The Determination of the Minimum and Operational Gas Flow Rates for Sidewall Blowing in the AOD-Converter

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Gas flow rates from the sidewall tuyeres in the AOD-converter can vary within large range during processing. Back-attack phenomenon, blocked tuyeres, uneven wear of refractory lining and oscillation of the bath set inconsistent demands for the optimum tuyere diameter, number of tuyeres and the angle between each tuyere. Oscillation of the liquid bath, mixing and the penetration of the gas jets with different sidewall blowing procedures were studied by a physical model. The aim of the present study was to determine the criteria for minimum and operational gas flow rate in the actual AOD based on the studied physical phenomena. According to the tests, minimum and operational gas flow rates through the different sized sidewall tuyeres can be defined by modified Froude number based on the appearance of the tuyere blockage (or back-attack) and oscillation. In sidewall blowing, the main reason for the oscillation of the bath is the symmetry of the plume on the vertical axis of the vessels caused by deep penetration of the gas jets. The nominal frequency of the oscillation of steel bath in the actual AOD was determined by dimensional analysis. The gas flow rate, which should be avoid is limited by appearance of oscillation of the bath. Penetration of the molten steel into the tuyeres determines the minimum gas flow rate from sidewall tuyeres. Smaller number of sidewall tuyeres and also a smaller diameter of tuyeres provide larger operational area as far as gas flow rate is considered.

KEY WORDS: AOD-converter; sidewall tuyere; gas flow rate; oscillation; back-attack; jet penetration; symmetrical plume.

1. Introduction

In the AOD, decarburisation of stainless steel is carried out with an oxygen–inert–gas mixture, increasing stepwise the inert/oxygen-ratio to prevent excessive chromium oxidation. During the reduction period, oxidised chromium is returned from the slag to the metal phase simultaneously with desulphurisation. Gas flow rates from the sidewall tuyeres can vary with large range during processing. This causes inconsistent demands for the optimum diameter, number and angle between each tuyere. The low gas flow rate causes back-attack phenomenon,1,2 blocked tuyeres3,4 and uneven wear of refractory.2,3,6 But, on the other hand with high gas flow rate strong oscillation5 and splashing occurs.

Flow patterns in AOD have been studied by using numerous of physical1–5 and numerical models.6,13 Themelis et al.14 derived well-known equation for the jet trajectory in the liquid bath. Igwe et al.15 and Hoelele and Brimacombe16 made semi-empirical correlations for the penetration of the gas jet with the submerged gas injection. Hoelele and Brimacombe16 found out also that the penetration of the jet increases with the modified Froude number \( (N_{Fr}) \) and the density ratio \( (\rho_g/\rho) \) as Themelis’14 equation predicts. According to the previous studies,6,10–13,17 the sidewall blowing in AOD generates two asymmetric mixing zones: a smaller mixing zone near the sidewall with tuyeres and the larger main mixing zone away from it. The position of the recirculation flow moves farther from the tuyeres with increased intensity of sidewall blowing.6,8,12

Injection of the gas into the bath can, in certain circumstances, cause a characteristic motion courses in the shape of circular or oscillating waves. This oscillation of the bath affects not only to the blowing operation, but also encumbers a vessel construction and causes an enhanced abrasion of the refractory lining18,19 Strong oscillations in the AOD were reported during inert gas blowing period.7 The wave motion appears only if the gas flow rate exceeds a critical value, which depends on the blowing conditions (position of tuyeres) and vessel geometry (diameter and height of the bath).19–20 It is important to notice that the wave motion in sidewall blowing system like AOD can be controlled by the angle between each tuyeres8,9 and the gas flow rate.8,9,21 In previous studies, there have not been presented the reason for oscillation of the metal bath in a sidewall blowing converter. This lack of information will be corrected in the present paper.

Wei et al.8,9 studied the effects of angular separation angle between two tuyeres, gas flow rate and the geometry of the tuyere on mixing efficiency and fluid flow in the AOD bath. In general, in many studies6,8,10,11,17 the excellent mixing of the AOD bath and the absence of a large
stagnant zone has been found out. In the present study, the delay times between different parts of the AOD vessel (measured by conductivity of water) were used to define the penetration of gas jets and the direction of the fluid flows as well as flow conditions in general.

