Sonic injection into a PGM Pierce-Smith converter: CFD modelling and industrial trials

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Peirce-Smith converters (PSCs) are extensively used in the copper, nickel, and platinum group metals industries to remove iron and sulphur from the molten matte phase. This technology has not changed significantly since its inception in the early 20th century. The typical converting operation involves lateral purging of air/oxygen-enriched air into molten matte through a bank of tuyeres. This blowing operation occurs at low air pressure from the blowers, and the induced bubbling regime is considered inefficient from both a process and an energy utilization perspective. Inherent drawbacks include recurrent tuyere blockage, inevitable tuyere punching operation to clear airways, and low oxygen efficiency as a result of substantial air losses due to leakages.

Investigations in the 1980s demonstrated[1] that jetting into Cu and Ni converters could reduce or eliminate some of the process difficulties. In spite of these findings, very little progress has been made in the application of these concepts for converting of non-ferrous melts on a commercial scale.

As part of its operational improvement and energy reduction initiative, Western Platinum embarked on a full-scale industrial evaluation of generating a jetting regime by using sonic injection. Prior to full-scale industrial evaluation, a numerical assessment was conducted to ascertain the feasibility of implementing sonic injection on Lonmin converters. The work included flow characterization at high injection pressures achieving sonic velocity at the tuyere exit. The 2D and 3D simulations of the three-phase system were carried out using the volume of fluid (VOF) and realizable $k-\varepsilon$ turbulence models to account for the multiphase and turbulence nature of the flow, respectively. These models were applied using the commercial CFD numerical code FLUENT.

This paper discusses the key findings regarding understanding of gas plume extension, velocity distribution, shear wall stress analysis, and phase distribution characteristics in the system. Plant trials are also discussed with reference to the commercial aspects of a full-scale implementation of sonic injection in the smelter.

Introduction

Although Pierce-Smith converter (PSC) technology has been employed for more than a century, the mode and principle of operation have not changed significantly. Some modifications have involved different versions of the typical PSC, a notable one being the Hoboken converter fitted with a siphon that permits process gas collection without atmospheric dilution (Bustos *et al.*, 1995). Hoefele and Brimacombe (1979) attribute the resistance to change to historical conservatism rather than to technological limitations.

Small-scale versions of copper-nickel PSCs are used in platinum group metal (PGM) smelters for removing Fe and S from PGM-rich Cu-Ni mattes. Lonmin Plc operates PGM PSCs of approximately one-third the working volume of a typical copper-nickel PSC. The bubbling regime that results from the subsonic flow conditions currently employed in these operations gives rise to several problems: namely, tuyere blockage, which necessitates frequent punching operation; high refractory wear in the tuyere region; substantial splattering and splashing, which generates significant

[1] Brimacombe, J.K. and Hoefele, E.O. 1980. Method of converting a bath of non-ferrous molten metal matte. US patent 4,238,228. US Patent and Trademark Office. Washington, DC.

amounts of reverts (Richards *et al*., 1986; Wraith *et al*., 1994; Kapusta, 2010), as well as operational downtime with intermittent off-stack periods for cleaning the converter mouth and aisle; and reduced oxygen efficiency due to the punching operation, which results in substantial air losses due to leakages, limiting the converter capacity or the reprocessing of reverts and dusts. These process inefficiencies are also accompanied by energy inefficiencies or 'excess' power consumption related to punching machines, leaks at the tuyere body due to punching (wasted blower air), and unreacted injected air.

The conversion process occurs in a high-temperature environment in a refractory-lined steel vessel, which preclude visual observation and experimentation. In order to delineate critical process parameters, physical and numerical modelling techniques have been developed. Physical models with different liquids simulating matte and slag were developed to study the gas plume, splashing, mixing, phase distribution, and mass transfer phenomena (Hoefele and Brimacombe, 1979; Richards *et al*, 1986; Chibwe, Akdogan, and Eksteen, 2011; Chibwe *et al*., 2011a, 2011b). Richards *et al*. (1986) concluded that the main cause of splashing was the development and intensification of slopping resulting from the manifestation of a uninodal wave. Their analysis showed that gas-liquid coupling increases with tuyere submergence, hence the reduction in splashing. For the small working-volume PSCs used in the PGM industry, tuyere submergence is insignificant relative to that found in Cu-Ni PSCs (Brimacombe *et al*., 1984). In this regard, any possible injection consideration in the small PSC should take this limitation into account.

