Novel Method for Stirring BOF Melts in Conjunction with Slag Splashing

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Introduction

Basic oxygen furnace (BOF) is used to convert iron into steel by blowing oxygen into the hot metal to remove carbon and impurities. In a BOF, blowing oxygen through molten iron lowers the carbon content of the metal. The process also uses fluxes of burnt lime or dolomite, which are chemical bases, to adjust the slag and promote the removal of impurities and protect the lining of the vessel. The metallurgy and efficiency of top oxygen blowing can be improved by use of bottom stirring. In bottom stirring, the molten metal is stirred by introduction of gas from the bottom or side of the BOF vessel. The benefits of combined top blowing and bottom stirring are well established in the literature [1, 2, 3]. The combined blowing improves the kinetics and makes the temperature more homogeneous, enabling better control over the carbon-oxygen ratio, resulting in improved yield and dephosphorization, higher manganese yield, and reduction in consumption of alloying agent.

Economic benefits of combined blowing

Table 1 shows the outline of economic benefits of using bottom stirring in conjugation with top blowing. The savings due to improvement in yield, reduced flux usage, higher Mn residuals and other benefits is estimated to be ~$3.9 per ton of hot metal. The cost of the installation and the stirring gases is estimated to be ~$1.12 per ton of hot metal. The net savings from the use of combined blowing is estimated to be ~$2.78 per ton of hot metal. These benefits are well-known in the oxygen steelmaking community.

Table 1: Comparison of Net Benefit Due to Use of Bottom Stirring

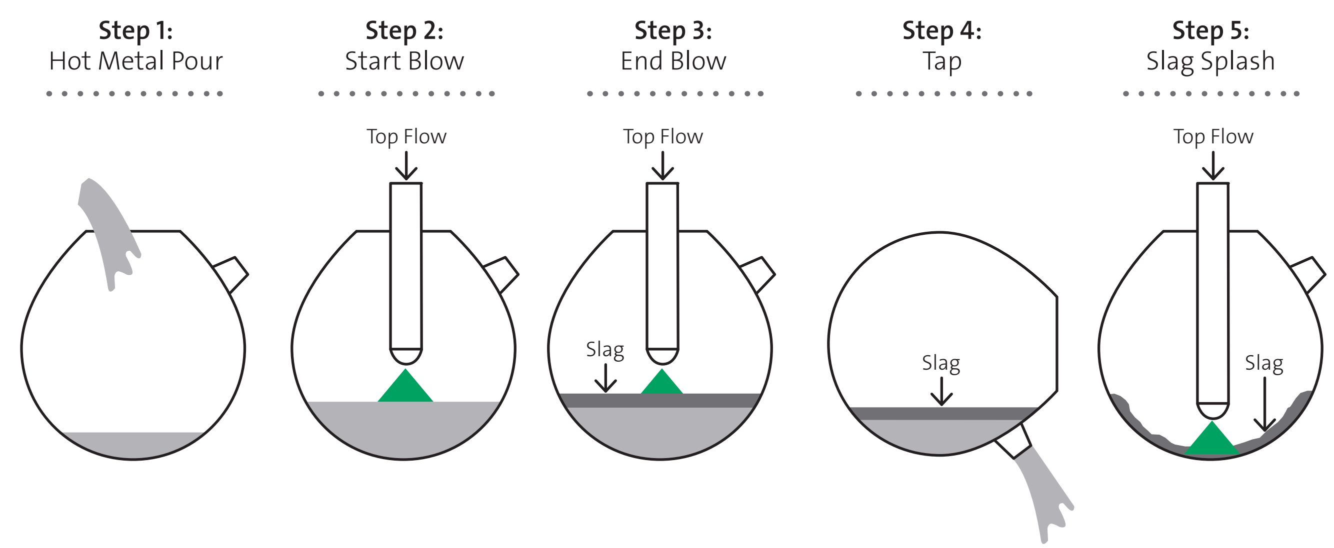
Savings	Value (per THM)
Improved yield (0.5%)	~$2.50
Other	~$1.40
Total estimated savings	~$3.90
Costs	**Value (per THM)**
Stirring gases (Ar, N_2)	~$0.72
Other	~$0.40
Total estimated costs	~$1.12
Net benefits	**Value (per THM)**
Net benefits	~$2.78

Current BOF process without bottom stirring

In the integrated steel mills (typically in the US), the BOF steelmaking process has four phases, shown by different steps in **Figure 1**: a charge phase (Step 1), a blow phase (started by Step 2 and ended by Step 3), a tap phase (Step 4), and a slag splash phase (Step 5). The cycle repeats, so after Step 5, the process recycles to Step 1.