The most used and important dimensionless number for determining the dynamic similarity for gas injection into the liquid bath is Froude number and its modifications.\(^5\),\(^8\),\(^22\)–\(^25\) It has been used in studies where mixing time\(^22\)–\(^26\) was determined and the preconditions for mass transfer during reactions\(^27\) were classified. Furthermore, the trajectories of gas jets in the bath\(^14\),\(^16\) and the shape of the plume\(^28\),\(^29\) are function of the modified Froude number. Modified Froude number has also been utilised to specify the penetration of molten steel to tuyere and based on that define the criteria for the minimum gas flow rate through tuyere.\(^3\)

In the present study, the effects of diameter of tuyeres, gas flow rate from tuyeres and angle of tuyere sector on oscillation of the bath, mixing (delay time) and trajectories of gas jets in the AOD were studied. The experimental tests were made by the dynamically scaled water model. The criteria for minimum and operational gas flow rate in the actual AOD-converter were presented by modified Froude number based on the studied physical phenomena.

2. Experimental Set-up

The fluid flows outside of the plume are generated by the gas injection through sidewall tuyeres. This means that flow patterns in AOD bath are mainly governed by gravity, buoyancy and inertial force \((\text{viz.}, \text{considering } N_{Fr}\gg N_{Re})\)\(^30\) Modified Froude number \((N_{Fr})\) is the most useful dimensionless number for describing those forces and dynamic similarity was defined for sidewall blowing by Eq. (1)\(^35\):

\[
N_{Fr} = \frac{\rho_u U_{g, nom}^2}{\rho_l g d} \quad \text{...............(1)}
\]

Where \(\rho_u\) is the gas density \((\text{kg/m}^3)\), \(\rho_l\) is the liquid density \((\text{kg/m}^3)\), \(g\) is acceleration due to gravity \((\text{m/s}^2)\), \(d\) is the diameter of the tuyere \((\text{m})\) and \(U_{g, nom}\) is the nominal velocity of the gas in the tuyere \((\text{m/s})\). Modified Froude number for the model and the actual AOD are presented in Fig. 1 as a function of gas flow rate. Modified Froude number was calculated for air in the model and for air and argon in the actual AOD. Dynamic similarity between the model and the actual system with the dimensionless diameter \((d)\) of tuyeres between 1.1–1.4 \(d\) is reached.

Water was used as a liquid phase in the isothermal cold model because of the nearly equal kinematic viscosity of water and liquid steel, \(\text{i.e.}\) slag layer was neglected. Geometric similarity between the model and the actual system was achieved (Fig. 2). Top lance was neglected because its effects on the shape and sizes of mixing zones in the bath are insignificant.\(^5\),\(^11\) Furthermore, the top lance is not even used during whole processing period in the actual process. The geometrical and operational parameters of the model and actual process are presented in the Table 1. In the Table 1 \(D\) means inner diameter of actual AOD and \(d\) is dimensionless diameter of tuyere. The tests were made with varied angle of the tuyere sector \((16\degree, 18\degree\text{ and } 20\degree)\) between each tuyere; Fig. 3 and air flow rate from each tuyere being \((0.020 \text{ Nm}^3/\text{min}, 0.050 \text{ Nm}^3/\text{min}\text{ and } 0.080 \text{ Nm}^3/\text{min})\). Furthermore, two different diameters of the tuyeres \((2 \text{ mm and } 3 \text{ mm})\) were used in the model.
The mixing and delay times were measured by the electrical conductivity method. Nine (9) copper electrodes were installed inside the model according to the Fig. 4. The tracer solution (NaCl) was injected to the liquid surface at the centre of the vessel at the vicinity of the electrode EL01. Measurements were done three (3) times with a constant concentration of the tracer solution at each experimental condition. The change of the ohmic resistance of water as a function of time was measured and collected by a data logger. The noise caused by gas bubbles was filtered away.

Delay time was defined as a time which fluid flow takes to transfer from an electrode to other. The hypothetic flow patterns in the model are based on the previous studies6,10–13,17) including two mixing zones.