PSC campaign life depends on the integrity of the refractory in the converter. Due to subsonic flow conditions, the refractory in the tuyere line has commonly been observed to deteriorate much faster than in the rest of the converter. Three mechanisms of refractory wear have been identified: chemical corrosion, thermal spalling, and mechanical wear (Gonzalez *et al*., 2007). Goni *et al*. (2006) found that 35–65% of the refractory wear in a PSC was due to chemical and thermo-mechanical processes. This type of refractory erosion results from a combination of gas dynamics in the proximity of the tuyere nozzle, where high temperature gradients exist, and the punching operation, which generates mechanical shock.

Brimacombe *et al*. demonstrated at both the laboratory (Hoefele and Brimacombe, 1979; Brimacombe and Hoefele, 1980; Brimacombe *et al*., 1990) and plant scales (Brimacombe *et al*., 1984; Bustos *et al*., 1987) that sonic injection (jetting regime) into copper or nickel converters could reduce or eliminate the above-mentioned phenomena and energy inefficiencies. In 1979, Hoefele and Brimacombe carried out the first experimental studies on sonic injection into a PSC using air-water, air-$ZnCl_2$, and air-Hg systems coupled with plant trials. Pressure measurements in both the laboratory and plant showed that only the air–mercury system had the same bubble frequency as the plant, indicating the important influence of the gas–liquid density ratios on the dynamics of submerged injection processes. Strikingly improved penetration of gas into liquid was observed at sonic conditions. Subsequent plant trials with straight-bore tuyeres designed for sonic flow were conducted at the ASARCO smelter in the USA (Brimacombe *et al*., 1984), the Toyo Smelter in Japan (Kimura *et al*., 1986), and the Noranda and INCO copper smelter in Canada (Bustos *et al*., 1987). The salient points from the above work were as follows:

- The relatively lower horizontal penetration force compared to the buoyancy force exerted by the bath
- The stability of the tuyere accretions formed depends on converting cycle
- Punchless operation is possible at higher injection pressures.

Based on the understanding of accretion formation and stability, coupled with the process benefits of sonic injection operation, the Air Liquide Shrouded Injector (ALSI) technology was developed (Bustos *et al*., 1995). With ALSI technology, oxygen enrichments between 30% and 40% have been achieved without detrimental refractory erosion. Commercial implementation of ALSI technology was inaugurated at the Falconbridge Smelter in Canada (Bustos *et al*., 1999) and subsequent notable applications include Thai copper smelter (Kapusta *et al*., 2007).

Lonmin intends to implement sonic injection technology on a commercial scale. Prior to implementation, key process aspects needed to be evaluated, including slopping, splashing, and mixing characteristics, refractory integrity, and the possible extension of air penetration into the bath in these relatively small converters with shallow tuyere submergence. A realistic presentation of such a system needed to be developed in order to obtain a conclusive interpretation for initial trials. Moreover, a rigorous system satisfying the geometry and with dynamic similarity is also needed.

For this purpose, the dynamics of the three-phase (air, matte, and slag) flow in the PSC used at Lonmin were characterized at high air-pressure injection (sonic velocity at the tuyere tip) by using CFD simulations. The 2D and 3D simulations of the three-phase system were carried out using the volume of fluid (VOF) and realizable turbulence model to account for the multiphase and turbulence nature of the flow, respectively. These models were implemented using the commercial CFD numerical code FLUENT. The simulations from the current investigation yielded both qualitative and quantitative results for flow characteristics in the converter, which assisted in planning the trials and selecting the converter to equip with sonic tuyeres. The full-scale plant trials were successfully completed, with promising results.

Numerical simulations

In this work, 2D and 3D simulations were carried out based on a slice model of a Lonmin Plc PSC. Table I gives the dimensions of the actual converter and slice model.

