1. Introduction

Relative to other refining methods of stainless steel, the most conspicuous advantage of the argon–oxygen decarburization (AOD) process is its excellent effectiveness of removing the carbon and reducing the chromium loss, and it has now become an integral component part in the modern producing route of stainless steel. In the recent years, as a technological progress of this refining process of stainless steel, using high carbon and chromium hot metal as the main raw material with altering from simple side blowing into combined side and top blowing1–5) has been a tendency in order to lower the energy and scrap consumptions as well as the manufacturing cost. Several large combined side and top blowing AOD converters have been completed and put into operation in China.

The fluid flow in the bath during the blowing process is closely related with the heat and mass transfer, thus with the dynamic and combined equilibrium and rates of all the refining reactions, governing the efficiency and result of the AOD refining to a large extent. In a traditional AOD process, several annular tuyeres set up on the side wall near the bottom of the vessel are usually employed to conduct horizontal side blowing and injection. Due to the high speed and high pressure of the gas blow, the momentum of the gas streams can agitate the liquid in the vessel, and the gas jets from the top lance can create a high-velocity gas flow and flow pattern in the bath.

In a traditional AOD process, the gas blowing rate and the angle of the tuyere have a significant effect on the fluid flow and mixing characteristics in the bath. A large blowing rate will create a vigorous fluid flow pattern in the bath, whereas a small blowing rate will result in a weak fluid flow pattern. The angle between each tuyere also affects the fluid flow pattern, and the larger the angle, the more uniform the mixing of the gas blowing streams will be. Moreover, the angle between each tuyere also affects the efficiency of the gas blowing, and the larger the angle, the more efficient the gas blowing will be. Therefore, it is important to select the appropriate blowing rate and tuyere angle to achieve a uniform fluid flow pattern in the bath.
combined side and top blowing, the available reports in the literature are few. Impact of a gas top blowing jet against the bath surface would be able to change the flow pattern of the bath liquid resulted from the gas side blowing streams. Fabritius et al.\(^3\)–\(^5\) performed some water modeling studies of the fluid flow and mixing and others in the bath during the combined side and top blowing process of stainless steel in a 90 t AOD converter. According to the obtained results, they improved the former blowing technology and certain effectiveness was achieved. However, they ignored the influence of the gas jet from a top lance\(^3\)–\(^5\); and the comparision between the model and its prototype was not full, thus their results obtained were not necessarily able to reflect truly the real situations in their experiments was not full, thus their results obtained were not necessarily able to reflect truly the real situations in the prototype. At the prerequisite of keeping the kinematic similarity between the model and its prototype as high as possible, Wei et al.\(^12\),\(^13\) conducted preliminarily the physical modeling of the combined side and top blowing refining process of stainless steel in a 120 t AOD converter. Nevertheless, since the converter was not completed at that time, some key data, including the dimension of the side tuyere and blowing operation and others, were all set up in terms of the technological design and had considerable disparities from the actual practice. In that case, it was difficult to evaluate precisely the friction factors of side main tuyeres and subtuyeres to gas streams for both the model and its prototype, and the calculation accuracies of the gas blowing rates used for the model were also lower, leading to that the kinematic similarity between the model and its prototype was also insufficiently kept. On the basis of the preliminary investigation, with the 120t AOD converter completed and put into operation as a prototype, the factors and the gas side and top blowing rates used for the model were precisely determined to ensure the kinematic similarity between the model and its prototype being sufficiently high; and the gas stirring as well as the fluid flow and mixing characteristics in the bath, the back-attack phenomenon of the gas side blowing streams and its effect on the erosion and wear of the refractory lining and others during the combined blowing refining were systematically studied using water modeling. The influences of the related blowing technological and geometric factors were examined. The results concerning the gas stirring and fluid flow characteristics in the bath are reported in the paper.

