A NEW APPROACH TO BOF MIXING ELEMENT DESIGN

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ABSTRACT
In the final 30% of the oxygen blow in a BOF, bath mixing decreases due to the drop in CO evolution. To help sustain slag-metal mixing and enhance thermal and chemical homogeneity in the melt, the bath is agitated by injecting inert gas through mixing elements in the vessel bottom. Element designs include tuyères and various configurations of single- and multi-hole plug, all of which promote localized wear which in many cases will limit the service life of the lining. Wear arises from a combination of thermo-mechanical stresses associated with, for example, the operational vessel thermal cycle, local cooling by the injected gas, and molten bath circulation induced by the injected gas stream, often compounded by accretion growth, localized lining erosion and metal penetration. A comprehensive post mortem study of used multi-port tuyères shows in addition that steel bath wetting effects in current element designs may be a significant factor in the wear process. A new injection element design is proposed in an attempt to reduce the magnitude of these effects and thereby extend vessel lining life. The design is based on slotted gas channel geometry with materials selection optimized for the specific task. A prototype was tested by water modelling to establish its gas injection behaviour. The results and analysis of these tests are discussed, with indications for future work.
Key words: BOF, bottom mixing, tuyère, water modelling.

INTRODUCTION

During the BOS process, pure oxygen blown at high velocity onto the surface of the bath is used to convert carbon-saturated hot metal, scrap mixtures and lime into steel and slag. Extra heat generated during oxidation of the carbon is utilised to dissolve steel scrap while impurities such as silicon, aluminium and phosphorus are removed in a lime-rich slag[1]. The effectiveness of top-blown BOFs was improved by introducing submerged gas injection to enhance mixing in the bath. Gas injection through elements installed in the vessel bottom led to reduced iron content in slag and dissolved oxygen in metal, higher manganese content in metal at tap and improved phosphorus removal[1,2]. Other benefits of this process included increased scrap consumption, reduced flux consumption and reduced nose and lance skulling. The only disadvantage of the process was increased wear of bottom refractories, especially in close proximity to the injection elements[2].

Different steel manufacturers developed different variations of the bottom mixing technology, aiming to optimise its availability through injection element design, material selection, flow rate control and maintenance practice. Examples include:

1. Improvements in mixing by simultaneous blowing with argon through the bottom mixing elements, and a mixture of oxygen and argon through the top lance[3].
2. Bottom mixing gases – nitrogen or argon – injected through a system of individual tuyères[1].
3. Nitrogen and argon injected through 'canned bricks' – grooved refractory bricks in a steel envelope, allowing large gas flow rates at relatively low gas pressures (4 to 6 bar)[4].
4. Gas injection through low flow porous refractory plugs[1].
5. Mixed-blown systems, where a portion of the process oxygen is injected through the bottom alongside the inert gases[1,5]. Such mixing elements were similar to tuyères used in bottom-blown converters, enabling the injection of protective shrouding gases, e.g. natural gas.
6. Introduction of replaceable stainless steel tuyères in place of canned bricks.
7. Substitution of expensive argon by recycled carbon monoxide or carbon dioxide[6].

In most cases, the designs sustain gas injection rates in the range 50 - 300 Nm^3hr^{-1} at supply pressures of up to 16 bar. They incorporate metal tubes or canning materials that are exposed to the bath at the hot face. This exposure contributes to element and bottom wear as discussed below. The present paper introduces a new tuyère design that eliminates the need for any metallic structural material at the hot face, thereby contributing to longer element and bottom service life.

GAS INJECTION

The purpose of bottom gas injection is to promote bath mixing by transferring the buoyancy and circulation forces of rising gas packets or bubbles to the melt. Plant data suggests that bottom inert gas injection enables mixing between molten steel and oxidised slag to continue when evolution of the natural stirrer in the process – carbon monoxide gas – drops significantly. It is likely, therefore, that bottom injection benefits BOS for only about the last 30% of the oxygen blow as the decarburisation diminishes[4-6]. Bath agitation improves mass transfer between both the steel and gas phases and the steel and slag phases, leading to a lower oxidation state of the steel at tap, higher yield and better phosphorus partition. The effectiveness of mixing is measured by the CO product in steel (the multiple of carbon content in % and O_2 content in ppm)[3-5]. Steelmaking conditions are at equilibrium at a value of 15, but in the large scale manufacturing environment, a value around 20 ensures delivery of the benefits of the process.