Table I. Lonmin converter and slice model dimensions

Dimensions	System	
	Lonmin Converter	Slice Model
Diameter inside refractory (mm)	2248	2248
Length inside refractory (mm)	3658	165
Tuyere inner diameter (mm)	48	32
Number of tuyeres	18	1
Average tuyere spacing (mm)	165	-

The computational domain was discretized into small control surfaces/volumes (for 2D/3D) for the calculations. A multi-size variable mesh scheme employing finer mesh elements in the matte-slag domain was used. Modelling was done on an Intel® Core ™ i7 CPU with 3.46 GHz processor and 8.0 GB installed RAM. The commercial CFD code ANSYS FLUENT, version 14.0, was used for the calculations on a high-power computing (HPC) cluster with an installed capacity of eight 2.83 GHz processors per node with 16 GB of RAM.

In this paper, simulations conducted at midway of a typical blow condition will be presented, as this period accounts for more than 85% of the converting cycle time. In order to reduce the computational time during the simulations, the flow in the sonic tuyere was not included but simulated separately, and the flow conditions at the tuyere exit were taken as the inlet boundary condition of the computational domain. This value was calculated using the isentropic flow theory. Only two simulations were conducted, with a 300 mm tuyere pipe coupled to the converter to model the development of air flow into the converter. A segregated solver with an implicit approach was used to calculate the pressure, velocity, turbulence, and density through solving unsteady and compressible flow conservation-governing equations – namely continuity, momentum, and energy. In order to account for the multiphase nature of the flow, the VOF model was used. The interfacial behaviour of air, matte, and slag was captured by this model using a compressive discretization scheme. This is accomplished by surface tracking of the phase interfaces in the system through solution of the VOF continuity equation. In the model, the different phases are treated numerically as interpenetrating continua, thus inevitably introducing the concept of phasic volume fraction where the volume fractions in each computational cell sums to unity. The effects of turbulence on the flow field in the model were incorporated by using the realizable k–ε model, which offers improvements in the overall energy transfer. The flow-conservation governing equations, the VOF equation, and turbulence model equations were solved with FLUENT version 14.0. This package is a finite volume solver using body-fitted computational grids. A coupled algorithm was used for pressure-velocity coupling. A compressive interface capturing scheme for arbitrary meshes (CICSAM) discretization was used to obtain face fluxes, when the computational cell is near the interface using a piecewise-linear approach. This scheme was necessary due to the high viscosity ratios involved in this flow problem (ANSYS, 2011). A time step of 0.0001 seconds was used and found to be sufficient for maintenance of numerical convergence at every time step and stability. Convergence of the numerical solution was determined based on surface monitoring of integrated quantities of bulk flow velocity and turbulence, and scaled residuals of continuity, x-, y-, z-velocities. The residuals of all quantities were set to , and the solution was considered converged when all the residuals were less than or equal to the set value.

Results and discussion

CFD modelling

The computed plume extensions for current (subsonic) and envisaged sonic operation are plotted in Figure 1.

A dimensionless parameter (x/d_e), where (x) in (mm) is the exit jet distance and (d_e) in (mm) is the exit tuyere diameter, were used to visualize the extent of the plume penetration into the converter.

In Figure 1, the plume extension into the bath for subsonic and sonic condition is given by 'Plume Sonic' and 'Plume Subsonic'. According to these results, the length of Plume Sonic penetration into the bath is four times that of Plume Subsonic. The extension of the plume region into the converter away from the tuyere exit area is essential, as it provides extra volume for chemical reactions to take place. In their mass transfer studies of the Peirce-Smith converter, Adjei and

Richards (1991) concluded that a substantial part of the chemical reactions in the converter are likely to occur in the tuyere plume region.

The simulations also reveal that the bath circulatory velocity outside the plume region is approximately 0.27 ms^{-1} for both flow conditions. These results are in consistent agreement with the assumption made by Bustos, Brimacombe, Richards (1988) in their development of a mathematical model for the growth of PSC accretions in both subsonic and sonic operations. In Figure 2, the velocity vector distribution around the tuyere exit for both flow conditions is shown. It can be observed that the sonic injection plume extends further into the bath with a higher velocity relative to the subsonic operation. Lower velocity regions can be clearly seen further away from the plume.