In Step 1 (Charging), scrap and hot metal (iron) are loaded or poured into the furnace vessel through the top opening. In Step 2 (Start Blow), a high flow of oxygen is injected through a lance inserted through the top opening of the furnace; during this blowing process, slag is formed on the top surface of the molten metal. In Step 3 (End Blow), the flow of oxygen is stopped, and the lance is removed from the top opening. In Step 4 (Tap), the furnace is tilted, and the molten metal is poured out through a tap hole on the side of the furnace, while the slag is left behind in the furnace. In Step 5 (Slag Splash), the furnace is returned to an upright position and nitrogen is injected through a lance inserted through the top opening of the furnace. The nitrogen for slag splashing flows at supersonic velocities similar to the oxygen blow, which causes the molten slag to splash onto the walls of the furnace vessel. This results in coating of the BOF vessel with a layer of slag, which in part replaces some of the vessel refractory that is consumed or eroded away during the BOF process and forms a protective layer on the refractory.

Figure 1: Typical BOF Steelmaking Process in U.S. Integrated Mills



	Gases	Step 1	Step 2	Step 3	Step 4	Step 5
Top Flow	Oxygen	No	Yes	Yes	No	No
	Nitrogen	No	No	No	No	No

Slag splashing, however, if done in a vessel with bottom stir nozzles, often results in partial or complete clogging of the bottom stir nozzles located at the bottom of the vessel. This clogging essentially prevents or restricts further flow of gases through the bottom stir nozzles into the BOF, and eventually, after multiple slag splashing, results in losing the ability to bottom stir at all.

Thus, a major challenge with using BOF bottom stirring elements is that over time they may develop partial or full blockage due to cooling of slag or metal from the stirring gas. It is possible that gas may continue to flow through the elements, but stirring effectiveness is diminished or lost altogether. These blockages are difficult to detect, especially if there is still flow through bottom stirring elements.

Due to common slag splashing practices in the US, bottom stirring is not practiced because of the poor reliability and difficulty maintaining the bottom stirring elements. In facilities around the world that employ bottom stirring along with slag splashing, the lifetime of the existing bottom stirring elements can be significantly less than the length of a furnace campaign. For example, the bottom stirring nozzles rarely last more than three to five thousand heats before they are no longer usable, while the BOF campaign can last for many thousand heats longer. Therefore, for at least half, and in some cases as much as 85% of the furnace campaign, bottom stirring is not available. This affects the quality of steel being produced and causes a 'dual practice' either with or without stirring. These facilities therefore must reline the furnace, more often to maintain the advantage of bottom stirring.

Novel device and process

The aim of the current invention is to provide a novel tuyere/nozzle that helps eliminate above discussed short comings while maintaining the advantages of the submerged (bottom or side) gas stirring operation in a furnace. The current tuyere design achieves this by providing operational flexibility in the tuyere with two different operation modes. The two operation modes are a stirring mode and a burner mode; the operation mode can be selected by use of a controller mechanism.

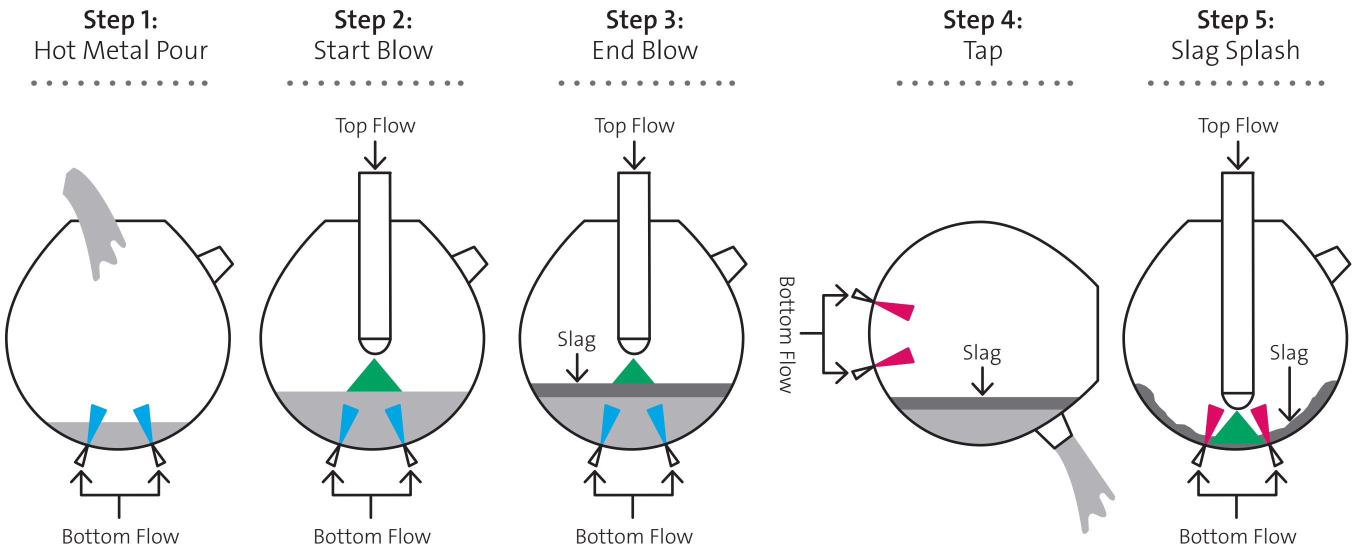
In the stirring mode, the tuyere aids in proper mixing of the bath above it. The tuyere operates in the jetting regime. The phenomenon of bubbling and jetting flow regime is well-established in the literature [4], which established that for a jet to be in a stable jetting regime, the fully expanded Mach number should be greater than 1.25. Jetting flow helps to: (a) prevent back attack on the bottom refractory, and (b) achieve more effective stirring.