In-situ Observations

Wear of the bottom mixing elements and surrounding refractories is a key factor limiting converter lining service life. Refractories surrounding the injection nozzles or tuyères in the element are subject to a combination of thermo-mechanical stresses. These stresses are associated with (i) the process thermal cycle, (ii) localized cooling originating from the stirring gas, and (iii) the localized agitation caused by the interactions between detaching gas globes and the liquid metal.

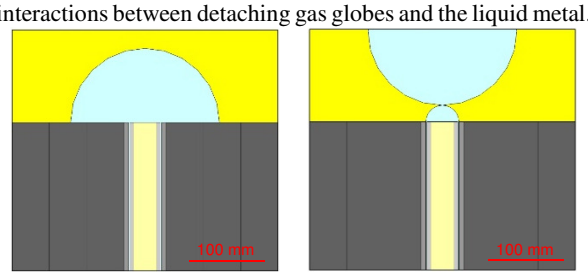

Fig. 1: Theoretical indication of gas globe growth and detachment from a multi-port tuyère[7].

Schematics in Figure 1 suggest two key steps in the repetitive gas dispersion sequence at an element surface: the growth of an initial hemispherical bubble and its evolution into a detached, rising envelope. This mechanism is discussed in greater detail below. After detachment, the gas stream at the tuyère is, like the hemisphere, momentarily pressed on to the surface of the element by liquid inertia, causing a localized impact. This is the 'back attack' effect. Another critical wear factor – the cooling effect – originates from the low temperature of the mixing gas blown through the element. As a result, the refractories surrounding it experience a two-dimensional thermal gradient. Its effect is visible in the

thermal image of a converter bottom, Figure 2, taken immediately after slagging the vessel off – the temperature of the tuyère is down to 1035ºC while the temperature of the surrounding lining is around 100ºC higher.
The back attack effect contributes mainly to the wear of the tuyère itself, while the cooling effect contributes to the wear of the adjacent refractories. The evolution and lateral growth of every gas packet generates local cooling at the element surface, and gas globe detachment is followed by back attack. The scale of both phenomena depends upon the gas flow rate. Increasing flow rate intensifies the back attack effect and increases the extent of the intermittent cooling effect as the basal diameters of gas packets increase. Finding the right balance between the gas flow rate and the wear rate is therefore essential for extending the service life of converter refractories while maintaining the benefits of the gas-assisted bath mixing process.

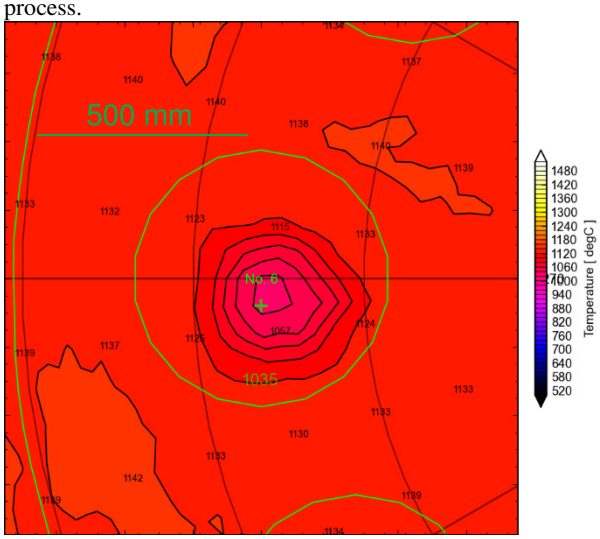

Fig. 2: Thermal image of a BOF tuyère after slagging off.

