INCREASING REFRACTORY LIFE IN A PIERCE-SMITH CONVERTER THROUGH NUMERICAL SIMULATIONS

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ABSTRACT

The converter, in copper metallurgy, is a reactor where molten sulfides (matte) are oxidized in order to obtain blister copper (99% Cu). The Pierce-Smith converter is the most common vessel for this process and its refractory wear and converting efficiency are strongly influenced by the flow pattern of the matte and the blown air. In this work, numerical simulations were performed to study the dynamics of gas injection under different tuyere line configurations. The influence of design variables such as the size, number and position of tuyeres was evaluated regarding the amount of bubble overlapping between tuyeres, blown air penetration, contact region between the air and matte and turbulence. By comparison of these parameters, it was possible to optimize the tuyere line design towards reduced refractory consumption and increased converting efficiency of the equipment.

INTRODUCTION

Converting of matte into blister copper is a crucial step in copper pyrometallurgy and refractory performance is very often a limiting factor in the converter campaign. Among the different converter design possibilities, the most common is the Pierce-Smith Converter, which consists of a refractory-lined horizontal cylinder with a bank of tuyeres where the oxygen is blown. Fig. 1 shows a schematic of a Pierce-Smith Converter, showing the molten bath and the tuyere line.

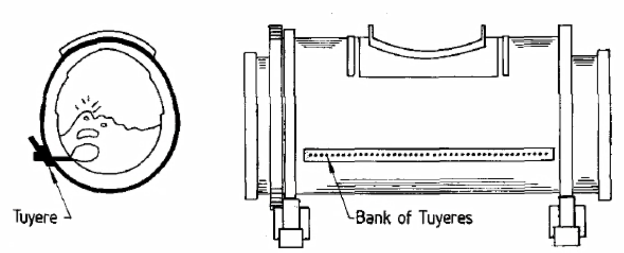

Fig. 1: Schematic of a Pierce-Smith Converter.[1]

The working environment for the refractories in a copper converter is harsh. The lining's performance is often limited by local wear at the tuyere line. This region is critical because it is subjected not only to chemical attack but also to physical wear mechanisms, such as mechanical erosion, local heating due to the exothermal reaction inside it and refractory detachments caused by the punching practice.

From the listed wear mechanisms, it is possible to conclude that there is a close correlation between the fluid dynamics of air blowing and the tuyere refractory life. Therefore, a CFD (Computational Fluid Dynamics) analysis is a valuable tool to find alternatives to increase refractory performance for this equipment.

This work aims to increase refractory performance in a Pierce-Smith Converter by optimizing its tuyere line design, through fluid dynamic numerical simulations. The studied variables are the tuyere diameter and position, and also the number of active tuyeres. First, a review of the main wear mechanisms at the tuyere line was made. Then, the numerical model configuration and results were discussed and an alternative to increase refractory performance was proposed.

REFRACTORY WEAR MECHANISMS AT THE TUYERE LINE

HOEFELE and BRIMACOMBE[2] correlated the problem of tuyere line refractory wear to the rearward penetration of the blown oxygen. Due to its density being much smaller than the matte's, the gas bubbles would rise almost immediately after entering the molten bath. By ascending too close to the back wall, these bubbles would contribute to an accelerated wear rate due to a pumping action on the lining and local heating caused by the exothermal oxidation reaction. Therefore, to reduce wear rate at the tuyeres, one should avoid the gas to flow too close to the back wall.

In their work, an empirical correlation was developed through water modeling experiments to predict the submerged gas penetration distance in a liquid medium. Equation 1 shows the calculation of the modified Froude Number, which is then used to calculate the dimensionless gas penetration in Equation 2:

$$Fr_m = \frac{\rho_g u_0^2}{g(\rho_l - \rho_g)d_0} \quad (1)$$

$$l/d_0 = 10.7\left(Fr_m\right)^{0.46}\left(\frac{\rho_g}{\rho_l}\right)^{0.35} \quad (2)$$

u_0 – Bulk velocity of gas [cm/s]
g – Constant of gravitational acceleration [cm/s²]
d_0 – Gas injection tube diameter [cm]
ρ_g – Gas density [g/cm^3]
ρ_l – Liquid density [g/cm^3]
l – Gas penetration distance [cm]

Another studied cause of premature wear was the build-up of accretions at the tuyere mouth, caused by the back washing of the bath against the tuyere between successive bubbles detachment. These accretions would end up blocking the gas flow, leading to the necessity of periodic punching at the tuyeres to clean the channel, which also contributes to reduce refractory life.