The penetration of the gas jets into the liquid bath was defined by visual observations and conductivity measurements. Appearance of oscillation and the frequency of oscillation were determined visually. Oscillation frequency was calculated from the time demanded for 30 oscillations in the model.

3. Experimental Results

3.1. Mixing and Delay Times

The aim of the conductivity measurements was to examine mass transfer by convection in the liquid bath and to specify flow patterns with different blowing procedures. Mixing of the bath is described by time, which is demanded for one circulation of main circular flow. This is determined by observing and summarising delay times from electrode to other. The hypothetic flow patterns in the model are based on the previous studies6,10–13,17) including two mixing zones.
of 2 mm diameter. The velocities of main flows are higher when tuyeres of 3 mm diameter are used. The deviation between measurements was quite high because of the low sampling time of the data logger. According to the experiments, wide tuyere sector (20° angle between two tuyeres) provides more effective mixing. This agrees with the results of the study made by a water model with two sidewall tuyeres. Mixing measurements indicated clearly that mixing is effective in AOD bath regardless of the studied blowing procedures.

3.2. Oscillation of the Bath

Kato et al.\(^\text{19}\) demonstrated in their studies two kinds of wave motions: type A and type B (Fig. 7). When the gas flow rate from the tuyeres exceeds the critical value in the present work, the whole bath oscillates from a trunnion to the other trunnion as seen in the case of oscillation of liquid in a U-shaped tube (type A in the Fig. 7(a)). According to the tests, the type A is the dominant in the case of the model also. There existed casual rotational wave in some studied cases.

The oscillation was not observed in all studied blowing procedures. The frequencies of the observed oscillations and used blowing procedures are collected in the Table 2. The results of experiments show clearly that the frequency of the oscillation in the model is independent of the gas flow rate, the diameter of tuyere or the angle between each tuyeres (Table 2). These results agree well with the findings of Xie and Oeters.\(^\text{18,20}\) They measured equal value of oscillation frequency for the model with similar diameter to in the present work.\(^\text{18}\) However, the appearance of oscillation is dependent on the blowing procedure (the gas flow rate, the diameter of tuyere and the angle between each tuyere). Larger tuyeres (3 mm) need higher gas flow rate and narrower angle between each tuyere than smaller tuyeres (2 mm) for generating oscillation of the bath.

3.3. Penetration of the Gas Jets

The jet trajectories in the model bath with the diameter of 2 mm and 3 mm tuyeres during sidewall blowing are presented in the Fig. 8. It shows that the flow patterns in the all cases with tuyere of 3 mm diameter are analogous with the earlier studies\(^\text{6,10–13,17}\) (Fig. 8(A) and Fig. 9(A)). When 2 mm diameter of tuyeres were used, the flow patterns change with the most intensive blowing (0.080 Nm/min/tuyere) used in the present work (Fig. 8(B)). In this case, the penetrations of gas jets are great and only one large mixing zone was formed far from the tuyeres and the direction of the main circular flow is contrary (Fig. 9(B)).

The measured average penetration of the gas jets in the model are summarised in the Table 3. Presented values are average penetrations of the jets with the different angle between each tuyeres (16°, 18° and 20°). The increase of the
gas flow rate provides better penetration of the jets but the circular motion of the liquid arrests the increase of the penetration. Therefore, the increase of the penetration is minor and lesser than e.g. Themelis’s equation\(^{14}\) predicts. When the direction of the main circular flow changes (2 mm; 0.080 Nm\(^3\)/min/tuyere), the penetrations of the jets increase more clearly with the parallel liquid flows. Dimensionless penetration of gas jet \((D_m')\) in the model was calculated by Eq. (2)

\[
D_m' = \frac{l}{D_m} \quad \text{(2)}
\]

where \(l\) is the measured average penetration of gas jet into the liquid bath (m) and \(D_m\) is the inner diameter of model.

Table 3 shows that jets penetrated nearly on the centre of the model if gas flow rate 0.080 Nm\(^3\)/min/tuyere was used with 3 mm tuyeres and 0.050 Nm\(^3\)/min/tuyere with 2 mm tuyeres.