Recent plant data obtained by the authors suggest that the number of mixing elements installed in the bottom of a BOF has a much greater effect on efficiency of the mixing process than the individual gas flow rates. For example, trials with 3 tuyères operating at an individual gas flow rate of 300 Nm^3h^{-1} and 6 tuyères set to an individual injection rate of 125 Nm^3h^{-1} showed that mixing can be improved, gas saved and wear rates significantly reduced by choosing the right strategy for the mixing process. Furthermore, slag splashing and slag washing play a major role in extending the availability of the injection elements while maintaining the metallurgical benefits of the process. It is important to analyse the profile of the thermal cycle of a vessel before designing the slag maintenance practice. Analysing the slag chemistry in isolation can be misleading because improved mixing produces a more refractory slag that then enhances the effectiveness of slag maintenance by promoting thicker cover on the tuyères, which in turn results in reduced efficiency of the mixing process. Finally, it is important to minimise interactions between cavities in the bath created by the oxygen lance and the inert gas plumes originating from the bottom because reduced quantities of slag in the vicinity of the jet impact zone weaken mixing between steel and slag, while the force of the oxygen jets increases wear rate of the injection element[8].

POST MORTEM ANALYSIS

A detailed post mortem study of BOF multi-port tuyères consisting of a ring of small ports set between concentric stainless steel tubes with an MgO refractory core installed by ramming[9] revealed a typical cross-section of a 'hot end' tip shown in Figure 3. The porous accretion or 'mushroom' on top of the tuyère resulted from cooling by the stirring gas. This was present only on tuyères that were flowing when the vessel went out of service after a completed campaign (the tuyères isolated in the middle of a campaign did not have metal build up on top of the refractory core). The mushroom thickness varied between 10 and 35 mm, depending on the position of the tuyère in the converter, and whether it was formed either directly above the gas channel between the two stainless steel tubes, or on the refractory core.

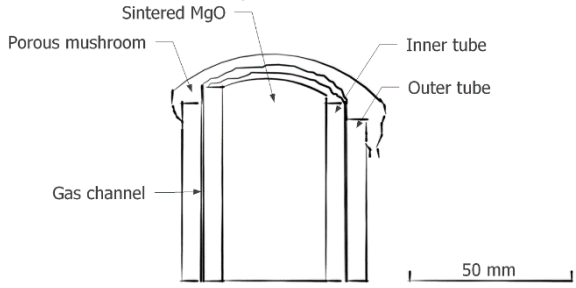

Fig. 3: Cross-section of a 'hot end' tip of a multi-port tuyère.

Careful examination revealed three types of metal penetration: (i) between the tuyère and the surrounding refractory bricks; (ii) into the gas channels; and (iii) between the inner stainless tube and the refractory core. The magnitude of the first type of metal penetration was proportional to the extent of wear of the refractory bricks surrounding the element; the more the bricks were worn, the deeper the metal could penetrate along the length of the tuyère. Metal penetration into the gas channels was found only in the tuyères that were isolated during the campaign.
The outer stainless steel tube was usually found to be shorter than the inner one. The difference in length varied between 5 and 30 mm, depending on the thickness of the mushroom and the extent of type (i) metal penetration. The refractory core was found to protrude above the two stainless steel tubes. MgO castable at the 'hot end' of the tuyère tip was surrounded by a mushroom in the form of a carbon steel build-up that solidified on the stainless steel tubes and above the monolithic refractory. The exposed MgO was always found in sintered form. The thickness of the sintered layer varied between 3 and 55 mm depending on the depth of metal penetration between the stirring element and the refractory lining[9].

Tab. 1: Overview of selected stirring element designs.

	Multi-Port Tuyère (MPT)	Single Hole Plug (SHP)	Multi Hole Plug (MHP)	Annular Slot Tuyère (AST)
No. of gas channels	30	1	24-32	1
Gas channel geometry	Semi-circle	Circle	Circle	Slot
Gas channel arrangement	Circle, 44.5 mm dia.	N/A	Rectangle, 36 x 84 mm	Annulus, 67 mm dia.
Material selection	Stainless steel, MgO	MgO-C, stainless steel	MgO-C, stainless steel	MgO-C
Method of production	Machining, ramming	Pressing	Pressing	Pressing
Method of installation	Cold or Hot	Cold	Cold	Cold
Min. gas flow rate [Nm^3h^{-1}]	100	50	100	50
Metallic accretion	+++	+/-	++	-
Slag protection	--	+/-	--	+

