

Article

# Flash Smelting Settler Design Modifications to Reduce Copper Losses Using Numerical Methods

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**Abstract:** A mathematical modeling approach was used to test different design modifications in a flash smelting settler to reduce the copper losses in slag, which is economically disadvantageous for copper processing using the pyrometallurgical route. The main purpose of this study was to find ways to reduce copper losses in slag by improving the settling and coalescence of copper matte droplets, in particular, the smallest droplet sizes of  $\leq 100 \mu\text{m}$ . These improvements inside the flash smelting (FS) settler were targeted through different settler design modifications. Three different design schemes were tested using the commercial computational fluid dynamics (CFD) software, Ansys Fluent. These settler design modification schemes included the impact of various baffle types, positioning, the height inside the settler, and settler bottom inclinations. Simulations were carried out with and without coalescence and the results were compared with normal settler design. The results revealed that the settling phenomenon and coalescence efficiency were improved significantly with these design modifications. It was concluded that a single baffle design was optimal for reducing copper losses and increasing coalescence efficiency instead of using multiple baffle arrangements. The top-mounted baffle outperformed the bottom-mounted baffle and inclined settler design.

**Keywords:** coalescence; population balance model; CFD; settling; Eulerian-Eulerian approach; baffles; slag/matte separation



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## 1. Introduction

Copper losses in slag are a continuing problem for the copper industry. Major savings are possible by preventing copper entrainment in slag tapping, particularly in an era where industries are moving towards sustainability and using every potential resource to reduce losses, increase productivity, and minimize environmental impact. This includes using different recyclable raw materials along with the main raw material to contribute to waste reduction and curb depletion of primary raw material resources, for example, by using waste electronic and electrical equipment (WEEE) scrap, which is a high grade secondary raw material for the copper flash smelting (FS) process [1].

Copper losses in the FS process consist of two types: entrained or suspended droplets in slag and dissolved copper ( $\text{Cu}^+$ ). During the copper flash smelting process, two types of slags are normally produced in smelters: smelting (SS) and converter slag (CS), with average reported copper losses of 1–2%, and 4–8%, respectively. These slags go to copper recovery processes, resulting in extra investment and operational costs for copper producers. In the literature, minimizing copper losses has been discussed in detail and the three main criteria presented in these studies are as follows: minimizing the amount of flux introduced during the FS process, reducing the losses due to entrained droplets by increasing the settling time, and post-settling copper recovery, either by means of an electric arc furnace or by mineral processing. Normally, entrained copper droplets are recovered either by pyrometallurgical reduction in an electric arc furnace or by mineral processing, which involves slow cooling and solidification followed by crushing, grinding, and froth flotation processes. The dissolved  $\text{Cu}^+$  is recovered by hydrocarbon reduction and matte settling [2–4].

Numerical studies have been conducted regarding copper matte settling and losses in slag and how to minimize these losses [1–3,5–12]. The transient behavior of copper droplets' settling and losses in slag were numerically studied with the presence of the gas phase using coalescence and varying slag viscosity by Schmidt, Montenegro, and Wehinger [9]. The authors explained that lowering the slag viscosity by one-third reduced the copper losses by 37%. Similarly, average copper losses were 0.98% when they included the coalescence phenomenon in their numerical simulations, which were close to matte losses in an industrial scale FS settler [9]. In their work, Cheng et al. revealed that entrained matte droplets in the slag phase are also associated with gas bubbles that cause the matte droplets to remain suspended. When gas bubbles are present in the matte layer, they can carry some small droplets from the matte phase into the slag phase. While doing so, they also disturb the settling through the slag phase [11].

In previous research related to copper matte droplets settling through the slag phase, small droplets have been found to be most unlikely to settle inside the settler, and therefore, end up being suspended in the slag phase [1,5,6]. Xia et al., Khan and Jokilaakso, and Jylhä, Khan, and Jokilaakso studied the settling of various sized copper matte droplets in slag and concluded that small size droplets, especially  $\leq 100 \mu\text{m}$ , require more time for settling and are likely to remain suspended in the slag phase even without gas bubbles. Gas bubbles present in the slag significantly aggravate this suspension phenomenon. Further extension of this work using the discrete element method (DEM) and the population balance model for droplets' coalescence by Jylhä, Khan, and Jokilaakso, 2020 [6], revealed that increasing the size of the matte droplets results in an increasing settling rate.

Similarly, various experimental studies have been conducted to estimate and reduce copper losses in slag [13–15]. Warczok and Riveros estimated that theoretical copper matte loss in an industrial scale electric arc furnace without coalescence is 3.38% [13]. In their work, Rüßen et al. varied the amount of calcined colemanite (CC) compound from 0 to 6% and revealed that copper losses in synthetic slag were reduced from about 0.6% to 1.5% when the reaction time varied from 0.5 to 4 h [14]. Topçu et al. revealed in their research work that adding CC during the flash smelting process can minimize the copper losses in slag. They concluded that a 2% CC compound can reduce the copper losses in CS from 4.45% to 1.2% at a temperature of 1240 °C with 3 h reaction time [15].

The main objectives of this research work were to study how to reduce copper losses during slag tapping, especially concerning the continuous tapping of slag. Khan and Jokilaakso revealed that continuous tapping of slag from the settler results in a slight disturbance of the settling phenomenon. When the slag phase is continuously tapped out of the settler, it forces the incoming slag/matte mixture immediately across to the opposite end of the settler towards the slag outlet and, therefore, copper matte losses are higher than normal [1]. These phenomena were confirmed by Schmidt et al. [9].

However, continuous slag and matte tapping with appropriate tapping rates may be advantageous to the industry. First, it can reduce the level of disturbance to the settling bath inside the settler compared to intermittent tapping at suitable tapping rates. Second, it can reduce phase entrainment, such as slag/process air entrainment. Finally, it does not require continuous external interruptions, which makes the process less labor intensive.

Hence, regarding the industrial advantages of continuous slag tapping, different design modifications of the settler were considered in this study to reduce the copper matte losses during continuous slag tapping. These results would also be useful in the case of the intermittent slag tapping settler setup currently used in the industry.

This study is an extension of previous studies conducted on the FS settler [1,5,6,9] to observe the impact of applying different settler design modifications in the reduction in copper droplet losses, especially for small droplet sizes  $\leq 100 \mu\text{m}$ , which are most at risk of staying suspended in the slag phase and being lost in tapping. Additionally, this work aimed to find ways to make the FS process more sustainable by reducing copper losses and making the settling part of the process continuous, whereby continuous streams of

matte and slag can be extracted through their respective tap holes from the settler without external interruptions.