Two flow regimes of gas injection were also studied: bubbling and jetting. Under lower injection pressures, a bubbling regime would predominate, causing the matte to periodically get in direct contact with the tuyeres, during the interval between successive bubbles. On the other side, at higher injection pressures, a steadier jetting flow regime was found to occur, reducing contact between the matte and the tuyere tip and consequently the build-up of accretions and punching frequency. Therefore, it was concluded that by having a steadier jetting regime instead of bubbling, one could increase refractory performance.

BRIMACOMBE et al[3] performed plant trials to compare high and low injection pressure practices. The results of this trial were not conclusive, but one potential advantage of adopting

higher injection pressure was shown: by reducing the number of open tuyeres, one could have more flexibility in its positioning, leading to operational advantages such as not having open tuyeres right below the converter mouth, were there is a higher risk of material ejection.
Another cause of premature wear at the tuyere line of copper converters was studied by NILMANI and DAS[1]. At their work, they analyzed the phenomenon of bubble overlapping in multipoint injection systems, which had been reported to be one of the causes of the uniformity of wear that is usually seen at the tuyere line. They concluded that interaction between adjacent tuyeres led to the formation of huge gas pockets, causing inefficient contact area between the oxygen and the bath, uneven distribution of gas and splashing. To minimize this, smaller diameter tuyeres and higher injection pressures should be used.

MATHEMATICAL MODEL DESCRIPTION

In order to analyze the bath behavior under different tuyere line configurations and find which design would provide the best conditions for a high refractory performance, a CFD analysis was performed. It consists in numerically solving the Navier-Stokes fluid motion equations, along with additional variables to account for turbulence and different fluid phase transport.
The domain geometry is discretized into millions of volumes, where the fundamental fluid motion equations are solved and combined through a numerical technique known as the Finite Volume Method. Fig. 2 shows the discretized mesh for the simulation domain. The critical areas for the model were the matte surface and the tuyere mouth region, consequently a higher number of volumes were generated for these regions.

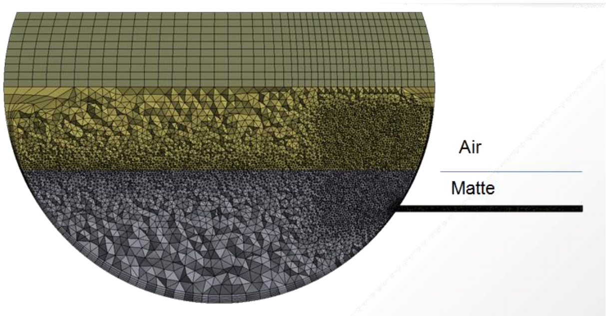

Fig. 2: Mathematical Model Mesh

To simplify the calculations, the system was considered to be composed of air and matte. The flow was considered to be isothermal and incompressible.
The turbulent behavior was modeled by using the standard k-epsilon model. This approach consists in decomposing the turbulent flow velocity into time-averaged and fluctuating components. The conservation and momentum equations are solved for the time-averaged component while the fluctuating component is taken into account through an additional transport variable, the turbulent kinetic energy. Production and destruction of turbulence are accounted for by another variable, denominated turbulent eddy dissipation. These two variables are then computed to calculate the eddy viscosity of the flow, which accounts for the transport of flow properties through turbulent diffusion, which is many times higher than molecular diffusion under high Reynolds number.
The multiphase behavior was modeled through a free surface inhomogeneous model. In this model, the composition of each phase in each cell is given by an additional transport variable, denominated volume fraction. The matte volume fraction is 1 at the cells where there is only matte, 0 at the cells where there is only air and between 0 and 1 at cells where both are present. The cells which contain both phases are located in the bath surface or in the blowing region. The former show a separated flow behavior while the latter show dispersed flow behavior, as the bubbles can be smaller than the grid resolution. An averaging procedure is performed to evaluate the volume fraction in the cells at the dispersed flow region, however the interface structure is not available after this calculation. Consequently, the mathematical model is not suitable to predict transition from bubbling and jetting regimes, as the averaging procedure in the blowing region will always give a smooth continuous result for the volume fraction.
Despite the assumptions, the model is able to give many useful results which are strongly correlated to the refractory performance, such as: interaction between adjacent tuyeres, average oxygen penetration and turbulence in the tuyere region. It is also able to evaluate the converter performance, as it calculates the contact regions between the blown oxygen and the matte, which should be the highest as possible for efficient operation.
Four different tuyere arrangements were studied, as shown in Fig. 3.