DESIGN FACTORS

Commercially available designs of bottom mixing elements have common features: the gas channels are circular or semi-

circular and made of stainless steel embedded in MgO or MgO-C refractory, and they can be installed cold, or hot after the campaign has commenced, but are difficult to protect using slag maintenance (Table 1). The presence of stainless steel at the working surface in the listed designs results in a common operational limitation: due to good wettability by molten metal, all of them require a minimum flow rate to both keep the stainless steel gas channels open and promote the growth of some sort of protective metallic accretion (which inevitably disrupts the gas dispersion mechanism). In cases of high wear rate, decommissioning and isolation of an element with steel components at the working surface is almost impossible: since operating temperatures are above the melting point of stainless steel, shutting the gas off is not an option as it would promote metal penetration into the brickwork, while poor wettability by molten slag would make the creation and maintenance of a slag cover very difficult.

The single-hole plug design shows slightly different behaviour to the other three diffusers listed in Table 1: due to a smaller total gas flow area, its maximum gas flow rate is relatively small. Consequently, the surrounding refractories experience proportionately smaller cooling effect, and the growth of metallic accretions is minimised, but at the cost of reduced effectiveness of the bath mixing process.

A NEW APPROACH

It should be clear from the foregoing discussion that the presence of metallic components in the working surface of a BOF gas injection element leads to operational shortcomings. The manufacturing convenience of using stainless steel tube, for example, to form gas flow channels through the refractory matrix of a tuyère block is self-evident provided that the performance-limiting risks of wetting and dissolution by liquid steel and blocking by accretion formation are considered acceptable. As modern BOF practice advances, lining wear and maintenance become increasingly prominent factors in vessel sustainability and operational costs. We suggest that premature lining maintenance due to the excessive localised wear and operational uncertainty of conventional bath agitation elements may have become counterproductive to an extent which now outweighs the apparent manufacturing advantages of their design.

Slot Technology

A slot shaped nozzle of almost any aspect ratio and flow area can be made by the simple expedient of placing two plates in parallel separated by spacing strips of suitable thickness and clamping them together. Likewise, a refractory slot-nozzle can be made by pressing and firing the matrix material around a fugitive strip of appropriate width and thickness. Key features of the refractory slot concept are that no secondary material, metallic or otherwise, is necessary to maintain the flow opening, and there is considerable freedom of choice for the channel dimensions.

Acknowledging these attributes, we have proposed a design of bath mixing element in which the gas flow path is a slot or annulus formed by fitting a circular refractory core into a circular hole in a refractory tuyère block with an appropriate annular spacing, the general overall dimensions being those of existing tuyère block designs[10]. The annular spacing and diameter can be chosen to emulate current bath agitation practice. As well as having considerable freedom to select flow path dimensions, an annular slot-based design offers wider freedom of choice of materials, enabling optimization of key properties such as wettability and thermal characteristics and enhancing the adaptability of the design to new applications.

WATER MODELLING

In order to find out how the injection characteristics of the annular slot tuyère compared with existing designs, a series of full-scale physical modelling experiments were done using helium injection into water over a range of injection rates from 50 to 200 Nm^3hr^{-1}. Two designs replicated in Perspex were investigated: a multi-port tuyère typical of current practice, and the new annular slot design. The dimensions are given in Table 1. Helium was used to model the process gas because the gas : liquid density ratio for He : water is similar to that of Ar : steel, thereby ensuring that jetting conditions at the point of injection would be dynamically similar. A digital camera operating at 250 frames per second recorded the injection events.

Two phenomena were highlighted because of their relevance to injection element performance: (i) the incidence and extent of back attack, and (ii) the formation of gas packets or globes. In both investigations, the dimensions and persistence of injection events were quantified by frame-by-frame analysis.