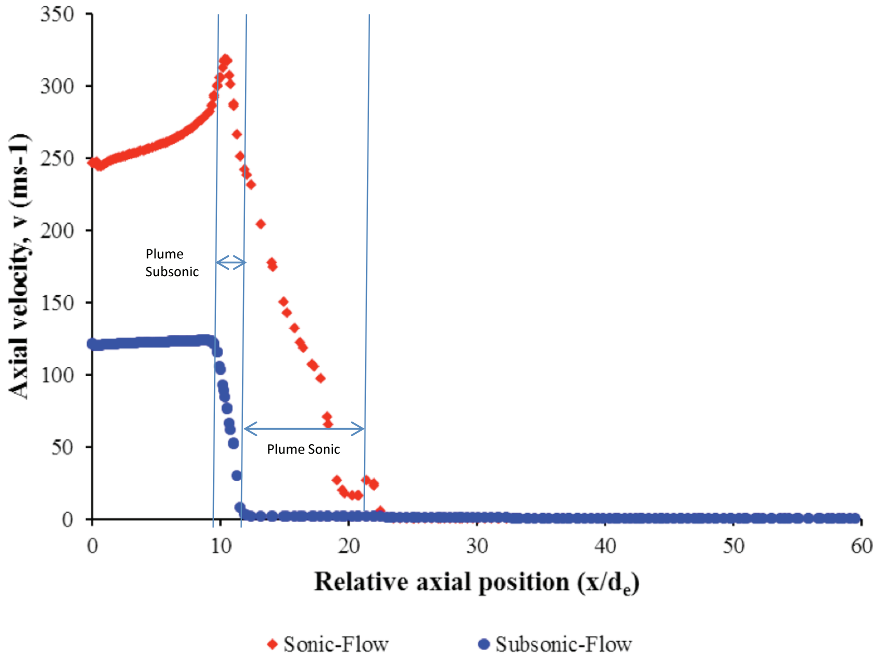

Figure 1. The axial velocity distribution on the tuyere centre axis for subsonic and sonic flow conditions

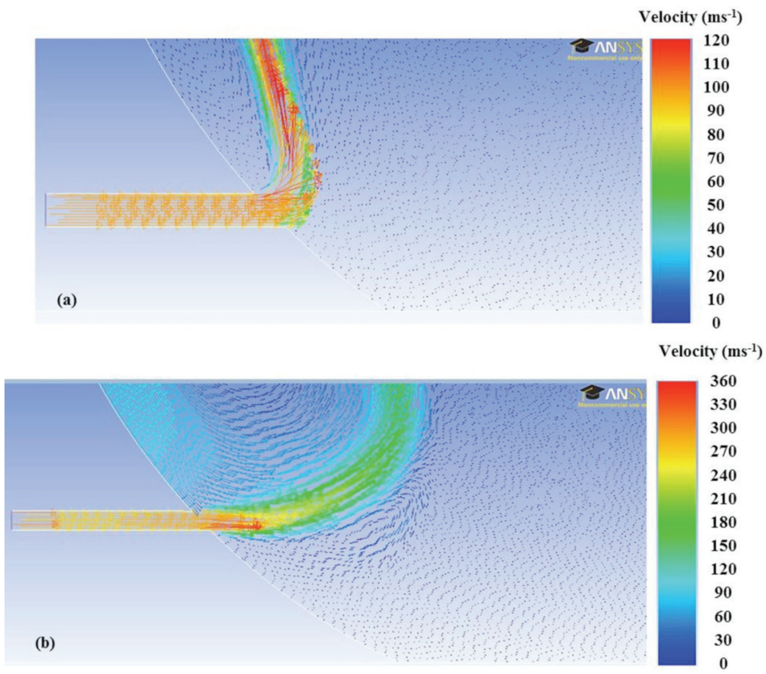

Figure 2. Velocity vector distribution around the tuyere exit at (a) subsonic and (b) sonic flow conditions

Figure 3 shows the phase density distribution for subsonic and sonic flow conditions. The higher air volume region in front of the tuyeres for sonic flow conditions can be clearly seen. This is consistent with the results shown in Figures 1 and 2. The agitation in the regions in front of the tuyeres results in a strong emulsification, leading to high reaction rates in this zone. This is in agreement with the observations of Rosales *et al*., (1999) in their study of fluid dynamics in a converter at Teniente.