## 2. Theory

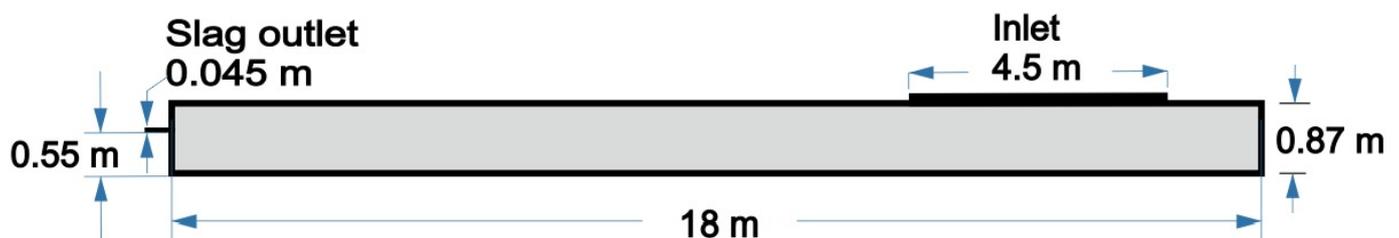
The effect of different baffle arrangements and of the settler bottom inclination angle on matte losses in slag were simulated with commercial CFD software. The boundary conditions and material properties for all the cases were the same. The different cases are presented in Table 1. Only two phases were considered for this study and the settler was initialized with full slag phase for the calculations.

**Table 1.** Design modifications/baffle arrangements.

| Baffle Arrangements/<br>Design Modifications | Baffle Types/<br>Explanation  | Without Baffle   |
|--|---|--|
| Multiple equidistant baffles                 | Bottom-mounted (BMB)<br>5 baffles with 2-m distance from each other; starting position for the first baffle 2 m away from inlet | Top-mounted (TMB)<br>5 baffles with 2-m distance from each other; starting position for the first baffle 2 m away from inlet |
| Single baffle                                | Baffle position 2/4/6/8/10 m away from inlet  | Baffle position 2/4/6/8/10 m away from inlet   |
| Inclined settler                             | Settler bottom inclined to 2.5/5 degrees  | Settler bottom inclined to 2.5/5 degrees   |

## 3. Geometry

Instead of a full-scale 3D FS model, a symmetrical 2D model was used to keep the computing time feasible, as the full-scale model is computationally very expensive. The symmetrical 2D model dimensions are presented in Figure 1.



**Figure 1.** Settler dimensions.

## 4. Numerical Models

A Eulerian-Eulerian model was used for the slag and matte phases. A Eulerian model uses a separate continuity equation for each phase and concerns the interfacial dispersion between phases. The numerical equations/models used in this work to solve slag/matte phases volume fractions and turbulence are similar to those used in our previous work [1]. These models/equations are presented below.

### 4.1. Population Balance Model

Inside the settler, the inhomogeneous indiscreet population balance Model (IIPBM) was used for matte droplet volume fraction classifications and tracking. This model not only accounts for the tracking of the various sized droplets but also assigns a velocity vector for each droplet classification instead of a single velocity vector for all droplets. Therefore, the IIPBM is more suitable for FS settling classifications as different sized droplets settle at

different rates. The equation representing the population balance model (PBE) in a control volume is shown in Equation (1):

$$\frac{\partial f(x, \xi, t)}{\partial x} + \nabla \cdot (V(x, \xi, t)f(x, \xi, t)) = S(x, \xi, t) \quad (1)$$

where  $f$  represents the density function with parameters  $x$ ,  $\xi$ , and  $t$ ;  $x$  represents the physical coordinates, and  $\xi$  represents the internal coordinates of the particle, e.g., diameter. Internal coordinates can be either scalar or vector depending on how many properties of the droplet or particle are included. In this work the diameter of the droplets is the focus, so  $\xi$  is considered to be a scalar. Finally,  $t$  represents time,  $V$  represents velocity, and  $S$  is an external source term.

#### 4.2. Coalescence Model

To account for the coalescence of the droplets, a turbulence model was used as the Luo model [16] overpredicts coalescence and requires coefficient adjustment through sensitivity analysis and validation through experimental data. The collision rate and coalescence rate in the turbulence model are determined by Equations (2) and (3), respectively:

$$a(L_i, L_j) = \zeta T \sqrt{\frac{8\pi}{15}} \dot{\gamma} \frac{(L_i + L_j)^3}{8} \quad (2)$$

$$a(L_i, L_j) = \zeta T 2^{\frac{3}{2}} \sqrt{\pi} \frac{(L_i + L_j)^2}{4} \sqrt{(U_i^2 + U_j^2)} \quad (3)$$

where  $\dot{\gamma}$  is the shear rate of the droplet, and  $\zeta T$  is the capture efficiency coefficient of turbulent collisions.

### 5. Material and Boundary Conditions

Material properties and boundary conditions for all the cases were the same to enable comparison of different baffle arrangements and settler bottom inclinations. The material properties and boundary conditions for all cases are presented in Tables 2 and 3, respectively. These boundary conditions and material properties are taken from [5].

Table 2. Physical properties of matte and slag [5].

| Materials/Phases | Physical Properties       |                  |                      |                            |                         |
|------------------|---------------------------|------------------|----------------------|----------------------------|-------------------------|
|                  | Density kg/m <sup>3</sup> | Viscosity kg/m·s | Specific Heat J/kg·K | Thermal Conductivity W/m·K | Diameter μm             |
|                  |                           |                  |                      |                            | All Cases               |
| Slag             | 3150                      | 0.45             | 1100                 | 6                          | Continuous phase<br>100 |
| Matte            | 5100                      | 0.04             | 850                  | 15                         |                         |

Table 3. Boundary conditions.

| Boundaries  | Temperature °C | Mass Flow Rate kg/s |       | Velocity m/s | Boundary Type   |
|-------------|----------------|---------------------|-------|--------------|-----------------|
|             |                | Slag                | Matte |              |                 |
| Inlet       | 1603           | 5.53                | 8.27  | 0.0007481    | Velocity Inlet  |
| Bottom wall | 1373           |                     |       |              | Wall/Thermal    |
| Side walls  | 1420           |                     |       |              | Wall/Thermal    |
| Slag outlet |                |                     |       |              | Pressure Outlet |

Only 100 μm droplets were introduced at the inlet in all cases as droplets  $\leq 100$  μm are more likely to stay suspended in the slag phase, as concluded in previous studies [1,5,6]. Therefore, it was decided to test the settler design modifications and coalescence effect in extreme conditions.

## 6. Numerical Schemes and Convergence Criteria

The Second order upwind discretization scheme was used to solve the mass, momentum, and Energy conservation equations. To solve the volume fraction HRIC method was used and for the pressure velocity coupling SIMPLE algorithm was used. The convergence criteria was set on the basis that when residuals of  $1 \times 10^{-4}$  for the continuity, volume fraction and velocity were achieved for each time step.