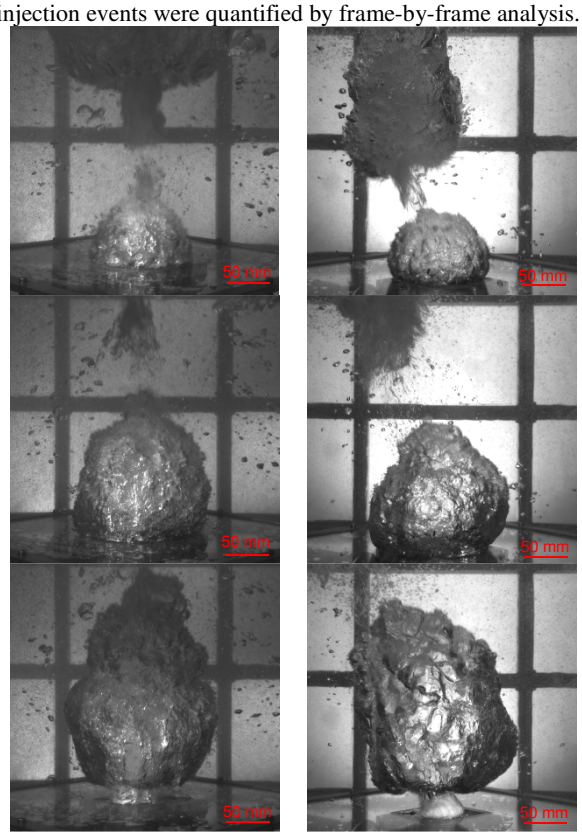

Fig. 4: Water modelling representation of gas globe growth and detachment from multi-port tuyère (left) and annular slot tuyère (right) at helium flow rate of 175 and 180 Nm^3h^{-1} respectively.

Gas Injection Behaviour

Upward gas injection into a liquid through a circular nozzle in a horizontal surface generates a sequence of dispersion events whose character depends upon a complex combination of the geometric, fluid and gas flow properties of the system. At relatively large, slow-moving gas flow rates into low viscosity liquids, a two stage mechanism can operate in which an expanding gas envelope is first pressed to the surface around the nozzle by hydrodynamic reaction, and then subsequently rises away from the plate under buoyancy[7]. This is the process suggested in Figure 1.

If the nozzle is replaced by a small-diameter ring of narrow jets or an annular slot, the same mechanism operates because the localized jets of gas merge to form a slower-moving combined flow. The injected gas stream behaves as if its source were a nozzle comparable in diameter to the ring or annulus, and the two step mechanism of envelope growth now applies to the combined flow. This process is clearly illustrated in Figure 4.

Back Attack Effects

The extent of back attack in the two designs was quantified by measuring the average spread of the initial envelope across the nozzle surface, as presented in Figure 5. The selected injection rates, 50 and 175/180 Nm^3h^{-1}, are representative of standby and operational conditions found in commercial practice. The annular slot tuyère produced marginally bigger gas globes at the two injection rates, but at impact diameters > 75 mm, the back attack behaviour of both designs was much the same despite the smaller diameter of the multi-port tuyère. The frequency of back attack for both designs at 75 mm impact diameter was in the range 7 to 10 Hz.

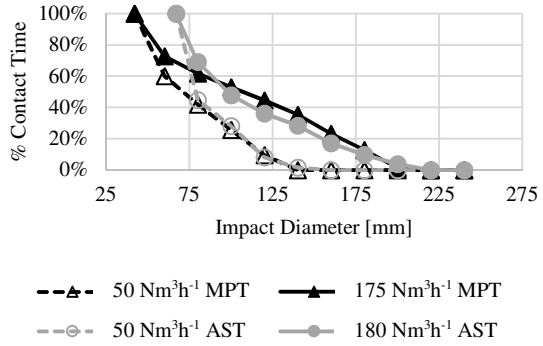

Fig. 5: Diameter of impact area vs. % contact time.

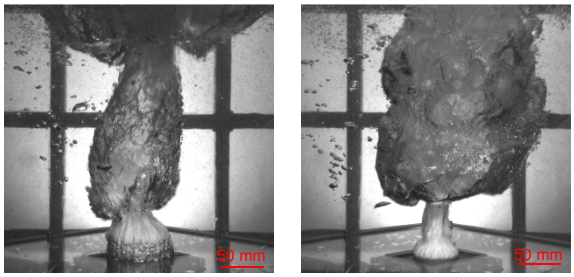

Fig. 6: Water modelling indications of mixing: pulsating gas column (left) and large gas envelope (right).

Gas Dispersion

Figure 6 shows two types of dispersion. In the first, successive envelopes have joined up in the rise path to form a pulsating gas column, illustrating possibly a less effective transfer of stirring energy to the bath. In the second, a large single envelope is seen, showing how circulation at the base draws in the liquid phase as it rises. This represents a more effective transfer of mixing energy.