The effects of bath circulation and bath density on the walls of the converter were evaluated by calculating wall shear stress along the converter wall boundaries. Figure 4 shows the wall shear stress distribution for subsonic and sonic flow conditions. Near the tuyeres, for subsonic flow conditions, a maximum wall shear stress of 200 Pa was obtained, compared to 125 Pa for sonic flow. This might suggest a possible mitigation for refractory wear with sonic injection, attributed to mechanical erosion around the tuyere region. At the wall in the opposite side of the tuyere line, the stress is higher for sonic injection due to the propagation of waves further away from the tuyeres carrying energy to the opposite sidewalls. This is desirable for achieving better mixing conditions in the converter, whereas at subsonic conditions energy is instantly dissipated just above the tuyeres, as shown in Figure 2, which might lead to increased refractory erosion.

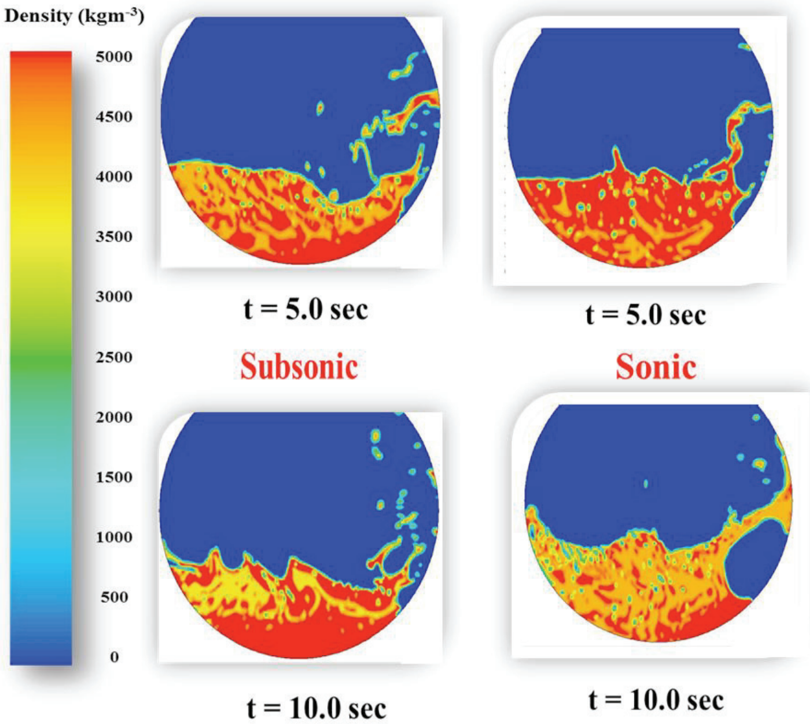

Figure 3. Phase distribution density contours at subsonic and sonic flow conditions

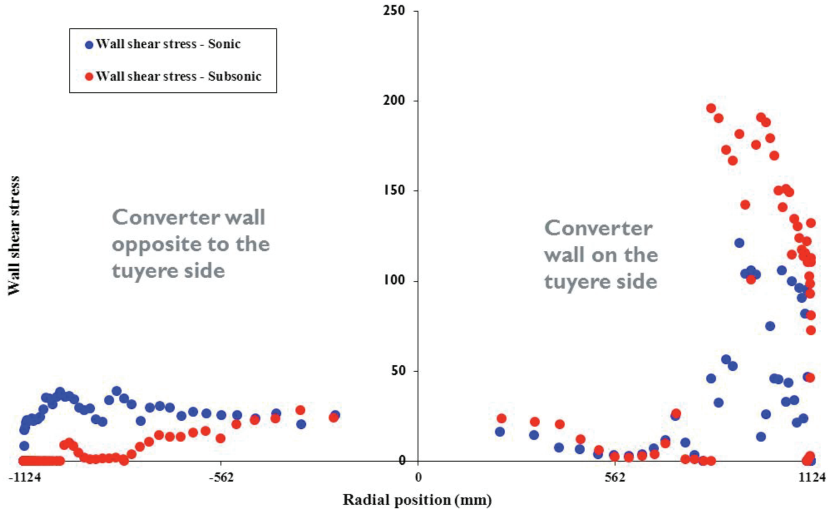

Figure 4.Wall shear stress distribution for subsonic and sonic flow conditions

Plant trials

Once the target total flow rate of compressed air into the converter and the number of sonic tuyeres had been finalized, sonic tuyeres were designed and dimensioned. All of the necessary equipment for the supply and control of the compressed air flow to the converter was also sourced in preparation for the trials. A new reline was installed and the punching machine was removed. The sonic tuyeres were then installed using the same tuyere body as for normal operation. SCADA programming, alarms, and control set-points were then carefully evaluated and implemented to ensure the safe and controlled operation of the converter during the sonic injection trials.