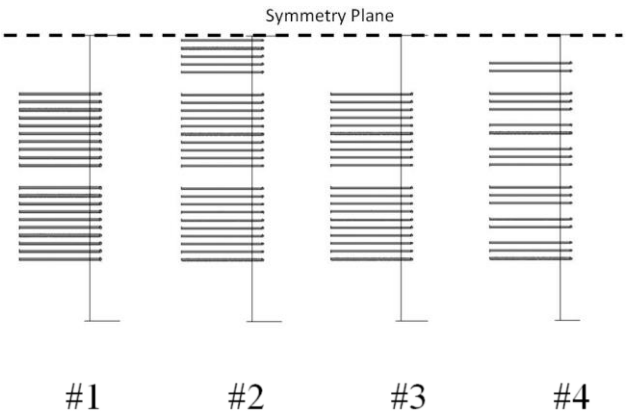

Fig. 3: Different Tuyere Configurations Studied.

The base geometry of the Converter has five blocks of ten tuyeres each, giving a total of 50 tuyeres. The first studied case has the central block closed, due to it being located just below the converter mouth, and 4 blocks of open tuyeres, each having a diameter of 63.5 millimeters. The second case has all five blocks active, with each tuyere having 50.8 mm diameter. For the third, the setup is the same as #1 but with smaller diameter tuyeres. Finally, configuration #4 has the fourth and eighth tuyere of each block closed, and the six middle tuyeres of the central block inactive as well. Table 1 lists the number and diameter of the tuyeres for each configuration.

Table 1: Tuyere line parameters for the Study.

Configuration ID	**Number of Active Tuyeres**	**Tuyere Diamenter (mm)**
#1	40	63.5
#2	50	50.8
#3	40	50.8
#4	36	50.8

The total oxygen flow rate was kept the same for all configurations. Therefore, the configurations with fewer and smaller tuyeres had the highest gas injection velocity per tuyere. The exact value of the gas flow rate is proprietary data and will not be disclosed in this paper. The considered matte and air properties are listed in Table 2:

Table 2: Matte and Air Properties.

Material Property	Value
Matte Density	5250 kg/m^3
Matte Viscosity	0.01 Pa.s
Air Density	1.185 kg/m^3
Air Viscosity	7.45×10^{-5} Pa.s

RESULTS DISCUSSION

Injection Pressure

As the inlet boundary condition is defined by the total gas flow rate, the mathematical model calculates the necessary pressure at the inlet to overcome the head losses in the domain. Table 3 shows the dimensionless pressure results at the inlet for the simulated configurations:

Table 3: Dimensionless Pressure Results at the Inlet.

Configuration ID	Static Pressure	Total Pressure
#1	1.00	1.00
#2	0.96	1.15
#3	1.11	1.40
#4	1.40	1.80

The results show that by decreasing the number of active tuyeres and their diameter, the injection pressure will increase. This has many benefits regarding refractory performance and converter operation, however it is necessary to make sure the blowing equipment is able to deliver the necessary power for the higher pressure configurations.

Blown Air Penetration

One of the results of great interest for refractory performance is the penetration of the blown air in the matte. As it has been pointed by previous researchers[2], this parameter is strongly correlated to refractory wear at the tuyere line.
Equations 1 and 2 can be used for an empirical estimation of the gas penetration in the matte. These results can be compared to the numerical simulation results for validation purposes. Table 4 shows the normalized results for the gas penetration, obtained by dividing each value by the penetration result for #1:

Table 4: Normalized Penetration Results.