## 7. Results and Discussion

As shown in Table 1, design modifications were divided into three main categories: multiple and single baffle arrangements, and an inclined settler bottom. Additionally, two types of baffles were used for the design, BMB and TMB. The results from each of these categories were compared with the normal FS settler design results in terms of copper matte losses in slag. These design modifications were studied to reduce the copper losses in continuous FS tapping considering the process and construction complexities. Therefore, each category was analyzed regarding that factor, and the priority was to optimize the design with minimum changes and maximum throughput in terms of less copper matte losses via the slag outlet. Initially, the number of baffles, best baffle type, position, and height were defined inside the settler without coalescence of matte droplets, and then these optimized baffle conditions were checked with coalescence. Finally, simulations were conducted by shortening the length of the settler with design modifications to check the effect on copper losses and whether it would be possible to shorten the length with these design modifications. These results with each category are discussed and compared separately, and conclusions and suggestions have been made for the possible design modification of the FS settler.

The volume fraction contours of 100  $\mu\text{m}$  copper matte droplets inside the settler without any design modifications revealed that a channeling flow behavior of copper matte droplets formed at the settler inlet, which was discussed in detail in our previous publications [1,6]. Most of the 100  $\mu\text{m}$  matte droplets introduced inside the settler were suspended in the slag and spread throughout the settler. Next, we discuss the impact of the modifications on increasing the coalescence so that settling can be amplified by larger droplet sizes.

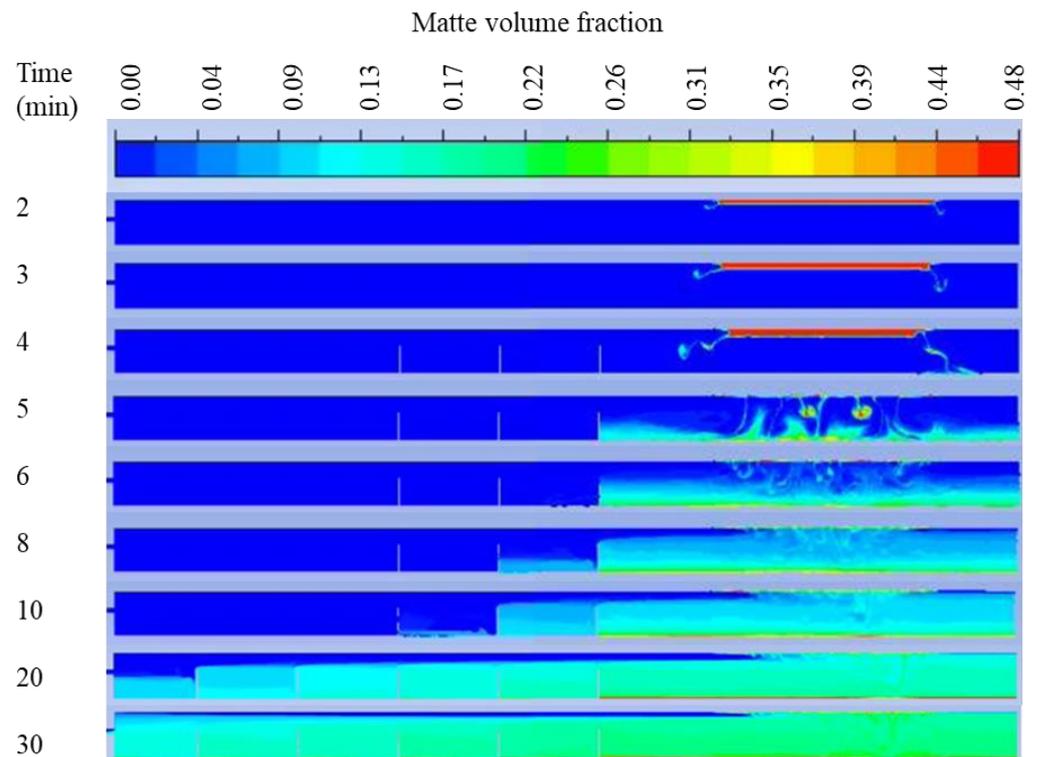
The channeling flow is one of the reasons why the settling rate is higher than that theoretically calculated with the Hadamard–Rybczynski equation. The calculated settling velocity for 100  $\mu\text{m}$  matte droplets through the slag phase is  $3.4 \times 10^{-5}$  m/s and, consequently, the required settling time through the 0.87 m slag layer is approximately 7 h, whereas a typical settling time in an industrial FS settler is 4–5 h [3].

$$W_b = \frac{2}{3} \frac{R^2 g (\rho_b - \rho_o)}{\mu_o} \frac{\mu_o + \mu_b}{2\mu_o + 3\mu_b} \quad (4)$$

where  $W_b$  is the settling rate of the droplet/bubble,  $R$  represents the radius of the droplet,  $g$  represents gravitational acceleration,  $\rho$  is density,  $\mu$  is viscosity,  $o$  represents the fluid medium (in this case slag), and  $b$  represents the droplet/bubble. [17]

### 7.1. Multiple Baffle Arrangements

Five TMB and BMB with an equal distance of 2 m between them were defined inside the settler. The results indicated that bottom-mounted baffles have a clear advantage over top-mounted baffles. The working principles of TMB and BMB can be explained as follows: In the case of TMB, the dispersed droplets follow the diverting flow to the bottom of the settler, which results in enhanced settling. However, BMB, as shown in Figure 2, act as weirs where droplets accumulate before each baffle and hence settle downwards.



**Figure 2.** Volume fraction of copper matte droplets in slag with bottom-mounted baffles.

### 7.2. Equidistant Baffle Arrangement

One of the aims of these two arrangements was to compare them in terms of performance to decrease copper losses in a continuous settler. The results revealed that both types of baffles decreased the copper losses significantly; however, in the case of BMB, the losses were zero at the slag outlet after 10 min of simulation. Therefore, BMB show better performance than TMB. From the flow profiles of the equidistant TMB and BMB, it was also concluded that one baffle should be enough to obtain the same flow profiles for both cases and should have a similar impact on minimizing copper losses. Therefore, for further investigation of the baffle design, the total number of baffles was reduced to one for both top- and bottom-mounted cases.

### 7.3. Single Baffle Arrangements and Optimization in Terms of Baffle Distance from the Inlet

Initially, single TMB and BMB baffles were arranged close to the inlet, slag outlet, and at the center between the inlet and slag outlet to check the effects of different locations inside the settler. For the TMB, a clear increasing trend in copper matte losses was obtained when the baffle was placed further away from the inlet towards the slag outlet. However, in the case of the BMB, when the baffle was placed close to the inlet, copper matte losses were higher than when the baffle was placed close to the outlet, and when placed at the center the losses were zero. Therefore, more simulations were performed to confirm this random phenomenon in which the baffle location was more suitable in the center.