In the burner mode, the tuyere provides a mechanism of cleaning of any moderate blockage of the solidified or semi-solid matter at the exit of the tuyere. The tuyere thus keeps itself unclogged to maintain the effectiveness of stirring for a longer campaign by removing any potential buildup of material at the exit of the tuyere or further downstream from the exit of the tuyere.

Proposed modified BOF process

Figure 2 illustrates the operation strategy of the self-sustaining bottom stir tuyeres, and, illustrates how the proposed patent pending process differs from the standard process of BOF steelmaking [5]. In Steps 1 to 3 (during the pour phase and the blow phase), the bottom stirring tuyeres operate in the stirring mode, while in Steps 4 to 5 (during the tap phase and the slag splash phase), the bottom stir tuyeres operate in the burner mode.

Figure 2: Proposed New BOF Steelmaking Process



	Gases	Step 1	Step 2	Step 3	Step 4	Step 5
Top Flow	Oxygen	No	Yes	Yes	No	No
	Nitrogen	No	No	No	No	Yes
Bottom Flow	Argon	No	No	Yes	Yes/No	Yes/No
	Nitrogen	Yes	Yes	No	Yes/No	Yes/No
	Fuel	No	No	No	Yes	Yes
	Oxygen	No	No	No	Yes	Yes

In Step 1 (Charging), a flow of inert gas through both tuyere passages is initiated (or continued) prior to starting the pour of hot metal into the furnace, and the flow of inert gas is maintained through the pour. This prevents the bottom stir elements from overheating and/or clogging. In Step 2 (Start Blow), the flow of inert gas through both tuyere passages is continued, at the same or a different flow rate, to achieve stirring of the molten metal. In Step 3 (End Blow), the flow of inert gases is continued as during Step 2.

In Step 4 (Tap), when the BOF vessel is tilted to pour the metal out, the flow through the tuyere passages is switched over to fuel through one passage and oxidant through the other passage, to produce a flame. In Step 5 (Slag Splash), the flames prevent the tuyeres from clogging, and prevent the formation of any bridges over the tuyere exit. Thus, during Steps 4 and 5, fuel and oxidant are introduced through the bottom stir elements. It is recommended but not necessary to use the burner mode in all the slag splashing heat cycles.

In the next sections, the laboratory experiments using the Air Products proprietary tuyere and the results are discussed in detail.

Development of novel bottom stirring tuyere

Methodology

The overall proprietary tuyere development and testing methodology is outlined in **Figure 3**. The first step towards reaching the new process methodology for the bottom stirring operation was development of a new tuyere design. As discussed in the introduction section, this new tuyere would enable the operation of the tuyere in two different modes: stirring mode and burner mode. In the stirring mode, the tuyere operates in the jetting regime to provide efficient mixing of the bath and reduces the number of back attacks on the refractory wall. In the burner mode, the tuyere enables formation of a stable flame.