2. Similarity Conditions and Gas Flow Rates for the Model

The completed 120t combined side and top blowing AOD converter is equipped with seven tuyeres (annular tube type with constant cross-sectional area) and one top lance (Laval type with single hole); compared to the prototype taken in the preliminary investigation,\(^12\),\(^13\) the vessels of the both are same, but the sizes of the tuyeres and top lances used are different from each other. Like that done in the preliminary investigation, the modified Froude number \(Fr'\) was still taken as a decisive similarity number for both the side and top blowing in this system,

\[
Fr' = \frac{\rho_g}{\rho_l} \frac{u_g^2}{g d} \approx \frac{\rho_g}{\rho_l} \frac{u_g^2}{g d}
\]  

Here, \(u_g\) is the gas velocity, m/s; \(d\) is the characteristic dimension of the system, m; \(\rho_g\) and \(\rho_l\) are, respectively, the density of the gas and the liquid, kg/m\(^3\); \(g\) is the acceleration due to gravity, m/s\(^2\).

Under the prerequisite of maintaining the geometric similarity between the both, taking \(d\) as the inner diameter of the tuyere or the throat diameter of the lance, the gas flow rates at the standard state for the tuyere and lance of the model can be obtained from \((Fr')_m = (Fr')_p\) as follows,

\[
Q_m = Q_p \left(\frac{\rho_{g0} h_m}{\rho_{g0} h_p}\right)^{1/2} \left(\frac{\rho_{lm}}{\rho_{lp}}\right)^{1/2} \left(\frac{d_m}{d_p}\right)^{5/2}
\]  

where \(Q\) is the volumetric flow rate of gas at the standard state, Nm\(^3\)/h; \(\rho_{g0}\) is the density of the employed gas at the standard state, kg/Nm\(^3\); \(\rho_l\) is the density of the employed gas at the tuyere or lance outlet, kg/m\(^3\); subscripts m and p denote, respectively, the model and its prototype.

For a given model and prototype system, the key of the matter is the determination of \(\rho_{gm}\) and \(\rho_{gp}\), especially for those of the gas side blowing streams from their main tuyeres and subtuyeres; the reasonability of their values is directly concerned with the extent of kinematic similarity between the both. The gas streams in the tuyeres utilized for the model and its prototype can be regarded as adiabatic and heating friction flows, respectively. First of all, the friction factors of the tuyeres for the model and its prototype to gas streams during blowing processes must be fixed reasonably and accurately. Here, the values of these factors at the two kinds of flow were precisely determined by comparison of the pressure–flowrate relationships measured respectively in water modeling experiment and practical blowing to the results of the trial calculations of the gas stream properties, as shown in Table 1, in which the values taken in the preliminary investigation\(^12\),\(^13\) are also given for comparison. There are obvious discrepancies due to the different sizes of the tuyeres used in the both and the raise of measurement and calculation precision in this work.

![Table 1](image)

<table>
<thead>
<tr>
<th></th>
<th>Heating friction factor of side tuyere for 120 t AOD converter</th>
<th>Adiabatic friction factor of side tuyere for 120 t AOD converter</th>
<th>For water model (1:4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>for 120 t AOD converter</td>
<td>for 120 t AOD converter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Main tuyere** Subtuyere**</td>
<td>Main tuyere** Subtuyere**</td>
<td></td>
</tr>
<tr>
<td>Full blowing*</td>
<td>0.00379 (0.0036)</td>
<td>0.01041 (0.0062)</td>
<td>0.0034 (0.0028)</td>
</tr>
<tr>
<td></td>
<td>0.00872 (0.0072)</td>
<td>0.02187 (0.0034)</td>
<td>0.0062 (0.0110)</td>
</tr>
</tbody>
</table>

* The level heights of molten steel and water are 1940 and 485 mm, respectively.
** Obtained by estimation from results of empty blowing, with reference to data from side tuyere used for water model.
† The data in parentheses are the values used in the preliminary investigation\(^11\),\(^15\).
And the gas side blowing rates of the main tuyere and sub-
tuyere for the model corresponding to the gas blowing rates
of the prototype during the practical refining process were
determined in terms of the following two cases:

1) Considering only heating friction flow of the gas in
the tuyere used for the real refining process.

2) Taking both heating friction flow of the gas in the
tuyere employed for the real process and heat expansion of
the main tuyere gas after entering the bath into account.