### 7.4. Single Top-Mounted Baffle Arrangement

Figure 3 shows the increasing trend in copper matte losses as the top-mounted baffle is placed further away from the inlet. Visual representation of this phenomenon is given in Figure 4. More dispersed matte phase inside the settler can be observed as the baffle is placed away from the inlet or close to the slag outlet.

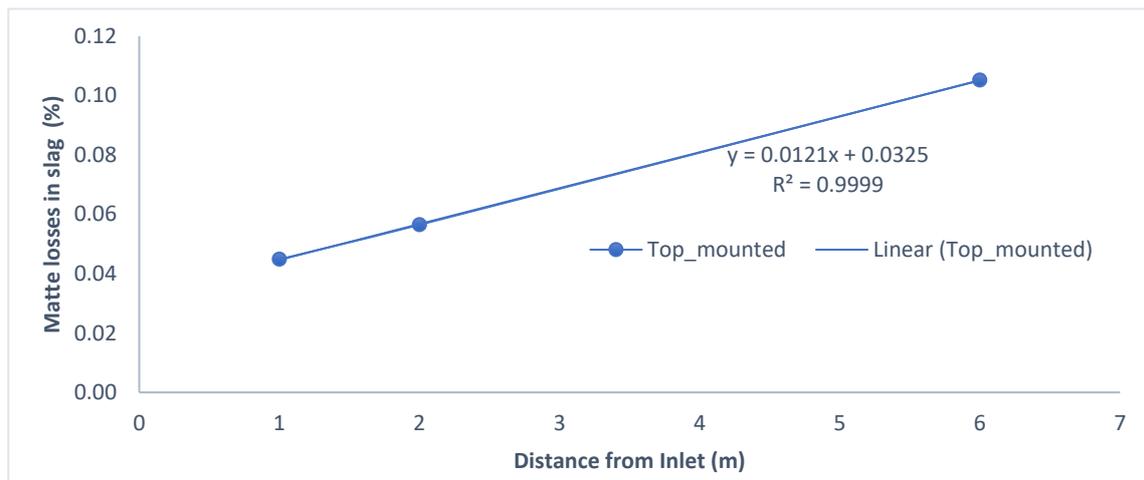


Figure 3. TMB position optimization.

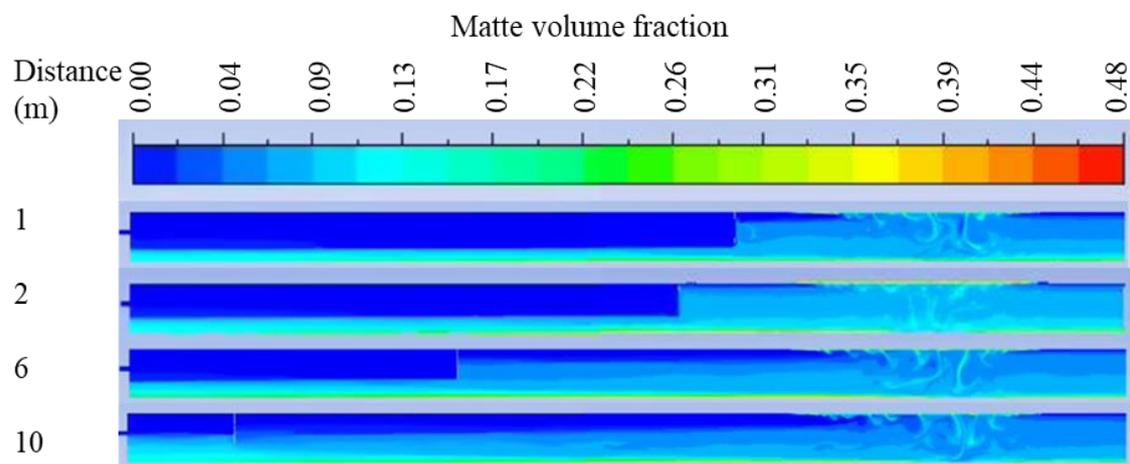


Figure 4. Volume fraction contours for matte phase for top-mounted baffle at different distances.

It can be deduced from Figure 4 that, when the TMB is positioned away from the inlet, the matte droplets or phase are more dispersed in the settler, which confirms that a single TMB is more efficient close to the inlet.

Figure 5 presents the complete flow of the optimized position of TMB at 1 m from the inlet. Compared to the non-baffled settler, there is considerably less dispersed matte phase inside the settler.

#### 7.5. Single Bottom-Mounted Baffle Arrangement

Figure 6 reveals that a single BMB is more effective at the center location between the inlet and the slag outlet. The baffle was placed at different locations inside the settler, starting from 1 m away from the inlet to 10 m from the inlet. Losses are higher when the baffle is positioned close to the inlet and there is a slight increase in losses again when the baffle is close to the slag outlet. The matte volume fraction contours for different BMB positions after 10 min of flow time are presented in Figure 7.

Figure 8 presents the complete pattern of flow for the optimized BMB position at 6 m from the inlet. The number of dispersed phase droplets inside the settler has significantly decreased compared to the non-baffled settler. However, compared to the BMB optimized position in Figure 8 and the non-baffled settler, there is considerably less dispersed matte phase inside the TMB settler in Figure 5. This also indicates that it was necessary in the case of BMB to further optimize the height of the baffle.