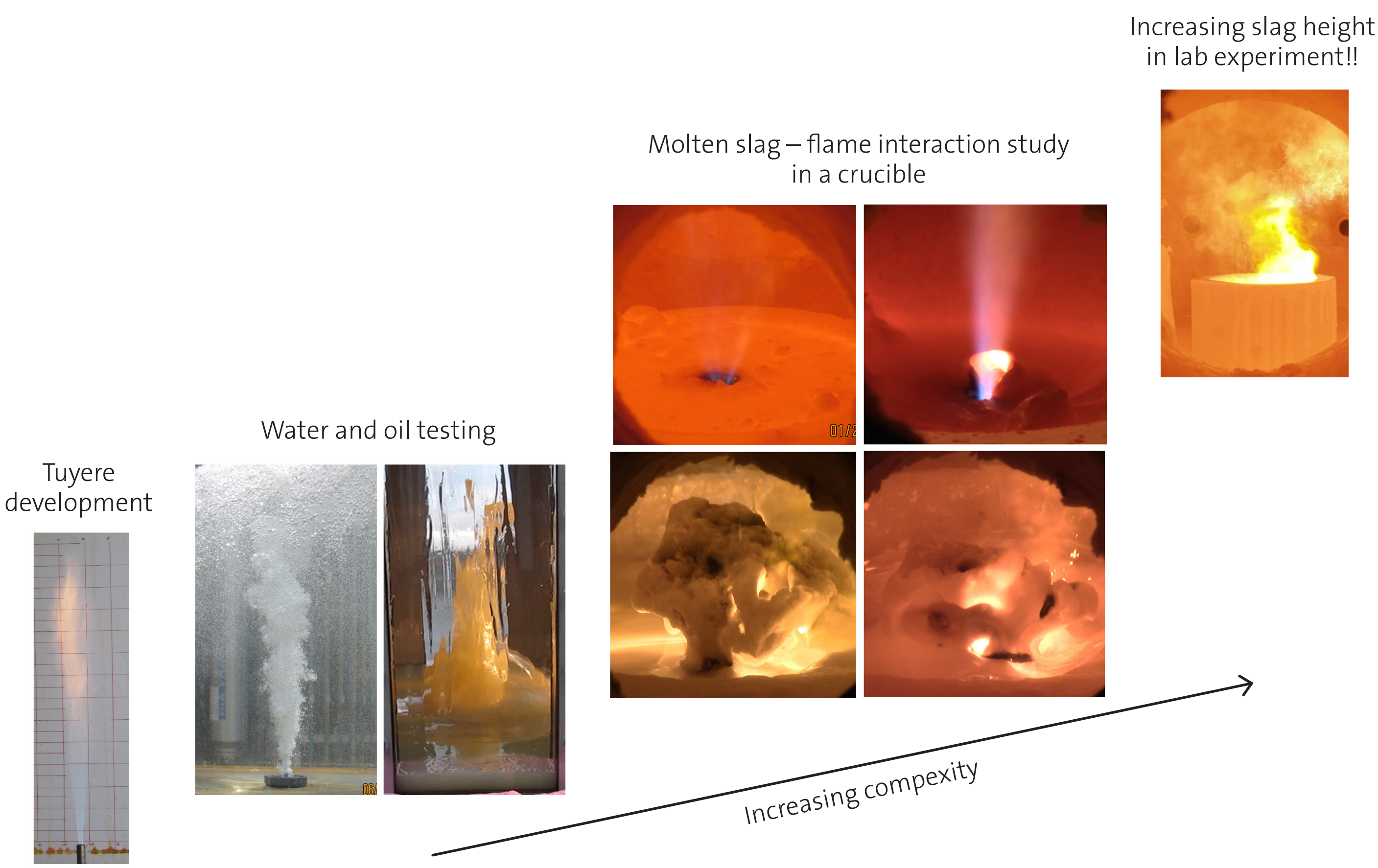
The next step in the development phase of the tuyere was to test the tuyere under ambient conditions to confirm the flow regime and robustness of the tuyere against any back flow of fluid inside the tuyere. These experiments were carried out in a tank using water and oil as a fluid media. After successful demonstration of the jetting flow regime of the tuyere, the tuyere was tested in the flame mode using BOF slag to understand the interaction of the flame and molten BOF slag.

The molten slag experiments were performed in a crucible. The idea of using a crucible was to replicate a portion of the BOF vessel bottom around a single tuyere. The interaction between different tuyeres is critical under mixing mode of the tuyeres, as demonstrated in studies Ref. [6,7], to optimize the bath mixing times. However, in the flame mode, each tuyere acts on its own around a small volume at tuyere's exit. The distance between two tuyeres is large enough that the interaction between any two flames would be minimal. Each tuyere will have to act on its own to provide enough heat release to melt the solidified slag or metal at its exits.

Ambient environment: water and oil media experiments

The flow regime characteristics of the new tuyere were tested in a model tank at atmospheric temperature and pressure. The tank dimensions are 1:6 the size of a typical BOF vessel. The tuyere was located at the center of the base of the vessel. The experiments were carried out using both water and oil as a media. Water was selected