Configuration ID	Normalized Penetration
#1	1.00
#2	1.10
#3	1.34
#4	1.53

Fig. 4 shows the simulation results for the oxygen penetration. The black line is the penetration value obtained through Equations 1 and 2. The results show good qualitative agreement between the empirical correlation and the numerical simulation. It is also shown that the configuration #4, which has fewer active tuyeres and with smaller diameters, has the deeper penetration of oxygen in the matte, being 53% higher than in configuration #1, suggesting reduced refractory wear at the tuyere line.

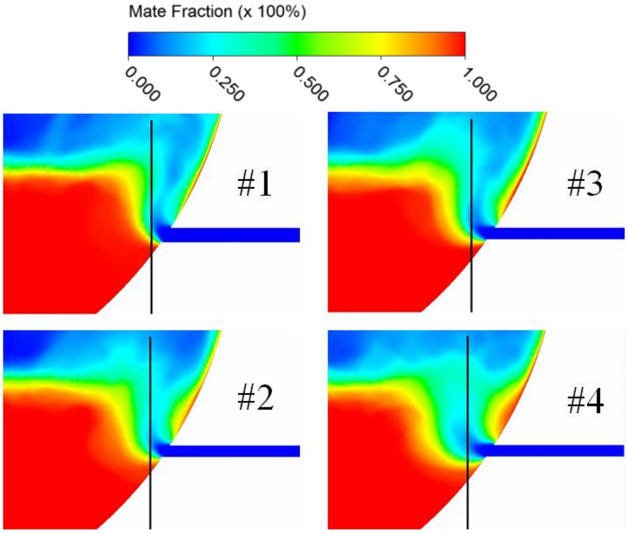

Fig. 4: Oxygen Penetration Results.

Interaction Between Adjacent Tuyeres

Another important result obtained through the mathematical model is the amount of interaction between adjacent tuyeres. Fig. 5 shows the top view of the gas distribution at the tuyeres plane:

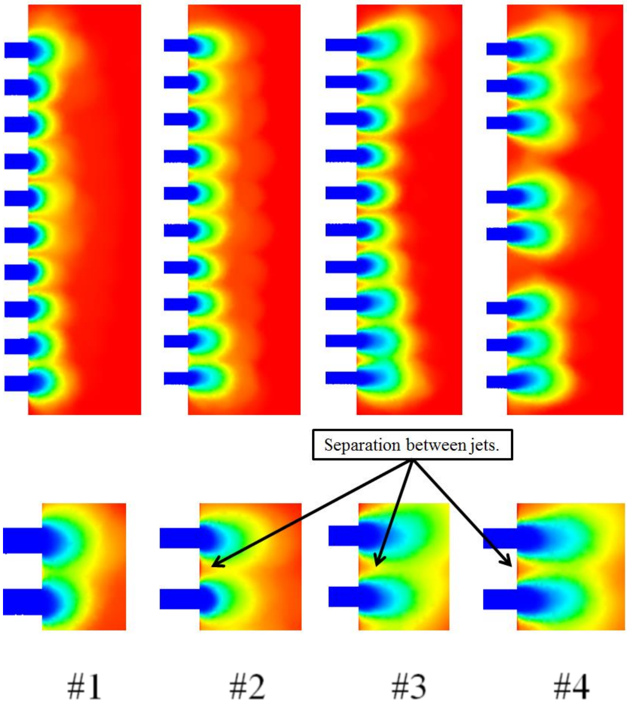

Fig. 5: Interaction Between Adjacent Tuyeres.

The designs with the smaller tuyere diameter showed the best results in this analysis, as there is a visible clearance between the adjacent air streams. Case #1 shows the worst results, with a high risk of bubble overlapping very close to the lining, which could cause unstable gas pocket formation and accelerated wear.
The larger tuyere diameter of configuration #1 is probably the main reason for its higher probability of bubble overlapping. Besides shortening the available distance between the streams, it also reduces injection velocity, which causes the bubbles to

penetrate less in the matte before their average paths interact with each other.