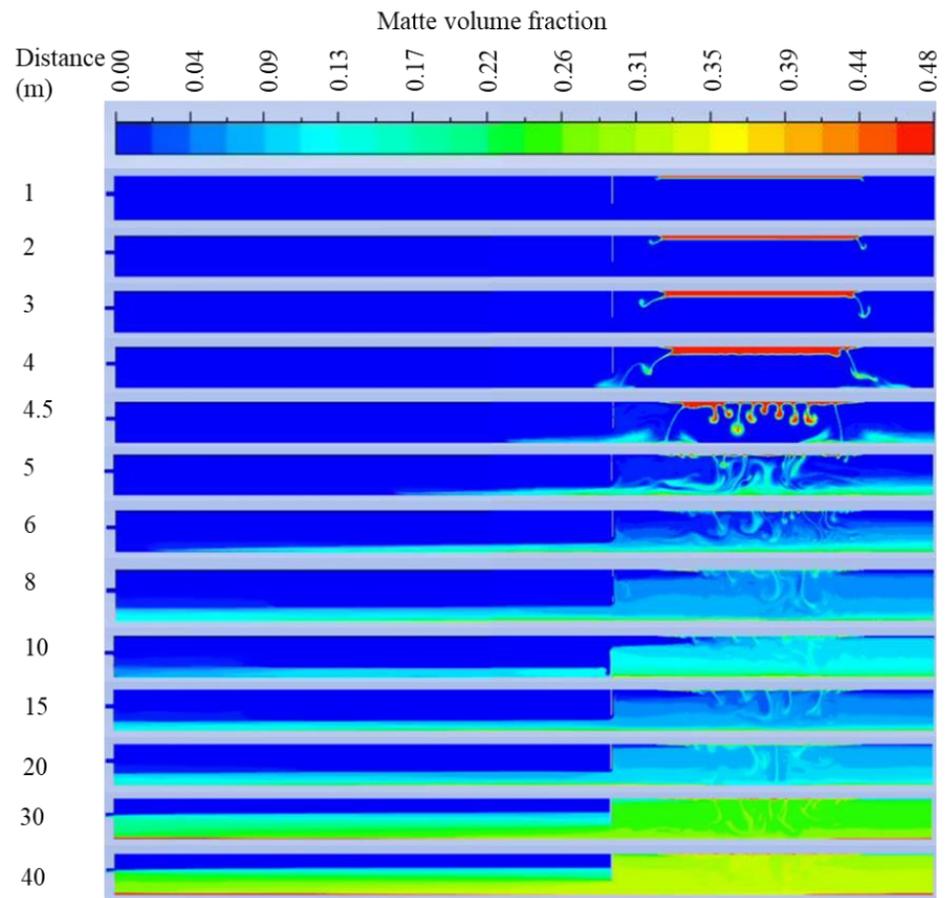


Figure 5. Volume fraction contours for a single TMB 1m from the inlet.

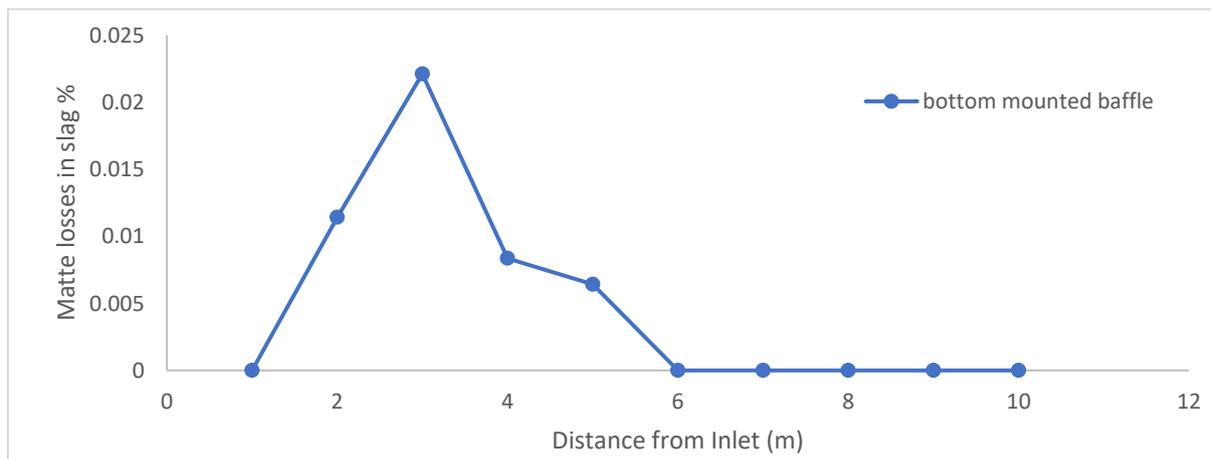


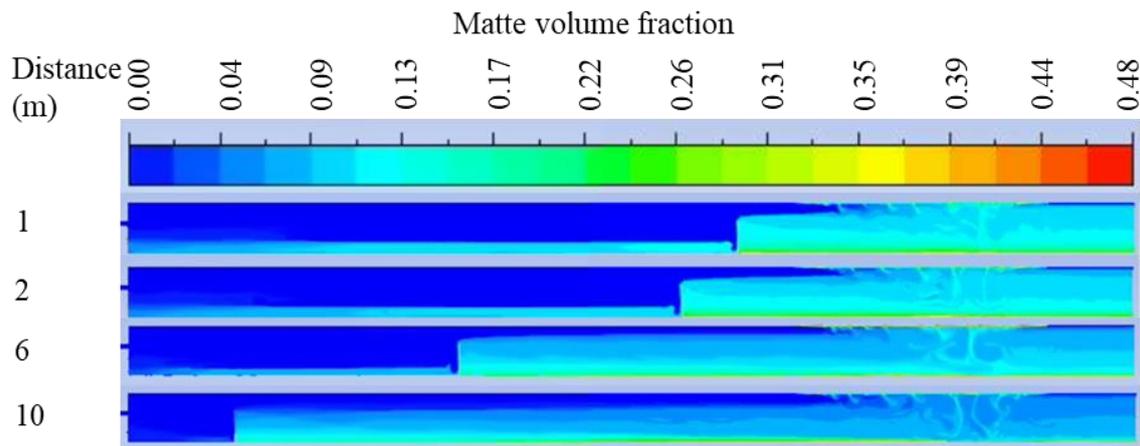
Figure 6. Copper matte losses for a single BMB at different positions inside the settler.

7.6. Comparison of Different Baffle Arrangements in Terms of Matte Losses

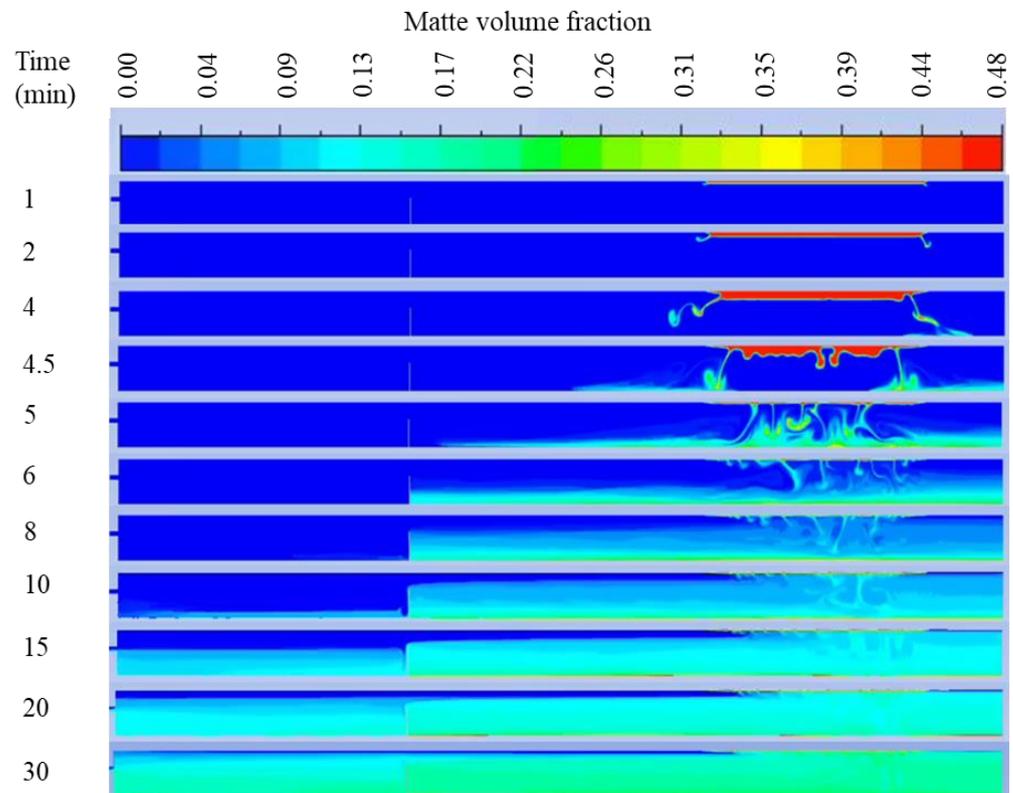
Table 4 shows the comparison of copper matte losses for BMB vs. TMP at different time intervals. These results are also compared with a normal settler without baffles.