The average penetrations of the jets calculated by Eq. (3), which is presented by Hoefele and Brimacombe,\(^{16}\) are lesser than the measured penetrations in the model. The Eq. (3) does not take into account the effects of the vessel diameter and the interaction of the other jets. Furthermore, the equation has been verified by experiments, in which blowing is mainly on the bubbling-area. On a bubbling-area the measured and calculated values agree quite well but on a jetting-area, especially with 2 mm tuyeres, the differences are large (Table 3).

### Table 3. Average penetration of the gas jet into the model bath.

<table>
<thead>
<tr>
<th>Tuyere (mm)</th>
<th>Number of test in Fig. 8</th>
<th>Gas flow rate (Nm(^3)/min/tuyere, S.T.P.)</th>
<th>Measured penetration (m)</th>
<th>Dimensionless penetration, (D_m')</th>
<th>Calculated by eq. (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>0.020</td>
<td>0.07</td>
<td>0.15</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.050</td>
<td>0.13</td>
<td>0.28</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.080</td>
<td>0.20</td>
<td>0.43</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.020</td>
<td>0.11</td>
<td>0.23</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>0.050</td>
<td>0.21</td>
<td>0.45</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.080</td>
<td>0.35</td>
<td>0.74</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

where \(l\) is the average penetration of gas jet into the liquid bath (m).

4. Discussion

4.1. Minimum Gas Flow Rate in the Actual AOD

The minimum gas flow rate through the tuyere is determined by the appearance of back-attack\(^{1,2}\) and the penetration of liquid steel into the tuyere during blowing.\(^{3,4}\) Both of those phenomena are the function of buoyancy or Froude number.\(^{1,3,4}\) Increase of the gas flow rate and decrease of the tuyere diameter minimise the risk for the penetration of molten steel into the tuyere\(^{5}\) and the appearance of back-attack.\(^{3}\) The criteria for penetration of molten steel to the vertically positioned tuyere demands that modified Froude number \((N_{Fr})\) for blowing must be higher than 2,500.\(^{3}\) According to Wei et al., the circular motion of the liquid in the bath strengthens the back-attack phenomenon. The buoyancy force not only increases the back-attack intensity but also enlarges the local wear of refractory lining.\(^{1}\) Thus, \(N_{Fr} = 2,500\) is the absolute minimum intensity for sidewall blowing. The minimums for argon and air flow rates through different sized tuyeres in the actual AOD are shown in the Fig. 10 and also in the Table 4. The criterion \((N_{Fr} = 2,500)\) is marked by vertical grey bar in the Fig. 10.

4.2. Operational Gas Flow Rates in the Actual AOD

In the present study, the operational feed pressure was not taken into account but operational intensity of blowing was determined on the basis of the appearance of the wave motion on the liquid surface. The observed oscillation is mainly from a trunnion to the other trunnion as seen in the case of oscillation of liquid in a U-shaped tube (type A). The energy of the wave motion in the type A is much higher than in the type B with constant stirring energy because

![Fig. 10. Minimum and operational gas flow rates for the actual AOD determined by modified Froude number (nominal gas velocity was used) with different sized tuyeres.](image-url)
of the higher amplitude of the wave.\(^\text{(19)}\) This is harmful for the constructions of the AOD.

According to Xie and Oeters,\(^\text{(18,20)}\) the frequency or the oscillation period of the wave motion is independent of the gas flow rate and the density of the liquid but mainly depends on the vessel diameter. The oscillation period \(T_0\) or vessels nominal frequency of oscillation can be represented by an undamped simple pendulum and be calculated by Eq. (4).\(^\text{(20)}\)

\[
T_0 = 2\pi \left( \frac{R}{g} \right) \left[ \frac{3.2}{\left( \frac{3}{13} \right)^{2/3}} \right] \left( \frac{2.5}{32R} \right)^{1/4} \] .................................(4)

where \(R\) is the radius of the vessel (m) and \(A\) is the amplitude of the wave (m). Relationship between amplitude and radius of the vessel is always quite small in the studied system and therefore the latest term on the right side of the Eq. (4) can be neglected. In addition to the Eq. (4), the dimensional analysis was utilised to determine the nominal frequency of metal bath oscillation in the actual AOD. On the basis of the evidence available in the literature,\(^\text{(18–20)}\) the oscillation frequency of the gas-stirred bath is a function of geometric parameters and gravity and therefore can be presented according to the Eq. (5):

\[
f = \varphi (H, D, g) \] .............................................(5)

where \(H\) is the height of the liquid bath (m) and \(D\) is the diameter of the bath on the surface (m). Solving the dimensional analysis by matrix method\(^\text{(18)}\) two different dimensionless numbers \((\pi_1, \pi_2)\) can be derived from the Eq. (5).