The results of theoretical calculations of the properties for
the gas stream and evaluation of the heat transfer between
the stream and liquid steel in the converter demonstrated
that the outlet temperature of the subtuyere gas stream
would have achieved or slightly exceeded the mean value of
the gas in the bath, therefore, it would not be necessary to
consider heat expansion of the subtuyere gas in the bath.

The results obtained for the main decarburization period
of the blowing process of 304 grade stainless steel in the
120 t AOD converter with the values of some related pa-
rameters are shown in Table 2, being markedly different
from those given in the preliminary investigation, and hav-
ing also much higher accuracies. Relevantly, the kinematic
similarity between the model and its prototype is much bet-
ter than that in the preliminary investigation.

In addition, besides heating friction flow of the gas in the
tuyere for the practical refining and heat expansion of the
main tuyuer gas after entry into the bath, an increase in the
gas flow rate caused by formation of CO in side blowing
process at a high initial carbon content of 3.5 mass% or so
was also considered, and the corresponding gas blowing
rate for the model was fixed.

Since the hot metal employed for the practical refining in
the 120 t AOD converter under consideration is all predesil-
iconized and the initial silicon concentration is very low,
the influence of formation of solid and liquid oxides (espe-
cially SiO₂) during the side blowing process on the gas
blowing rate of the main tuyere for the model was still ig-
nored in the present work, like that done in the preliminary
investigation.

For the top blowing process with a gas–liquid two-phase
system composed of a non-submerged gas jet and the bath
liquid, the relevant \( \rho_{\text{go}} \) and \( \rho_{\text{gol}} \) can be taken as \( (\rho_{\text{go}})_{\text{p}} \) and \( (\rho_{\text{gol}})_{\text{h}} \), and the gas flow rate for the top lance of the model
at a given oxygen top blowing rate of the prototype can di-
rectly be attained from Eq. (2).

Since the zone considered for a gas top blowing process
is at the bath surface (which belongs to a gas–liquid sys-
tem) and not at the lance outlet, the outlet March number of
the gas jet from the lance for the model and the relevant gas
supply pressure must be less than those for its prototype, in
order to satisfy Eq. (2) thus ensure the kinematic similarity
of the model with its prototype.

### 3. Experimental Methods

Except the tuyeres and top lance, the model apparatus
(including the tuyere position arrangement and the gas sup-
plying systems) of the 120 t AOD converter used for water
modeling experiments with a geometric similarity ratio of
1:4 (Fig. 1), was entirely the same as that used in the pre-
liminary investigation. It should be pointed out that the
geometrical similarity between the tuyeres for the model
and its prototype was not kept entirely because of the size
limits of the brass tubes and difficulty on mechanical work-

<table>
<thead>
<tr>
<th>120 t AOD converter</th>
<th>Side main tuyere</th>
<th>Side sub tuyere</th>
<th>Model (1:4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total gas flow rate for side blowing, Nm³/h</td>
<td>1110 x 7</td>
<td>90 x 7</td>
<td>7.446 x 7</td>
</tr>
<tr>
<td>( \rho_{\text{gp}} ), kg/Nm²</td>
<td>1.2846</td>
<td>1.1461</td>
<td>1.1845</td>
</tr>
</tbody>
</table>

- 1 and 2 are for cases where heat expansion of side main tuyere gas after entry into bath of 120 t AOD converter was not and considered, respectively.
- * If it was treated in terms of the geometric similarity ratio of 1:4, the value of \( \rho_{\text{gp}} \) was 550.74, being equal to the value of the prototype, but the appropriate value of \( \rho_{\text{gol}} \) was somewhat different from the value calculated theoretically, about being 97.13 m/s.

![Fig. 1. Schematic diagram of the model unit of the 120 t AOD converter utilized for water modeling experiments.](image-url)
ing. However, the difference from the sizes needed by the geometrical similarity was small, and the inner diameter of the main tuyere and the width of the subtuyere were still maintained geometrically to be similar to the prototype. Polystyrene particles of 1 mm diameter and 0.97 g/cm$^3$ density were taken as a tracer, an SLV-50 adjustable green laser generator with frequency scanning offered a laser slit light source. The flow patterns of the liquid in the bath were demonstrated and photographed under these conditions. Besides directly visualizing the gas stream trajectories and liquid flow patterns in the bath, as well as the fluctuation and splashing extents of the liquid at the bath surface, photographs of the gas side blowing streams and the liquid surface at each operating mode were gotten with incandescent light shadowgraph. The whole process of the experiment was also recorded using a video recorder.