Before the sonic injection trials began, it was found that one of the main characteristics of subsonic injection was the high variability of both the air flow rate and the injection pressure, as shown in Figure 5. This is a direct consequence of the formation of blocking accretions, resulting in lower flow and higher pressure, and the unplugging of the tuyeres by punching, resulting in sudden higher flows and lower pressures.

In contrast, as shown in Figure 6, the air flow rate during sonic injection is less variable than during subsonic injection. A more stable air flow rate is one of the expected benefits of sonic injection. The flow rate curve shows significantly less variability compared to the blow shown in Figure 5. Even more significant is the stability of the pressure with sonic injection. The stability of both the flow rate and pressure of the compressed air demonstrated that the new operating strategy was successful. Controlled splashing was also accompanied by a stable flow rate and pressure of compressed air, as illustrated in Figure 6. Also, the maximum refractory wear rate ranged between 10.3 and 11.1 mm per blow, which corresponds to 37 to 40 blows per campaign, or a 34% reduction in refractory wear with sonic injection compared with conventional subsonic injection. The above measurements of refractory wear, although over a short period of time or a limited number of blows, nevertheless provide an industrial validation of the theory that the accretions formed during sonic injection are indeed protective, rather than disruptive.

When operated in sonic mode, the converter capacity for reprocessing reverts was found to be as much as 200% higher that of the low pressure bubbling regime, owing to the higher oxygen efficiency. In summary, sonic injection offers significant flexibility for periods of high production of furnace matte – reducing the reverts reprocessing rate to take full advantage of fast sonic blows – or for periods when high reverts reprocessing is needed. Table II highlights some of the benefits of using the sonic regime in the converters, and the success of the plant trials.