\[
\pi_1 = H^1 \cdot D^{0.5} \cdot g^{-0.5} \] .............................................(6)

\[
\pi_2 = H^1 \cdot D^{-1} \] .............................................(7)

On the basis of the Buckingham’s theorem, the Eq. (6) is valid if the Eq. (7) could be proven to be true. Because the Eq. (7) describes relationship between linear dimensions, it is clear that for the geometrically similar vessels Eq. (7) is always true. Then the frequency of the oscillation in the actual AOD could be calculated by Eq. (8) formed from Eq. (6).

\[
f = k \cdot \frac{g}{D} \] .....................................................(8)

where \(k\) is constant (\(-\)). According to the oscillation tests, \(k=0.28\) for the geometry of the model. Measured and calculated frequencies of the oscillation in the model and in the actual AOD are summarized in the Table 5. The agreement with measured and calculated values is good. According to the findings of Xie and Oeters,\(^\text{(20)}\) the oscillation demands so-called ‘starting time’ for the regular high amplitude wave motion. The regular wave motion starts rapidly if the high bath depth and the strong gas flow rate are used.\(^\text{(19)}\) Thus, in the actual AOD the oscillation with the nominal frequency \(f=0.43\) Hz should be observed by sensors. If the oscillation with the nominal frequency is observed, the oscillation can be avoided by changing the gas flow rate through the tuyeres before it causes damage for constructions of AOD vessel.

The main reason in the studied blowing procedures, for the oscillation of the bath was the symmetry of the plume on the vertical axis of the vessel (Fig. 8). Only if the jets penetrated into the centre of the vessel and the plume on the surface was symmetrical, the oscillation of the bath was observed. This was noticed clearly by blowing procedure \(0.080\) m\(^3\)/min/tuyere through \(3\) mm tuyeres and \(0.050\) m\(^3\)/min/tuyere through \(2\) mm tuyeres regardless of the angle between each tuyere (Fig. 8, Table 3). Xie and Oeters\(^\text{(18)}\) found out that with nozzles positioned at the near of the centre of the vessel bottom facilitated the formation of the oscillation. Wei et al.\(^\text{(31)}\) have reported violent oscillation and splashing of the liquid with high gas flow rate in the water model of AOD when the angle between two tuyeres was more than 130 degrees. The results of these previous studies\(^\text{(31)}\) support the principles presented in the present work.

The penetrations of the gas jets with different sized tuyeres are able to present by modified Froude number \((N_{\text{fF}})\). The effects of the compressibility of gas and the dependence of the sonic velocity from the feed pressure were not taken into account and therefore nominal gas velocity was used for calculation of Froude number. Modified Froude numbers in the actual AOD and in the model with \(2\) mm tuyeres are shown in the Fig. 10 as a function of argon and air flow rates. The appearance of the oscillation \((0.3 \cdot 10^4 < N_{\text{fF}} < 0.75 \cdot 10^4), i.e. the gas flow rates which must be avoided in the actual AOD, are marked by ruled box in the Fig. 10. The penetrations of gas jets into the bath with different blowing procedures are described by vertical bar on the left of the Fig. 10 and by numbers 4–6. Numbers 4–6 and their penetrations have been presented in the Fig. 8. In the Table 4 the avoidable gas flow rates with argon blowing are summarised for different sized tuyeres in the actual AOD. Model studies indicate that the direction of the main circular flow changes when the intensity of gas blowing in the model achieves value \(N_{\text{fF}}=0.75 \cdots 0.80 \cdot 10^4\) (dark grey vertical bar in Fig. 10). Figure 10 and Table 4 show that operational area is larger with tuyeres of \(1.1d\) and \(1.2d\) diameter. When larger tuyeres \((1.3d\) and \(1.4d)) are used, operational
area between the appearance of back-attack and oscillation is very narrow. It is possible to extend the operational area by decreasing the number of tuyeres. In this case, the modified Froude number for an individual gas jet will increase if the total gas flow rate is unchanged.