The influences of the angle between each tuyere, the tuyere number, the gas side and top blowing rates on the gas agitation and liquid flow, as well as the stabilities of the bath and liquid surface and others were examined. For more effectively investigating the role of the gas side blowing rate and comparing better to the practical refining process, besides the three cases mentioned above, the relevant gas side blowing rates for the model were also determined in terms of the assumed three other cases, which were (1) adiabatic friction flow of the gas in the tuyere for the real process, (2) adiabatic friction flow of the gas in the tuyere with gas heating expansion, and (3) adiabatic friction flow of the gas in the tuyere with gas heating expansion and the generation of CO. Corresponding to the real oxygen flow rate of 6 600 Nm$^3$/h (being 7 200 Nm$^3$/h in the preliminary investigation) and the assumed two rates of 6 000 and 5 400 Nm$^3$/h for the top blowing, the gas flow rates for the model were calculated, respectively being 79.87, 72.61 and 65.35 Nm$^3$/h. The operating modes used in this work are given in Table 3, with a total of 240 operating modes.

Compared to the operating modes taken in the preliminary investigation, the total side blowing gas flow rates of the model main tuyeres used in the present work were much larger, while the appropriate gas top blowing rates were reduced to some extent. These were resulted from the changes in the size of the tuyere for the prototype and the practical blowing technology, as well as from a raise of calculation precision. Although the total gas side blowing rate of the prototype subtuyeres was still 630 Nm$^3$/h, the gas side blowing rates of the model subtuyeres used in the present work were also larger than those in the preliminary investigation. Moreover, a set of gas side blowing rates and a gas top blowing rate were added in this work, i.e. VI and No. 3 in Table 3. Thus, with increasing by 90 operating modes, their influences can be better and more comprehensively examined. The gas flow rates and operating modes given here also provide a reliable basis for water modeling of the mixing in the bath as well as the back-attack phenomenon of side blowing gas streams and its effect on the erosion and wear of the refractory lining.

### Table 3. All the operating modes utilized for water modeling experiments in the present work.

<table>
<thead>
<tr>
<th>Assumed situation of gas stream in side tuyere used for the prototype*1</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total gas flow rate for side tuyeres, Nm$^3$/h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for main tuyeres</td>
<td>45.49</td>
<td>62.92</td>
<td>79.38</td>
<td>52.12</td>
<td>73.05</td>
<td>92.16</td>
</tr>
<tr>
<td>for subtuyeres</td>
<td>5.28</td>
<td>7.43</td>
<td>7.43</td>
<td>9.62</td>
<td>9.62</td>
<td>9.62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top gas blowing rate, Nm$^3$/h</td>
<td>79.87</td>
<td>72.61</td>
<td>65.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side tuyere number/Angular separation between each tuyere, deg</td>
<td>18, 22.5</td>
<td>22.5, 27</td>
<td>22.5, 27, 31.5</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid level height in bath, m</td>
<td>0.485</td>
<td>Distance of top lance outlet from bath surface, m</td>
<td>0.500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*1 – adiabatic friction flow; 2 – heating friction flow; 3 – considering heat expansion of side main tuyere gas; 4 – considering CO generation in side blowing process.

### 4. Experimental Results

Corresponding to the side blowing gas rates of case VI (92.16 Nm$^3$/h for the main tuyeres and 9.62 Nm$^3$/h for the subtuyeres) and the top blowing gas rate of No. 1 (79.87 Nm$^3$/h) shown in Table 2, the liquid flow patterns and the formations of gas streams and liquid surface in the bath obtained at different tuyere numbers and angular separations between two adjacent tuyeres are presented in Figs. 2–6. Here, Fig. 2 shows those under the conditions of the simple side and combined blowing with the given tuyere number of 7 and an angle of 18° between each tuyere. Figures 3–6 illustrate the relevant results during the simple side and
combined blowing when using 7 tuyeres with 22.5°, 6 tuyeres with 27°, 5 tuyeres with 31.5°, and 4 tuyeres with 45°, respectively.