For the initial 10 min flow time, both the single TMB and single BMB show a significant reduction in copper matte losses compared to the normal settler. However, after 20 min flow time, the losses with the single BMB increased significantly and were equivalent to those in a normal settler. In contrast, the single TMB still shows a significant decrease in copper matte losses compared to the normal settler. However, the situation was reversed with multiple baffle arrangements where the BMB design performed better, and losses

were almost zero after 20 min of flow time compared to the non-baffled settler and the TMB settler, where the losses were almost equivalent to the non-baffled settler. The height of the baffles for all designs was initially kept constant, at 0.55 m just above the slag outlet level in the case of BMB and below the slag outlet level in the case of TMB. However, these results for a single BMB indicated that the 0.55 m baffle height for a single BMB was not sufficient to reduce the copper matte losses once the droplet volume fraction had increased inside the settler. Additionally, the single 0.55 m TMB showed more promising results than the single 0.55 m BMB. Therefore, further optimization in terms of baffle height was simulated with a BMB. This is shown in Figure 9 in the BMB height optimization, where a significant reduction was achieved with increasing baffle height.



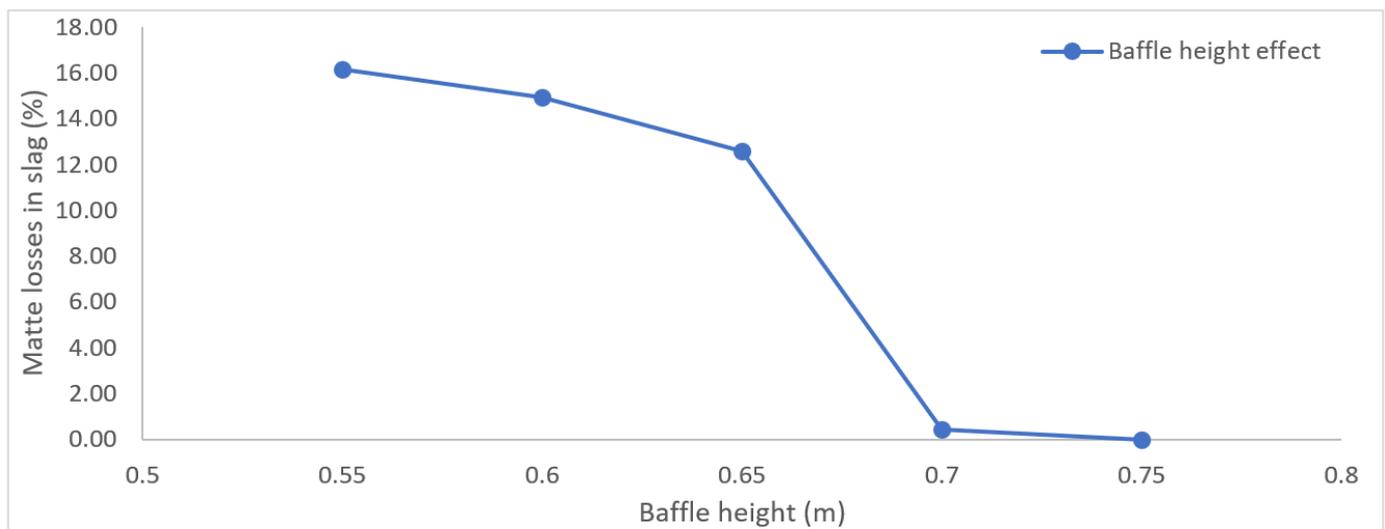
**Figure 7.** Copper matte volume fraction contours for BMB at different locations inside the settler.



**Figure 8.** Volume fraction contours for BMB at 6 m from the inlet.

**Table 4.** Copper matte losses for different baffle types.

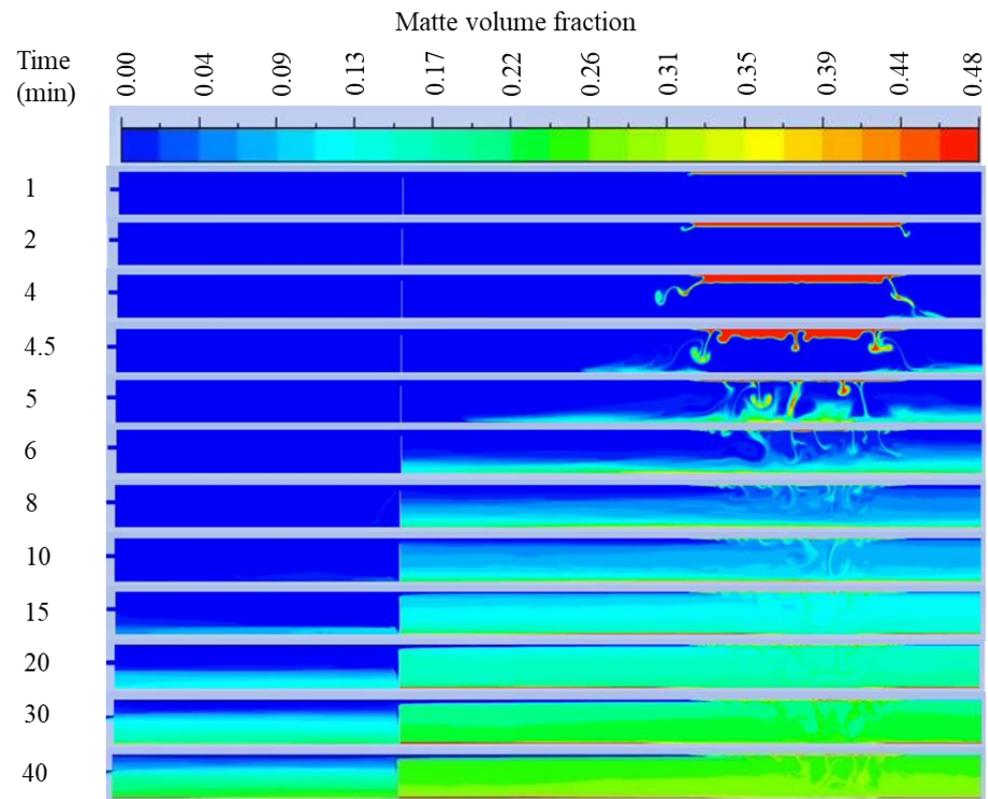
| Baffle Type     | Number of Baffles | Distance from Inlet (m) | Baffle Height (m) | Time (min) | Losses in Slag (%) |
|-----------------|-------------------|-------------------------|-------------------|------------|--------------------|
| Without baffles | 0                 | NA                      | NA                | 10         | 3.773              |
|                 |                   |                         |                   | 20         | 16.030             |
| Top-mounted     | 5 equidistant     | 2                       | 0.55              | 10         | 0.004              |
|                 |                   |                         |                   | 20         | 15.510             |
|                 | 1                 | 1                       | 0.55              | 10         | 0.045              |
|                 |                   |                         |                   | 20         | 1.654              |
| Bottom-mounted  | 5 equidistant     | 2                       | 0.55              | 10         | 0.000              |
|                 |                   |                         |                   | 20         | 0.399              |
|                 | 1                 | 6                       | 0.55              | 10         | 0.000              |
|                 |                   |                         |                   | 20         | 16.160             |