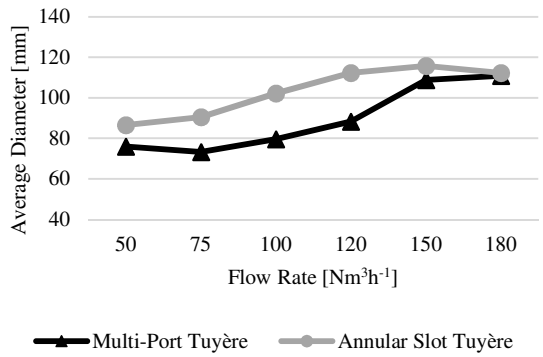

Fig. 7: Average diameter of back attack contact region (see Figure 4).

Figure 7 suggests the scale of the envelopes that form intermittently as a function of gas injection rate. The average diameter of the back attack impact region is seen to increase with gas flow rate for both modelled designs, but the tendency to form independent envelopes diminishes, and beyond a gas flow rate of 150 Nm^3h^{-1}, the growth in average impact diameter levels off. The relationship between the maximum spread of the initial envelope across the nozzle surface and the injection rate remains a continuing subject of study.

CONCLUSIONS

In-situ observations and post mortem studies reveal materials selection as a primary factor in the wear of current BOF stirring element designs and surrounding refractories. Wetting by liquid steel of the stainless steel present at the working surface not only promotes accretion formation and the resulting disruption of the gas dispersion but also facilitates metal penetration.

A new all-refractory design based on gas injection through an annular slot is proposed which offers greater freedom of choice of gas injection dimensions, materials and manufacturing method than is possible with existing designs. In addition, the absence of life-limiting metal components at the working surface is considered to offer valuable operational advantages.

A visual comparison of injection performance between the annular design and an existing multi-port ring design by full-scale water modelling with helium injection showed generally comparable gas dispersion behaviour over a range of injection rate from 50 to 180 Nm^3h^{-1}. The marginally larger diameter of the annulus promoted the growth of larger single gas envelopes, implying a reduced frequency of back attack events at comparable gas flow rates in the operational range of gas injection.

Continuing study will focus on the relationship between annulus geometry and wear parameters such as back attack intensity, element materials properties and operational practice.

REFERENCES

[1] Fruehan, R J. The Making, Shaping and Treating of Steel Steelmaking and Refining Volume. 11th. Pittsburgh : The AISE Steel Foundation, 1998.

[2] Kotraba, N L. PNEUMATIC STEELMAKING Volume One Tuyere Design. Warrendale : The Iron and Steel Society, 1988.

[3] Krieger, W, et al. ADVANCE IN THE LD PROCESS WITH BOTTOM STIRRING. Linz: VOEST-ALPINE AG, n. d.

[4] Normanton, A S, et al. Technical Status and Joint Development of the BSC/Hoogavens Bath Agitation Process and Scrap Enhancement in Basic Oxygen Steelmaking. [book auth.] N L Kotraba. PNEUMATIC STEELMAKING Volume One Tuyere Design. Warrendale : The Iron and Steel Society, 1988.

[5] Obakponovwe, O. Bath agitation literature review. Middlesbrough : Corus Research, Development & Technology Centre, 2006.

[6] Kishimoto, Y and Saito, N. Development and Prospect of Combined Blowing Converter in Japan. Tetsu-to-Hagane. 2014, Vol. 100, 4.

[7] Wraith, A E. Two stage bubble growth at a submerged plate orifice. Chem. Eng. Science. 1971, Vol. 26, 1659-71.

[8] Recent SMS Siemag Developments in BOF Steelmaking. Odenthal, H J, Schluter, J and Uebber, N. Trinec : Ocelot, 2014. EOSC 2014: Conference Proceedings.

[9] POST MORTEM ANALYSIS OF BOF TUYERES. Kubal, S K, et al. [ed.] D G Goski and J D Smith. Victoria : UNITECR, 2014. Proceedings of the Unified International Technical Conference on Refractories (UNITECR 2013). pp. 471-476.

[10] Kubal, S, Wraith, A E and Pleydell-Pearce, C G. ACCESS PORT ARRANGEMENT AND METHOD OF FORMING THEREOF. WO 2016/046548 23 September 2015.