Figure 3: Development and Testing Methodology of Air Products Novel Tuyere

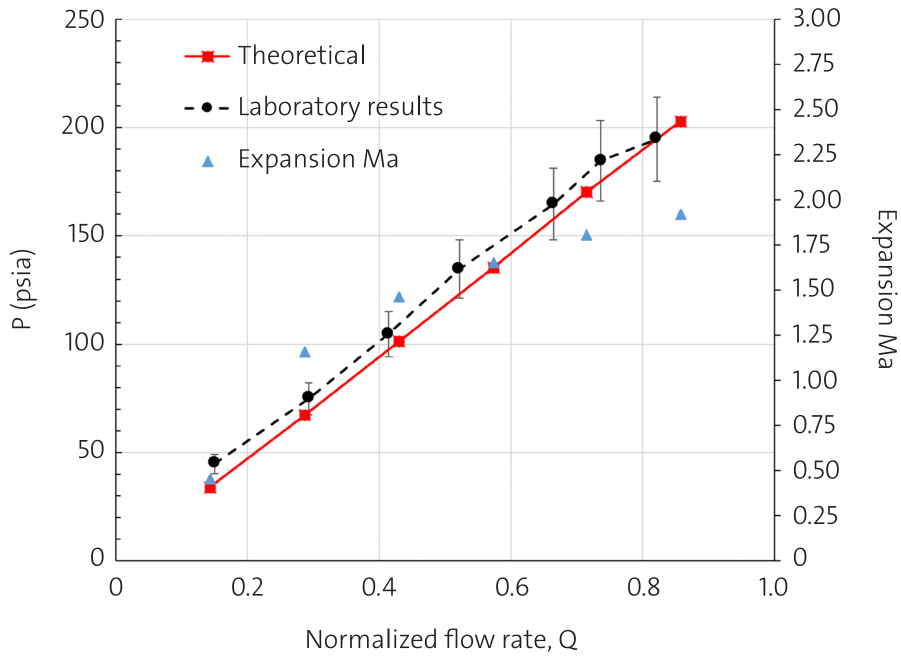


as it has a similar viscosity as that of the molten metal. The choice of oil was done to replicate the viscosity of the BOF slag. The primary aim of the testing in this tank was to replicate the tuyere operation in slag splashing mode: to make sure that no liquid penetrates back into the tuyere under any of the two modes: stirring or burner mode. The experiments in this tank replicates 'an area surrounding one tuyere' in a BOF vessel. This enabled us to use an actual prototype of the tuyere to be tested. An electrical circuit was used to ensure that no water penetrated back inside the tuyere under the two operation modes of the tuyere.

Hot metal and slag experiments

The hot slag and metal experiments were performed in a crucible. The tuyere was located at the base of the crucible and the crucible was loaded with either solid BOF slag, iron, or a mixture of solid slag and iron mixture. A pile of solid material was used as a test setup to replicate the worst-case scenario when the exit of the tuyere is partially or fully blocked by solidified slag or metal. The heat from the bottom flame is used to create a molten pool of metal or slag.

Figure 4: Pressure-flow Characteristics of the Prototype Tuyere Design



Results from laboratory experiments

Water and oil media: tank experiments

The prototype tuyere was tested in our combustion laboratories to verify the device functions and operates as per the design calculations. **Figure 4** shows the theoretical and laboratory determined flow-pressure characteristics for one of the prototype tuyeres. This plot also shows the expansion Mach number for the prototype tuyere. The left-hand side Y-axis is for fluid supply pressure and right-hand side Y-axis is for the expansion Mach number. The plot shows that at supply pressures above 80 psia, the expansion Mach number is above 1.25. This is the critical expansion Mach number above which the tuyere operates in the jetting regime [4]. **Figure 5 (a)** shows the operation of the tuyere in the jetting regime. The liquid level is 3 feet above the tuyere exit.

Furthermore, **Figure 4** shows that the supply pressures are achievable using a standard liquid supply tank, without the use of a compression device, to achieve jetting flow regime. Additionally, measured flow-pressure characteristics in the laboratory are within 10% of the theoretically-determined pressure-flow characteristics of the tuyere.

The testing of the prototype tuyere in the vessel using the water media established that as long as flow is present through the tuyere, no fluid penetrates back inside the tuyere. The tuyere operation was also tested using oil, which has similar viscosity to that of BOF slag, as a fluid media in the tank. Air, with same momentum as that of fuel and oxidizer, was used as a fluid through the tuyere during testing with oil as a media. The oil level in the tank was kept at approximately 18” from the tuyere exit. **Figure 5 (b)** shows that the momentum of fluid exiting from the tuyere is high enough to displace the oil column above it.

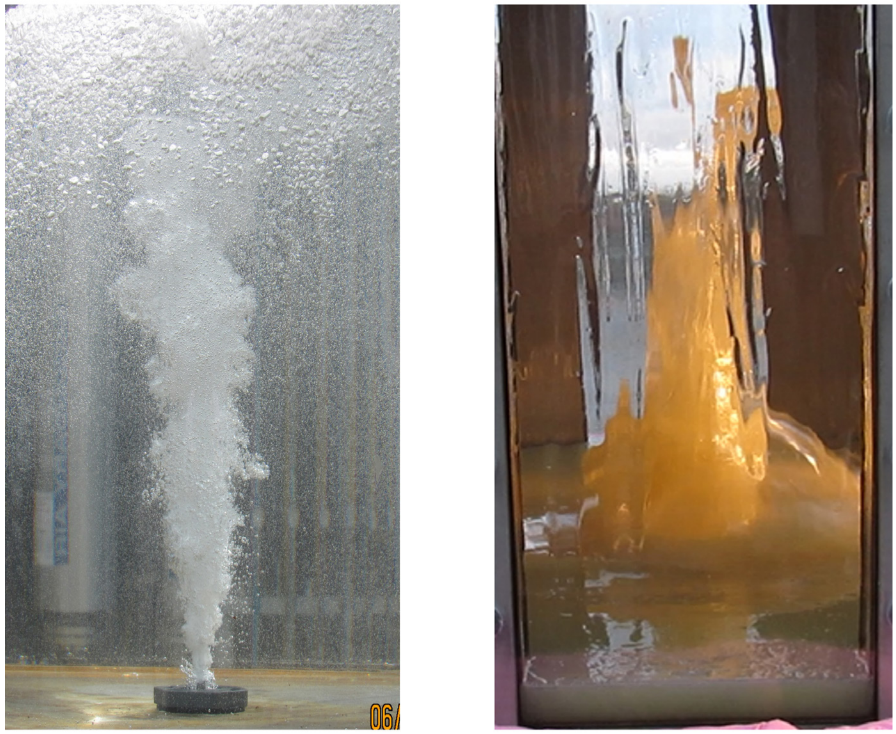
The ambient condition experiments helped build confidence in the tuyere design and in the next section, the experiments using molten BOF slag are discussed.