**Figure 9.** BMB height optimization.

### 7.7. Optimization in Terms of Baffle Height

Therefore, to optimize the baffle height, simulations were run for 20 min so that the settler was filled with sufficient copper matte. The results for a single bottom-mounted baffle at different heights in terms of copper matte losses in slag are shown in Figure 9. The copper matte losses in slag decrease with increasing baffle height; they are almost zero near the 0.75 m baffle height.

The contours for the copper matte volume fraction are shown for the normal 0.55 and 0.75 m baffle height in Figures 8 and 10, respectively. The baffle height of 0.75 m significantly reduced the flow of dispersed droplets to the outlet when compared to the baffle height at 0.55 m and without a baffle.



**Figure 10.** Volume fraction contours for copper matte phase for 0.75 m BMB height at 6 m from the inlet.

### 8. Inclined Settler Bottom

The third design modification in this study was the impact of settler bottom inclination on the flow and settling behavior and on reducing the matte losses in slag. These results were compared with the normal settler and with the design modifications of its other counterparts; for example, with TMB and BMB. The inclination started from the bottom right corner of the settler to a point 6 m from the inlet and after that the settler was flat bottomed up to the slag outlet. This design was chosen keeping in mind the best position of the BMB so that the BMB can be placed on the incline, thus enabling the combined effect of BMB and inclination to be analyzed for further studies.

The volume fraction contours presented for the 2.86-degree inclination angle after 20 min of flow time reveals that the inclination had a slight advantage over the flat-bottomed settler. This advantage increased with an increasing angle of inclination. The layer of matte phase in the upper part of the settler became slightly thinner with inclination. This means that less matte phase flowed out of the settler and settling improved slightly.

Although the decrease in matte losses with inclination is obvious, it is much less than with the other designs in this study. In the inclined settler, matte losses were around 12% with a 2.86-degree inclination after 20 min of flow time; however, with a single optimized BMB and TMB, the matte losses were 1.65% and 0.03%, respectively.

In Figure 11, it is evident that the matte phase accumulates towards the right corner of the settler just under the inlet and the settled matte phase layer is thicker in this part of the settler. However, the settling matte phase layer starts to become thinner towards the slag outlet. As the settler bottom is tilted towards the right corner, most of the matte is concentrated in this corner.

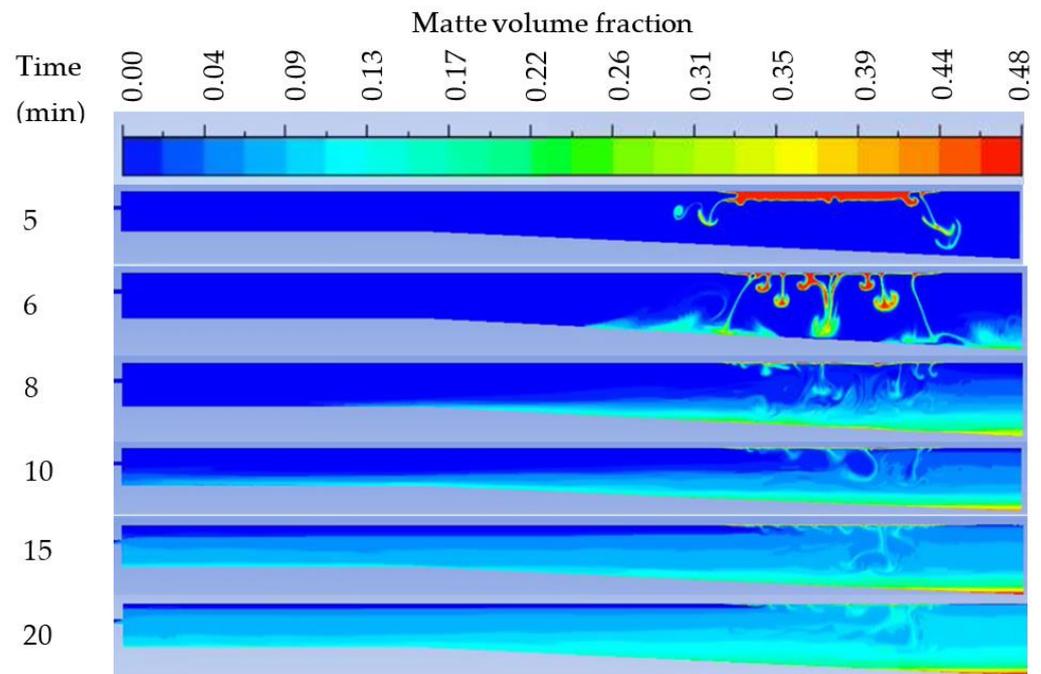


Figure 11. Matte volume fraction contours for 2.86-degree inclination.

### 9. Turbulence Intensity

The turbulence intensity profiles for different design options are presented in Figure 12. For a normal settler, turbulence intensity is higher just underneath the inlet, and close to the slag outlet. This means that the probability of the coalescence of matte droplets is higher in these two areas, as higher turbulence means higher chances of coalescence. This is one of the reasons why the other designs performed better when the coalescence phenomenon was added to the modeling. The 0.55 and 0.75 m BMBs have turbulence intensities higher underneath and close to the inlet, around the area near the baffle, and close to the slag outlet. Thus, turbulence intensity area increased near the inlet and one more area was added around the baffle. Therefore, coalescence efficiency increased in the BMB case compared to the designs without baffles. The TMB baffle at 1 m from the inlet outperformed all these designs because the turbulence intensity area increased significantly from the inlet to approximately the center. Additionally, losses decreased because the coalesced droplets had more time to settle inside the settler as they probably coalesced close to the settler inlet and just before the settler midway point.