It can be inferred that the situations at the side blowing gas rates of case VI and the top blowing gas rate of No. 1 given in Table 2 would more approach to the practice. For saving space, only a very small part of the experimental results are given here, but the gas agitation and fluid flow characteristics in the bath during the combined side and top blowing AOD process can still fully be reflected.

5. Analysis and Discussion of Results

5.1. Features of Gas Agitation and Liquid Flow in Bath under Conditions of Simple Side Blowing

It can be seen during the blowing experiments and from the photos given here that in the case of simple side blowing, on the whole, the gas stirring and liquid flow pattern in the bath were essentially similar to those observed in the preliminary investigation. It appears that changes in the main tuyere and sub tuyere sizes and their gas flow rates did not alter evidently the basic features of the gas stirring and liquid flow in the bath. However, due to the intensification of the gas agitation, by comparison, after the gas having blown into the bath through the tuyeres from the side wall near the bottom of the vessel, the respective penetration distances of the streams along the horizontal direction in the bath liquid deepened to some extent; during turning in swinging into an upward motion and ascending of the gas streams under the combined action of the inertial and buoyant forces, the streams located at the middle exerted a more obvious attraction on those at their both sides, and a more great quantity of smaller bubbles was generated; when escaping of the gas inside the gas–liquid two phase flow into the gaseous phase above the bath, the top liquid surface level of the two-phase zone was still higher than the surface.
level around the zone, fluctuating motion of the whole liquid surface of the bath caused by this part of the liquid dropped down under the action of the gravitational force was still more violent, resulting in even more strongly lashing and erosion on the sidewall opposite the tuyere outlets; vortices and eddies formed in the bath were still more, the liquid in the whole bath was in even more vigorous stirring and circulatory motion.

It can be expected that during the practical blowing process, the mixing efficiency in the bath of the 120 t AOD converter would be higher than that given in the preliminary investigation.

5.2. Effects of Side Number Tuyere and Position

The influences of the tuyere number and position (the angle between two adjacent tuyeres) on the characteristics of gas agitation and liquid flow in the bath were very obvious and could, to a great extent, govern the stability of blowing process, especially when the gas side blowing rate used being larger. At a given tuyer number and gas side blowing rate, the smaller the angle between each tuyere, the easier the intersecting and merging of the gas streams as they rose in the bath, the stronger the interactions among the gas streams, the more dynamic the bath liquid surface, and the worse the stability became. In the case of side blowing through 7 tuyeres, the interactions among the gas streams at an angular separation of 22.5° between each tuyere were weaker than those with an angle of 18° between each tuyere, and appropriately, the stability of the bath liquid surface was better. When using 6 tuyeres to conduct the simple side blowing, the sequence of the interactions among the gas streams from strong to weak was successively with an angle of 18°, 22.5° and 27° between each tuyere, the stability of the bath liquid surface was best with an angular separation of 27° between each tuyere. For the simple side blowing through 5 tuyeres, the bath liquid surface was most active at an angle of 18° between each tuyere, particularly at the operating mode corresponding to case VI in Table 2, the surface being acutely swinging, even making the whole model unit shake; correspondingly, the instability of the bath liquid surface successively decreased in terms of an angle of 18°, 22.5°, 27° and 31.5° between each tuyere. Under the conditions of the present work, the flow field of the bath liquid was also more uniform when using 4 tuyeres with an angular separation of 45° between each tuyere.

At a given tuyere number and gas side blowing rate, the larger the angular separation between each tuyere, the larger the total area of the sector zone included by the tuyeres; relevantly, the larger the area occupied by the gas–liquid two-phase zone at the bath liquid surface, and the more homogeneous the gas stream stirring to the bath was. With a larger gas side blowing rate (corresponding to cases III and VI in Table 2), the area occupied by the gas–liquid two-phase zone at the bath liquid surface was approximately (45~50)% of the cross-sectional area of the bath when using 4 tuyeres with 45° or 5 tuyeres with 31.5°. In the case of using 6 tuyeres with 27° or 7 tuyeres with 22.5°, the area occupied by the gas–liquid two-phase zone at the bath liquid surface could also reach about 40% of the cross-sectional area of the bath; appropriately, the penetrated distance of the gas streams in the horizontal direction was shorter than that at the former two kinds of tuyere equipment and arrangement schemes.