Turbulence

The turbulent energy has both positive and negative aspects regarding converter operation. Close to the lining, it accelerates refractory wear but further from the tuyeres it enhances the process due to increased mixing between the matte and the oxygen. Therefore, the optimum result would be to have higher turbulence away from the blowing area and reduced turbulence close to the wall.
The main source of turbulence in the analyzed phenomenon is the air stream, due both to its fluctuating nature, especially under bubbling regime, and to the shear layers between the fast moving gas and the slowly moving matte. Consequently, it is expected that the distribution of turbulent energy changes as the blowing configuration varies. Fig. 6 shows the results of turbulent kinetic energy for the studied configurations:

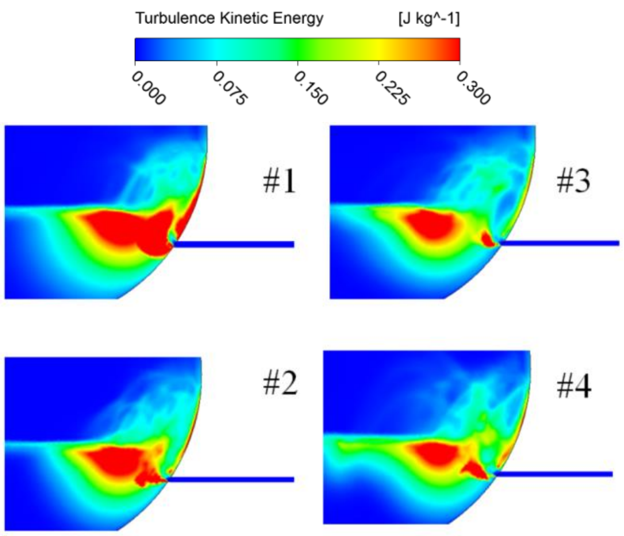

Fig. 6: Turbulent energy results

The configurations with smaller tuyere diameter, due to their higher injection pressure and velocity, showed the lowest turbulent energy adjacent to the refractory lining. This is probably due to their higher penetration values, which cause the air streams to rise further from the tuyeres and therefore generate turbulence deeper in the bath.

Useful Reaction Volume

The volume fraction distribution, which was evaluated to predict oxygen penetration and tuyeres interaction, can also be used to estimate the oxidation efficiency of each configuration. Besides other variables, for a chemical reaction to occur, it is essential that both reactants have contact with each other. By evaluating the total volume of cells where both oxygen and matte are present in the blowing region, it is possible to compare the operational efficiency of the different configurations. For this evaluation, only cells with volume fraction ranging between 5% and 95% were considered, in order to avoid accounting for cells with negligible mixture. Fig. 7 shows the useful reaction volumes distribution.

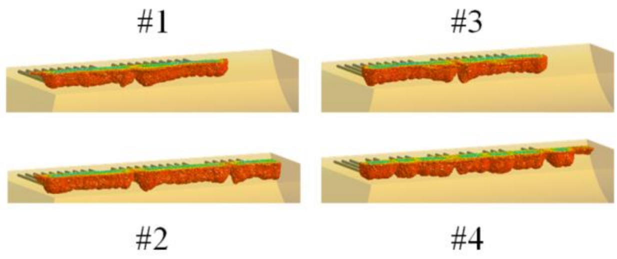

Fig. 7: Useful Reaction Volume Distribution.

Configurations #2 and #4 showed the largest useful reaction volumes, due to the central block not being entirely closed. #4 showed the best result due to it also having a deeper oxygen penetration.

Table 5: Useful Reaction Volume Results.

Configuration ID	Reaction Volume
#1	0.261 m^3
#2	0.388 m^3
#3	0.308 m^3
#4	0.395 m^3

CONCLUSIONS

From this study, it can be concluded that the numerical model is a valuable tool for developing solutions which increase refractory performance in copper converters. Four different configurations were studied, with different numbers of active tuyeres, position and diameters. Regarding the different design alternatives, it can be concluded that:

1. By reducing the diameter and number of active tuyeres, injection pressure and velocity will increase.

2. Higher injection pressures and velocities lead to deeper oxygen penetration and less tuyere interaction and turbulence close to the back wall, leading to a longer refractory life.

3. Shutting down the entire central block has a negative effect on the useful reaction volume of the converter.

4. By alternating open and closed tuyeres and opening only the side tuyeres of the central block, it is possible to combine good refractory performance and converter operation.

Consequently, from the studied configurations, #4 would be the best choice in order to increase refractory performance in a Pierce-Smith Copper Converter.

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