each rake should be considered in the design and construction to study rake deformation. The results show that the long rake had a 30 cm change in height caused by the gravitational force. The study of the horizontal force imposed on the rake shows that there is a possibility of rake deformation in 20–30 cm range in the horizontal orientation.
4. Conclusions

Changes in the entrance location of the feed have considerable effect on the flocculation process. Excessive increase of the turbulence results in the particle aggregate breakage. Alignment of the feedwell in the sediment bed drastically changes the flocculation process and sedimentation rate improves. The size of aggregates grows to a certain range. With excessive increase of the feed flow rate, the particle aggregates can fail again. Increased loading of the thickener requires a change in the feedwell and injection site. The feedwell of the tailing thickeners has been designed for the low flow rates. A system of two entrances in the feedwell is appropriate for the high flow rates. By using a half meter circular shelf inside the feedwell, the flocculation process and sedimentation rate improves.

Reducing the inlet concentration results increased aggregate growth, rapid sedimentation, and loss of sediment bed height, reduce rake force, reduce fluctuations of the excessive flocculant injection and ease the control of the operational conditions. By increasing the feed flow rate, the force on the blades and the value of the torque increases. The imposed force on the blade increases by increasing radius. The inlet flow rate of the tailing thickener has the ability to increase the loading capacity in different feedwell. The reduction in the torque range of the tailing thickeners is due to factors such as rake friction or low capacity of the engine, while the increase in the flow rate is possible to a certain range. The imposed force on the blades near to the center of the thickeners increases with increasing output concentration. Increased output concentration up to 45%, does not change the amount of torque very much, and the large increase in the torque is obtained after this percent.

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