At a given gas side blowing rate, an increase in the tuyere number decreases the gas flow rate for single tuyere, thus making the penetrated distance of the gas streams along the horizontal direction shorten. In the case of the simple side blowing with a total gas flow rate of 101.78 Nm³/h, the distance was approximately 1/3 of the bath radius when taking 7 tuyeres, and could come to about 2/3 of the radius with 5 tuyeres.

In fact, the tuyere number is not an independent variable. At a given tuyere position and gas side blowing rate, the variation of tuyere number can make the total area of the sector zone included by the gas streams and the agitation range change, also make the gas flow rate for single tuyere vary, leading to altering of the outlet parameters and penetrated depth along the horizontal direction for the gas streams and the interactions among them and others, thus influencing their stirring actions and the flow patterns of the liquid in the bath.

5.3. Influence of Gas Side Blowing Rate

The gas side blowing rate had a decisive effect on the gas stirring and liquid flow condition in the bath. At a given tuyere number and angle between each tuyere, the penetrated distance of the gas streams along the horizontal direction increased with an increase in the gas side blowing rate (see Fig. 7). Corresponding to a total gas side blowing rate of 50.77 Nm³/h (case I in Table 2), the distance was only approximately 1/4 of the bath radius under the condition of using 7 tuyeres with 18°, much lower than the penetrated effectiveness at a total gas flow rate of 101.78 Nm³/h. With regard only to the stirring, the larger the gas side...
blowing rate, the higher the stirring work input the bath, and the more vigorous the bath liquid surface became. At the maximal gas side blowing rate (case VI in Table 2), when using 5 tuyeres with 31.5° and 4 tuyeres with 45°, the liquid fallen down from the top level of the two-phase zone could form the waves as high as about 15 cm at the bath liquid surface and surge towards the sidewall opposite the outlets of the tuyeres, and make obvious oscillation of the bath surface generate. In this case, the stability of the bath surface was reduced, and the top of the gas–liquid two-phase zone was foamed to a considerably high degree.

At a smaller gas side blowing rate, the liquid flow pattern in the whole bath was more smooth and steady, only the liquid surface near the outlet side of the tuyeres was more dynamic due to continuously escaping of the gas into the atmosphere above the bath, but being unable to bring about serious splashing, and the caused fluctuation of the bath liquid surface being unable to lash and erode seriously the sidewall opposite the tuyere outlets.

5.4. Effect of Gas Top Blowing Rate

The experimental observations and the photos given here also demonstrated that by impact of the non-submerged gas jet blown from the top lance, a sunken pit was formed at the central location of the bath liquid surface. Simultaneously, violent fluctuation (with a different mode from that caused by the gas side submerged blowing streams) and serious splashing of the liquid occurred at the bath surface. This was also similar to that observed in the preliminary investigation. The impinging of the gas top blowing jet on the surface also increased the back pressure supported by the gas side blowing streams, which was taken into account in determining of the friction factors of the tuyeres mentioned above. At this time, the liquid below the central sunken pit flowed downward, exerting a restraining role to the gas discharge in the tuyeres and to the ascending motion of the gas–liquid two-phase flow formed by the gas side blowing streams, and also pushing the liquid below the sunken pit to flow towards the periphery wall. In addition, the liquid outside the sunken pit was forcedly pushed towards the periphery wall along the radius direction, then moved downward along the wall, forming the appropriate circulatory flow, which could also accelerate the upward (at the outlet side of the tuyeres) and downward (at the side opposite the tuyere outlets) motion of the bath liquid along the wall resulted from the gas side blowing streams. The bath liquid moved in this way under the impinging of the gas top blowing jet interacted with the moved liquid in the bath resulted from the gas side blowing streams, making the liquid flow pattern in the bath vary and the turbulent degree increase. The larger the gas top blowing rate, the larger the appropriate impinging force exerted on the bath surface, the deeper the sunken pit formed at the surface, and the more evident the change of the liquid flow pattern in the bath was. At a smaller gas top blowing rate (case No. 2 or 3), the sunken pit formed at the central location of the surface was shallower than that at a gas flow rate of 79.87 Nm³/h, relevantly, the disturbing intensity to the liquid motion in the bath brought about by the gas side blowing streams lowered, the splashing of the liquid at the bath surface markedly reduced, and the liquid surface was more stable. This situation is peculiar to a combined side and top blowing process. These results obtained showed that neglecting the role of the gas jet from a top lance is obviously improper. Under the conditions of combined side and top blowing, the motion state of the liquid in the bath would be a composite result from a common action of the multiple gas side blowing streams and the gas top blowing jet.