Molten BOF slag experiment

The novel tuyere was tested in the burner mode operation in a crucible using BOF slag. **Table 2** outlines the major components present in the BOF slag used in our experiments. **Figure 6** shows the top views of the crucible in which the burner operation mode of the tuyere was tested. A crucible was loaded with solid BOF slag and 5% by mass of iron. Iron was added to replicate the iron traces remaining in the BOF slag after the tapping operation (step 4 in **Figure 2**). Initially, the slag and iron in the crucible were cooled by the nitrogen flow from the bottom tuyere.

Figure 5: Tuyere Operation (a) Water Media, Stirring Mode, Jetting Regime: (b) Oil Media, Momentum Flux of Air Same as in Burner Mode Operation

Water and oil testing

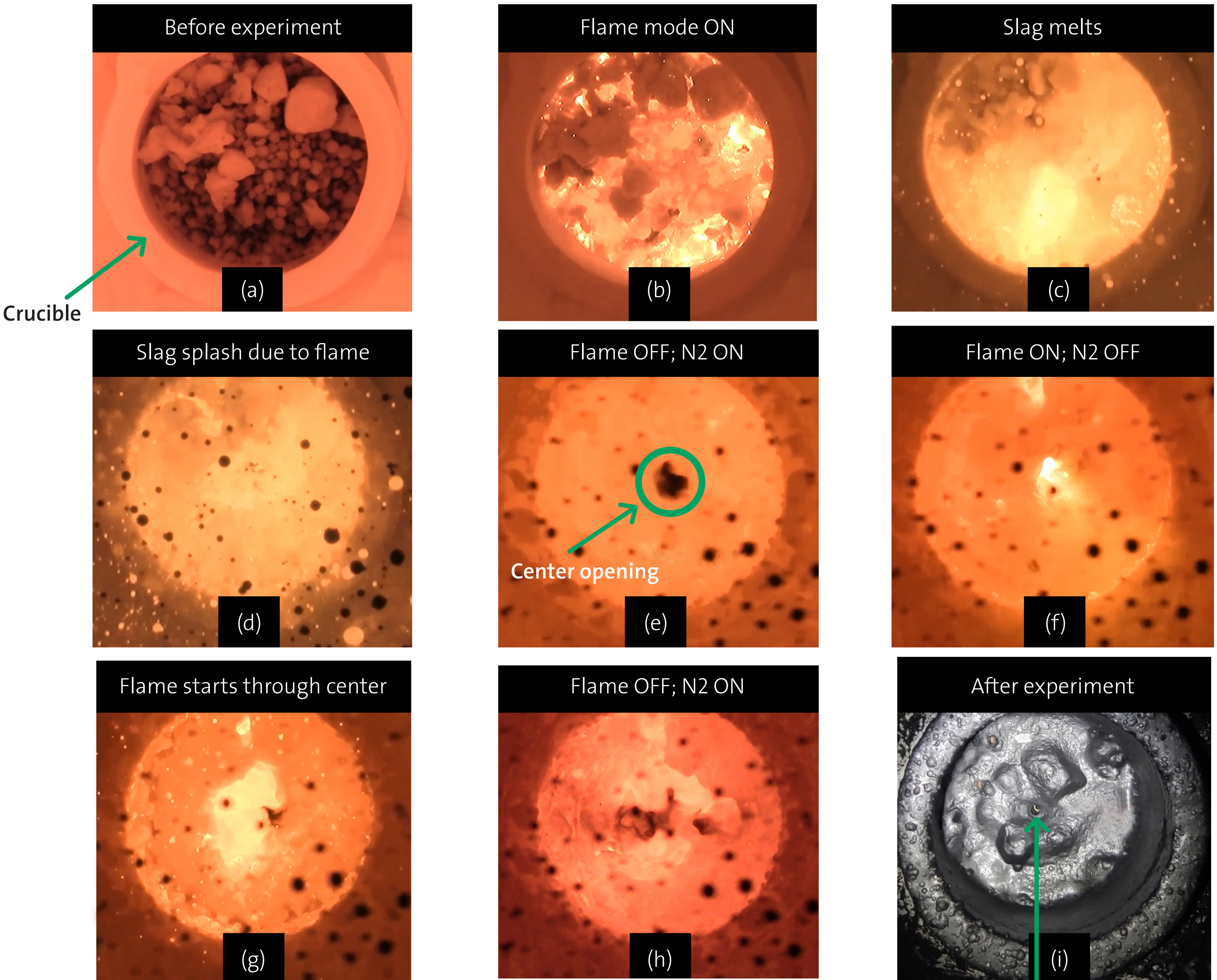


(a) (b)

Figure 6 (b) shows the initial stage when the burner mode of the tuyere was started. The flame is initiated as the temperature in the crucible is above the auto-ignition temperature of the fuel. The energy release from the bottom flame melts the BOF slag creating a pool of molten slag, and the combustion gases results in the splashing of the molten slag as observed in **Figure 6 (d)**. The slag splashed by the bottom burner results in solidified slag spots on the viewing windows located about 6 feet above the crucible. These ‘black spots’ are visible in **Figures 6 (d)-(h)**. The slag splashed by the bottom burner demonstrates the strength of the bottom burner to clear the volume of slag above the exit of the tuyere.