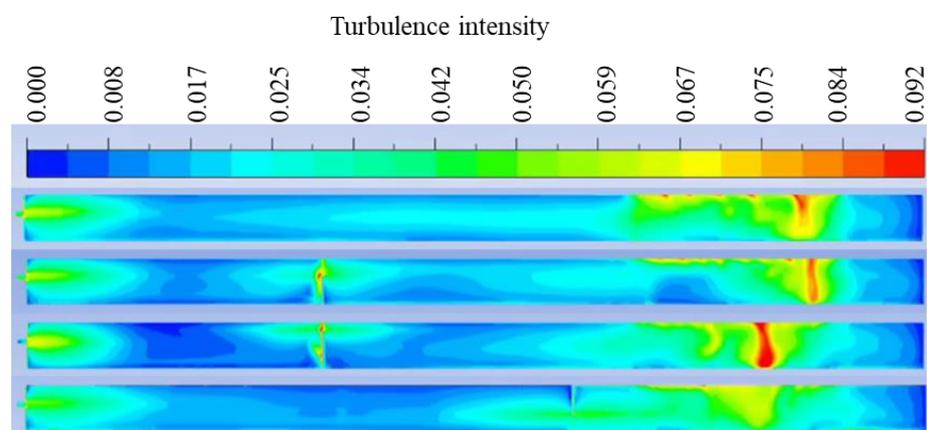


Figure 12. Turbulence intensity profiles for different optimized settler designs.

## 10. Coalescence Modeling

The coalescence phenomenon was added to the optimized BMB, the optimized TMB, and the normal FS settler. For the optimized bottom-mounted baffle, two different baffle heights were used. Of these, the 0.55 m BMB case appears to be the least feasible. Only 100  $\mu\text{m}$  matte droplets were introduced into the settler and, due to computational limitations, droplets inside the settler were only classified into three categories: 100, 300, and 500  $\mu\text{m}$  droplets through the inhomogeneous discrete population balance model (IDPBM). The IDPBM model assigned a different velocity vector for each category, so the settling rate for each category was different. The results were checked for the optimized bottom-mounted baffle location at the center of the settler, and for the baffle heights of 0.55 and 0.75 m. This is shown in Table 5.

**Table 5.** Coalescence results for different designs.

| Results with Coalescence at 30 min |                                |      |      |      |       |
|------------------------------------|--------------------------------|------|------|------|-------|
| Baffle Type                        | Droplet Size ( $\mu\text{m}$ ) | 100  | 300  | 500  | Total |
| 0.55 BMB at center                 | Losses in slag (%)             | 5.56 | 8.75 | 7.21 | 21.52 |
|                                    | Vol. fraction inside settler   | 5.8  | 6.13 | 5.59 | 17.52 |
| 0.75 m BMB at center               | Losses in slag (%)             | 2.66 | 1.72 | 1.27 | 5.64  |
|                                    | Vol. fraction inside settler   | 5.39 | 6.57 | 7.28 | 19.24 |
| 0.55 m TMB 1 m from inlet          | Losses in slag (%)             | 1.88 | 0.68 | 1.75 | 4.31  |
|                                    | Vol. fraction inside settler   | 4.88 | 6.40 | 7.90 | 19.17 |
| Without baffles                    | Losses in slag (%)             | 7.11 | 9.4  | 4.8  | 21.32 |
|                                    | Vol. fraction inside settler   | 5.57 | 5.49 | 5.97 | 17.03 |

The results show that adding the coalescence phenomenon to the numerical simulations reduced the copper matte losses in slag. As in the previous simulations, only 100  $\mu\text{m}$  droplets were introduced into the settler without the coalescence phenomenon. Table 5 also shows that without baffles and with the bottom-mounted baffle at 0.55 m, copper matte losses were almost equal after 30 min of settling time. This again demonstrates that a baffle height of 0.55 m is not very effective in accumulating the matte phase inside the settler and increasing the coalescence phenomenon or droplet coalescence. This was confirmed with the baffle height of 0.75 m, where copper matte losses were less with effective coalescence phenomenon than without the coalescence for the same baffle height, and less than with the normal FS settler. This also demonstrates that increasing the BMB height from 0.55 to 0.75 m also increased the coalescence phenomenon. In conclusion, the BMB height optimization is important for effective matte accumulation and droplet coalescence. However, the optimized 0.55 m TMB at 1m from the inlet performed better than the optimized 0.75 m BMB when coalescence phenomenon was added, as shown in Table 5.

The total copper matte losses in slag with the 0.55 m BMB and 0.75 m BMB, including all the droplet sizes, were higher than the total matte losses with the 0.55 m TMB. In addition, the total matte losses for the settler without baffles (WB) were slightly less than those with the 0.55 m BMB and higher than those with the 0.75 m BMB. Therefore, in terms of matte losses, the designs were rated as follows: 0.75 m BMB > 0.55 m TMB > WB > 0.55 m BMB. Further, to compare coalescence efficiency for each baffle type, the volume percentages of each droplet size inside the settler were calculated. These volume percentage calculations show that the volume percentages for the matte phase were lower in the case of a settler without baffles and the 0.55 m BMB. Both TMB and 0.75 m BMB showed higher volume percentages of matte phase present. Additionally, in the case of the 0.75 m BMB and 0.55 m TMB, there were higher volume percentages of large size droplets; for example, 300 and 500  $\mu\text{m}$ . Nonetheless, the volume % for 300 and 500  $\mu\text{m}$  droplets was lower in the cases of the 0.55 m BMB and WB, respectively. Therefore, in terms of design for coalescence efficiency, the rates were as follows: 0.55 m TMB > 0.75 m BMB > 0.55 m BMB > WB.

## 11. Conclusions

Electrification of transport and utilization of renewable energy, such as wind power, will strongly increase the demand for metals. Therefore, all metals' production processes should target an increasingly higher yield, which would also be good from a sustainability point of view. In this study, we investigated different options for reducing copper losses to slag in the flash smelting process. Using the commercial CFD software, Ansys Fluent, different geometrical modifications for the FS settler were simulated to analyze the copper matte droplet settling rate.

The results of this study indicate that a continuous settling process can be possible with a careful design modification of the settler; for example, with different baffle arrangements or a settler with an inclined bottom. Both the height of the baffles and angle of inclination showed a positive impact on reducing copper losses. The results also indicated that both types of baffle have their advantages and disadvantages; the bottom-mounted baffle was more suitable in most cases due to the construction complexity of the top-mounted baffles. Further, bottom-mounted baffles are more suitable for industrial purposes. As a future research topic, tapping flow rates should also be considered and studied for further options for minimizing copper losses.

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