For the practical refining process, the specified gas side and top blowing rates, large or small, are dependent on the real requirement of the refining reactions, their adjustability and flexibility are imperfect. Hence, the effects of the tuyere number and position given above are more significant, and may be utilized to be a consulting basis for selecting and optimizing the tuyere equipment and arrangement. The existing tuyere equipment and arrangement of 7 tuyeres with an angular separation of 18° for the 120t AOD converter cannot provide a perfect stirring and uniform liquid flow pattern in the bath, and would be altered.

In view of a much higher kinematic similarity between the model and its prototype, the results obtained in the present work would be closer to the real situations than those in the preliminary investigation, can still better reflect the gas stirring and fluid flow characteristics in the bath of the 120 t AOD converter, and used to test the reasonability and reliability of the results of mathematical modeling on the relevant fluid flow.

The back-attack phenomenon of the gas side blowing streams was clearly visualized during the experiments. Compared to those in simple side and bottom blowing processes, the gas side streams in the combined process showed themselves back-attack characteristics. It has also been investigated and the concerned results will be specially reported in other two papers.

5.5. Estimation of Gas Agitation Power

(1) For Side Blowing Gas

With respect to the gas agitation power in a gas stirring ladle system, there are different estimation equations in the literature, but all of those have some shortcomings, mainly, being that the considerations for buoyancy and expansion work during floating up of the bubbles are not so proper. A more comprehensive analysis for that was made by Wei et al. Using their following expression, the agitation power densities of the gas stream from side tuyere at the different operating modes, ε ms (W/t), were estimated,

$$ ε_{ms} = ϵ_b + η_1 ϵ_t + η_2 ϵ_b $$

where $ ϵ_b $ is the real “buoyancy power” term; $ ϵ_t $ is the expansion power term of the gas at a constant pressure near the tuyere outlet; $ ϵ_b $ is the kinetic energy term; $ M_i $ is the liquid mass ($ = 0.255 t $); $ P_0 $ and $ P_t $ are the pressures of the atmosphere and the gas at the tuyere outlet, $ P_0 $; $ H_i $ is the depth of the tuyere axis, i.e. the height of the liquid above
the tuyere axis, m; \( T_2 \) is the gas temperature at the tuyere outlet, K; \( T_a \) is the mean gas temperature reached after enter into the bath, K; \( u_g \) is the gas velocity at the tuyere outlet, m/s; \( \eta_1 \) and \( \eta_2 \) are the stirring efficiencies of the expansion power of the gas at a constant pressure near the tuyere outlet and the kinetic energy, separately. The various \( T_a \) were estimated in terms of the method described in Ref. 23). Not taking the power loss due to interaction among the gas side blowing streams into account, the results calculated are shown in Table 4. The total densities of gas agitation for the side blowing under the conditions of this work were about 230–600 W/t, much larger than those (150–320 W/t) in the water model of an 18 t AOD vessel.9) This is related to the discrepancies of the gas blowing rates and tuyere numbers used for the both. Also, these values are much higher than those (4.5–8.0 W/t) gotten by Figueira and Szekely8) according to two times of the “buoyancy power” for a 45 t AOD vessel and the intensity of induction stirring in a 50 t ASEA-SKF furnace as evaluated by Nakanishi et al.24) As pointed out by Figueira and Szekely, the kinematic similarity of the model to its prototype in their modeling experiments was very poor. Their results cannot truly reflect the actual situation.