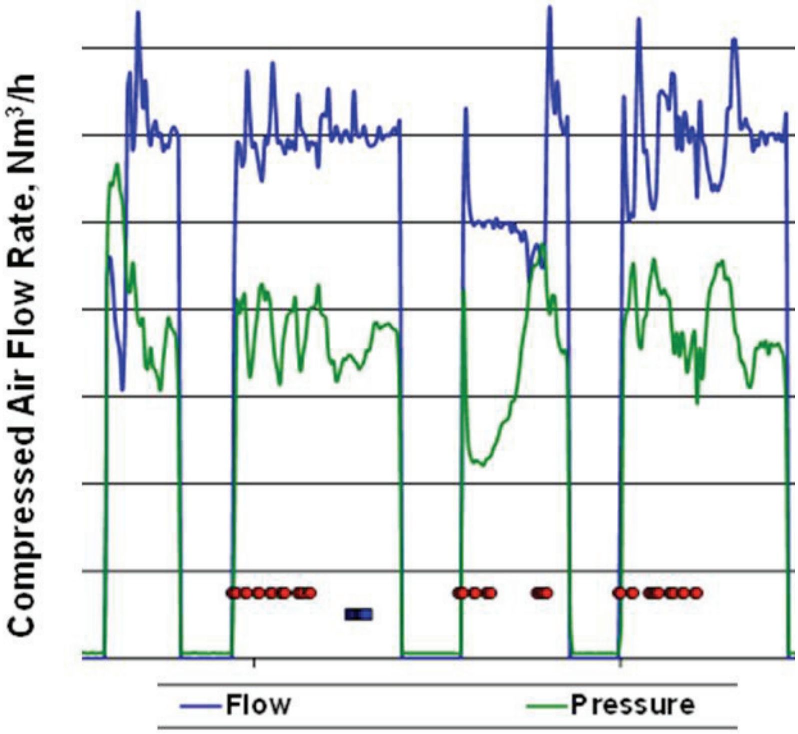

Figure 5. Flow and pressure variations for subsonic (conventional) blow

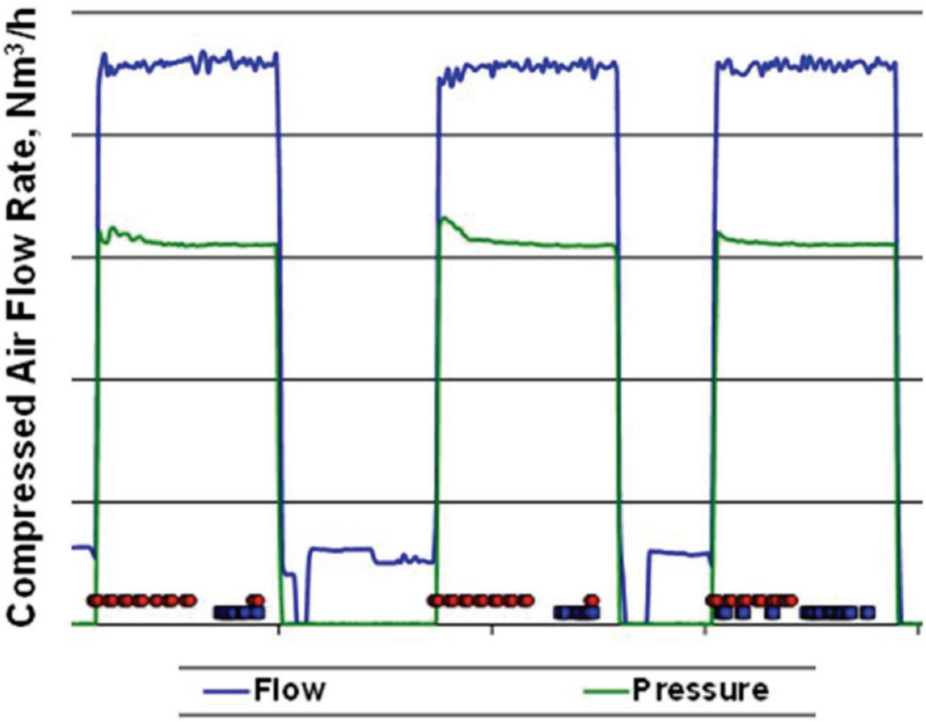

Figure 6. Flow and pressure variations for sonic blow

Table II. Comparison of sonic and subsonic trials at Lonmin

FACTORS	**OPERATION**	
	Subsonic (current)	**Sonic**
Punching operation	Yes	None
Oxygen efficiency (%)	65	92
Converter campaign (cycles)	26	37 – 40
Scrap reprocessing (ton)	2.97	9.30
In-stack time (min)	469	359

Conclusions

The CFD modelling formed part of an assessment to complement feasibility studies of implementing high-pressure sonic injection into relatively small Peirce-Smith converters (PSCs) used at Lonmin plc prior to the plant trials. The modelling work was carried out to characterize the fluid dynamics of three-phase (air, matte, and slag) fluid flow using high-pressure air injection at sonic velocity. The results provided a basis for further development of sonic injection technology into relatively small industrial PSCs with the ultimate objective of reducing energy consumption, improving process efficiency, and increasing throughput of the converting process. The results revealed the following:

- The gas plume extends into the bath approximately four times deeper at sonic flow conditions compared with subsonic flow conditions
- The wall shear stress is lower for sonic flow conditions, suggesting that sonic injection could possibly prolong refractory life with
- Higher pressure injection gives rise to high air volume regions in front of the tuyeres relative to low-pressure injection operation with subsonic flow
- The injected gas ascended near the converter wall above the tuyeres for a significant period of time and thus a high refractory wear in the tuyere region was expected relative to sonic injection.

These findings showed that high-pressure gas injection into PGM-PSCs is feasible.

Following the results from modelling, sonic injection trials in one of Lonmin's converters were successfully completed. Punchless operation was achieved with sonic injection, and the higher oxygen efficiency in sonic mode resulted in increased capacity to reprocess reverts. Refractory wear per blow or per ton of matte was reduced with sonic blowing, leading to longer campaign cycles.

In summary, sonic injection offers significant flexibility for Lonmin's converting operation by allowing operators to adjust their practice for periods of high production of furnace matte – reducing the reverts reprocessing rate to take full advantage of fast sonic blows – or for periods when high rates of reverts reprocessing are needed.

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