As soon as the slag starts splashing out of the crucible, the burner is turned OFF and the nitrogen flow is started from the bottom to solidify the molten slag. The solidified slag is visible, marked as ‘center opening’, in **Figure 6 (e)**. After the slag has re-solidified, the tuyere operation is changed to burner mode. **Figures 6 (f) and 6 (g)** show that the flame establishes itself at the center of the crucible where the tuyere is located. After ascertaining that the tuyere was able to create a clear hole above the tuyere exit, the tuyere operation is switched back to nitrogen flow. **Figure 6 (i)** shows the crucible at the end of the experiment. The results show a clear open hole through the solidified slag layer above the tuyere exit.

Figure 6: Prototype Experiment to Test the Burner Mode Operation of the Novel Tuyere



(a) Solid slag with 5% iron by volume
(b) Tuyere burner mode ON
(c) Slag and iron melts due to heat release from the bottom flame
(d) Slag splash due to the bottom flame, black dots are slag splashed on the viewing window of the furnace
(e) Flame turned off, Nitrogen started to cool the slag
(f) Flame mode re-started, Nitrogen turned off
(g) Flame starts through the center hole
(h) Flame turned off, Nitrogen started to cool the slag
(i) After experiment, remaining solidified slag in the crucible with center open hole

Table 2: BOF Stag Chemistry: Major Components

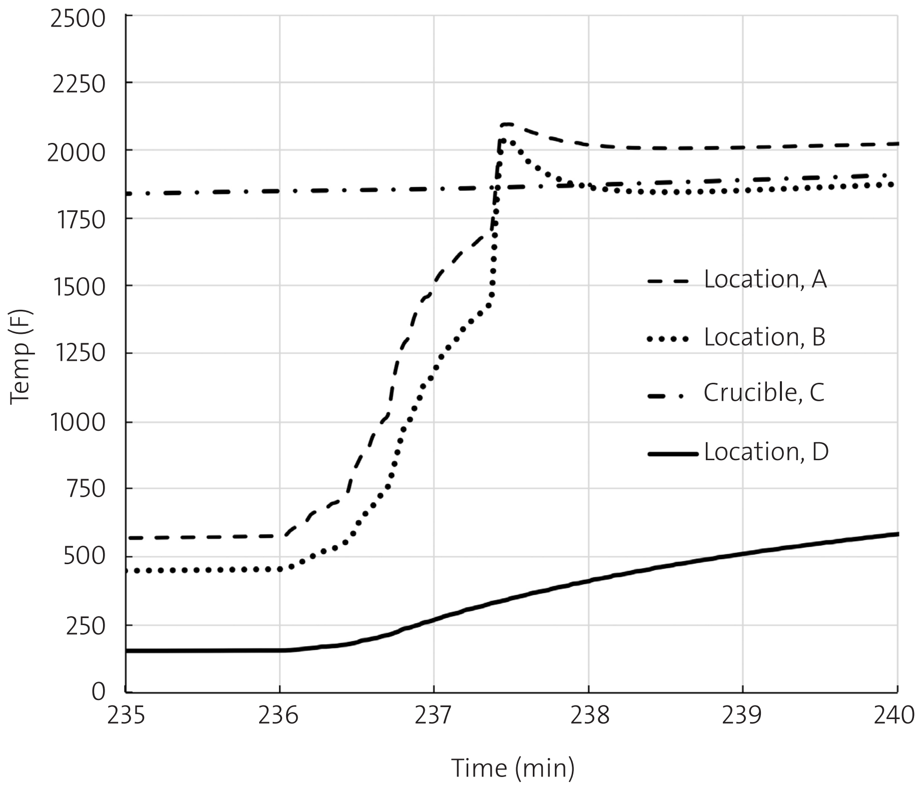
Oxide	CaO	Fe_2O_3	SiO_2	MgO	MnO	Al_2O_3	P_2O_5
Stag (wt%)	33.8	33	18.4	5.59	4.13	2.15	1.31

This experiment demonstrates that the transition between the stirring to burner mode back to stirring mode is smooth without any backflow of molten slag inside the tuyere. The flow skid and the control system worked perfectly, demonstrating practical switching between the two operation modes of bottom tuyere, as shown in proposed BOF process in **Figure 2**. This experiment simulated the worst conditions that would be faced by the tuyere, i.e. formation of solid slag crust on and around the tuyere.