As mentioned above, examinations show, that the penetrations of the gas jets define the behavior of liquid bath as a physical aspect. In the present study, isothermal cold model without chemical reactions was utilized to determine the penetration of the jets, although in the actual AOD thermal expansion of gas bubbles and reactions have important role. Thus, the effects of thermal expansion and reactions on gas trajectory must be discussed. According to the research of Oryall and Brimacome, the penetration of the jet in the steel-oxygen-inert gas system is clearly reduced because of the more rapid expansion of the jet. The reduced penetration is a result of higher liquid density and an increase in the buoyancy force acting on expanding cold bubbles due to heat transfer between the bubbles and liquid. The reduction of penetration will be amplified if the reactions between the gas and the melt are exothermic or if the reaction results in a net increase in moles of gas. Bubble expansion due to the heat transfer resulted in the increase of gas holdup in the radial direction. This agrees with the results presented by Figueras and Szekely that the penetration distribution of the gas jet in AOD is large and the jet angle varies between 20–155 degrees. It has to be notified, that Oryall and Brimacome and Iguchi have made their tests on a bubbling-area of blowing. But in the actual AOD, the sideway blowing is on a jetting area. In the present study blowing works on the jetting area with 2 mm tuyeres when gas flow rate 0.08 Nm³/min/tuyere was used. With lower gas flow rates it works in the transition area or in the bubbling area.

Previous calculations by Themelis’s equation predict that during decarburization the gas plume can be divided into two parts: inert gas concentrated head part and back part including reactive oxygen and its reaction products. The dividing of gas plume extends the jet cone angle in steel bath. Calculations and observations from the real AOD indicated that penetration of gas jets is deepest with inert gas blowing. Then, with relatively large tuyeres, the appearance of the oscillation is the most probable during reduction period or at the end of decarburisation period when the value of inert gas flow rate is highest (Fig. 8(A)). The appearance of oscillation is possible during decarburisation period; nevertheless, according to calculations and model tests the penetration of the jets should be over the centreline of the vessel (Fig. 8(B) compare with 0.080 m³/min/tuyere blowing).

The merging of the individual gas jets also affects on the trajectories of the jets. The merging of the individual gas jets happened in all studied blowing procedures. Merging is caused by Coanda effect which, based on the uneven pressure distribution surrounding of the jets. The merged jet acts in bath as an individual gas jet and facilitates the starting of the oscillation of the bath. The blowing was on the bubbling-area with 3 mm tuyeres in the present work. Bigger bubble size, achieved with 3 mm tuyeres, strengthens the Coanda effect and the oscillation appears with lower values of modified Froude number (Fig. 10).

According to the tests, the best blowing procedure for the actual AOD has 20° angle between each tuyere and tuyeres with 1.1d or 1.2d diameters. This procedure provides effective mixing and large operational area of sideway blowing. By this blowing procedure, the reaction zone will be far from the tuyeres during decarburisation and the oscillation of the bath will not occur because of the change of the direction of main circular flow. Furthermore, the risk of the blockage of the tuyeres and the appearance of back-attack is lower.

5. Conclusion

According to the model tests, following conclusions have been achieved based on the mixing and oscillation measurements.

1. Minimum and operational gas flow rates through the sideway tuyeres can be defined by modified Froude number based on the appearance of the physical phenomena like tuyere blockage, back-attack and oscillation.

2. Intensive gas blowing through sidewall tuyeres changes the direction of main circular flow in AOD bath especially with inert gas blowing if the ratio of the bath height and diameter is high.

3. In sideway blowing, the main reason for the oscillation of the bath is the symmetry of the plume on the vertical axis of the vessel caused by deep penetration of the gas jets.

4. With relatively large tuyeres the appearance of the oscillation is most probable during reduction period or at the end of decarburisation period because the penetration of the jets is highest while blowing inert gas.

5. On the contrary, with relatively small tuyeres the penetration of the gas jets is deeper and then the symmetrical plume and the oscillation of the bath is most probably achieved during decarburisation period.

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