Device to detect backflow: Loss of fluid flow in the tuyere

The control mechanism of detecting tuyere blockage and sending feedback to the tuyere control valve was tested in our laboratory. In this prototype design, thermocouples and flow rate measurement devices were used as active sensor elements to test and validate the control mechanism. Thermocouples were installed in the bottom wall of the refractory crucible and inside the tuyere at several critical locations A, B, and D.

Figure 7: Feedback Mechanism Sensors Inside the Tuyere



A molten pool of metal was created in a refractory crucible above the exit of the tuyere. A molten metal pool was used in this experiment due to its lower viscosity as compared to the slag; hence, molten metal would create a more worst-case scenario. To simulate a condition of loss of fluid flow, the flow rate of gas was reduced to zero. **Figure 7** presents temperature data obtained from the installed thermocouples in the refractory crucible and prototype tuyere. The temperature and time are on the y-axis and x-axis, respectively. The flow rate of gas was reduced to zero after 236.5 minutes of run time. **Figure 7** shows that when the flow starts to reduce, the molten metal flows back inside the tuyere resulting in an increase in the temperature reading of thermocouples A, B and D. The crucible bottom wall temperature stays close to 1775 F during this operation. The increase in temperature reading of thermocouples A and B is close to 725 F/min and can be used to provide feedback to the controller to initiate the secondary flow to avoid further backflow of molten metal or slag in the tuyere. The thermocouple reading D shows temperature rise of the tube due to loss of cooling effect of the fluid flow. The temperature reading D is lower than thermocouples A and B as the hot metal gets solidified before location D and doesn't reach the location of thermocouple D.

The depth to which the metal penetrates back inside the tuyere was approximately 2". This back penetration is representative of laboratory scale experiment and does not exactly replicate the process of a BOF vessel. In the next stage of the experiments, it would be critical to determine how the control feedback to the secondary flow to the tuyere can be used to contain and minimize the backflow of hot metal.

Benefits of the novel tuyere

The novel tuyere developed during this project is a one of its kind tuyere that can operate in two operating modes: stirring mode, where the tuyere operates in the jetting regime, and burner mode. The burner mode enables the tuyere to avoid and potentially clear any blockage that develops at the exit of the tuyere. This feature of the tuyere to self-clean helps it to maintain the stirring efficiency of the bottom nozzle for a longer BOF campaign than a standard tuyere.

The tuyere is an easy installation and can be installed without the need to wait until the next re-line of the BOF vessel. This easier installation makes it superior as compared to the bottom plugs (that are usually installed with new BOF reline) used for stirring. Additionally, the patent pending tuyere operates at supply pressure, for a similar gas flow rate, that is achievable from a standard high-pressure liquid storage vessel or an Air Separation Unit without the need of an external compressor. Absence of a compressor lowers the capital and operating cost of the system. Furthermore, the temperature and flow sensors installed in the tuyere helps detect any blockage of the tuyere and take corrective action by an active feedback.

Challenges and next steps

The tuyere has been successfully tested in laboratory scale experiments using molten and solid slag blockage above the exit of the tuyere. The use of solid slag at the exit of the tuyere is the worst case scenario that replicates blockage of a tuyere under operation in a BOF vessel. The experiments demonstrate that the new tuyere, when operated in the burner mode, can successfully melt the solid slag, eliminate the molten slag from the volume above the exit of the tuyere, and create a clear opening above the tuyere exit. The next steps in the continued development of this tuyere and process is to test the tuyere in a larger setup. This setup could be a large-scale ladle or an actual BOF vessel. These next sets of experiment will help study the operation of tuyere in a continuous fashion over several heat cycles of a BOF.

Additionally, laboratory scale experiments have demonstrated that the effect of flame on the refractory wall didn't significantly increase the refractory wall temperature during the flame mode of the tuyere. This observation needs to be confirmed in an actual operation in a BOF vessel over several thousand heats. The testing in a ladle or BOF vessel will help estimate the effects of flame, if any, on the refractory wall. These critical observations from a large-scale setup would help further tune the design of the tuyere, which could be in the form of changing the flame characteristics to change the heat flux profile of the flame, and/or changes in the new overall process shown in **Figure 2**.

Conclusions

A novel tuyere was developed for bottom stirring application that can maintain the stirring efficiency of the tuyere for a BOF campaign with slag splashing. In the laboratory experiments, the tuyere operation in the burner mode shows good capability to melt the solid slag above the exit of the tuyere and clear the path above the exit of the tuyere. Next steps for the tuyere and process development are to scale up the laboratory experiment, and field trial of the system at a BOF shop.

In the North American market, the new developed tuyere could enable use of bottom stirring in conjugation with slag splashing. This can significantly improve the economics and the batch quality. In the global market, this new tuyere can help maintain the efficiency of the bottom stirring for a longer campaign, possibly from 3000-5000 heats to more than tens of thousands of heats.

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