It is necessary to point out that the agitation power density of the side blowing gas is closely concerned with the outlet parameters of the gas stream for single tuyere. At a given total gas side blowing rate, the density would change with the variation of the tuyere number, the more the tuyere employed, the smaller the density will become.

(2) For Top Blowing Gas

There are more reports for the agitation of a top blowing jet to the bath in the literature, some expressions for calculating its agitation power have been proposed.25,26) Due to the concrete conditions used being different from each other, the expressions given by researchers are with large discrepancies, and not necessarily suitable for the present work. The following equation derived from the energy balance was used for evaluating the agitation power density of a gas top blowing jet, \( \varepsilon_{mt} \)27)

\[
\varepsilon_{mt} = \frac{1}{2} \frac{A_g u_g^2}{M_1} \sqrt{\frac{2k}{k-1} \frac{P_1^2}{RT_1} \left[ \frac{P_0}{P_1} \right]^{\frac{2k}{k-1}} - \left( \frac{P_0}{P_1} \right)^{\frac{k+1}{k}}} 
\]

where \( A_g \) is the cross-sectional area of the top lance outlet, m\(^2\); \( u \) is the velocity of the gas jet from the top lance reached at the liquid surface of the bath, m/s; \( P_1 \) is the gas supply pressure of the top lance jet, MPa; \( T_1 \) is the inlet temperature of the top lance gas, K; \( P_0 \) is the surrounding pressure, approximately being 0.1 MPa. Using the experimentally determined depth of the sunken pit formed by the gas top blowing jet at the bath surface (\( h_s \)), \( u \) was found in terms of \( \rho_g \frac{u^2}{2} = \rho_l gh_s \). As a consequence, for the gas top blowing rates of 65, 72, and 78.87 Nm\(^3\)/h used in this work, the calculated agitation power densities were about 35, 50, and 70 W/t, respectively.

Since the agitation power density of the side blowing gas varies with the change in the tuyere number at a given total gas side blowing rate, the contribution of the top blowing gas jet to the total agitation power density of gas also changes with the differences of the tuyere number and the gas side blowing rate.

Corresponding to the gas stirring and liquid flow pattern described above, there must be the relevant mixing characteristics in the bath. The related results to the mixing in the bath will be reported in the following paper.28)

6. Conclusions

With sufficiently high kinematic similarity between the model and its prototype, a water modeling study on the gas stirring and fluid flow in a 120 t AOD converter bath during the combined side and top blowing refining process of stainless steel was carried out. The results demonstrated that,

(1) The liquid in the whole bath is in vigorous agitation and circulatory motion during the gas blowing process.

(2) The gas side blowing rate has a decisive role on the gas stirring and liquid flow pattern in the bath. As far as only the stirring is concerned, the larger the gas side blowing rate, the higher the power input the bath, the more dynamic the bath and its liquid surface are.

(3) The angle between each tuyere can evidently influence the gas stirring and fluid flow in the bath. At a given tuyere number and gas flow rate of side blowing, the larger the angular separation between each tuyere, the more homogeneous the gas stream stirring to the bath becomes.

(4) The gas jet from the top lance can make the gas stirring and liquid flow pattern in the bath caused by the gas side blowing streams change and the liquid turbulence enhance; the larger the gas top blowing rate, the more obvious the appropriate variation is.

(5) The existing tuyere equipment and arrangement of 7 tuyeres with 18° for the 120 t AOD converter cannot provide a perfect stirring and uniform liquid flow pattern in the bath, and would be altered.

(6) The results obtained can be used to test the reasonability and reliability of the mathematical modeling for the fluid flow phenomena in the bath during the combined side and top blowing AOD refining process of stainless steel.

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**Table 4.** Agitation power density of gas at side blowing rates used in the present work (W/t).

<table>
<thead>
<tr>
<th>Gas side blowing rate, Nm(^3)/h</th>
<th>45.49</th>
<th>52.12</th>
<th>69.92</th>
<th>73.05</th>
<th>79.38</th>
<th>92.16</th>
<th>5.28</th>
<th>7.43</th>
<th>9.62</th>
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<tbody>
<tr>
<td>Number of side tuyere</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>224.64</td>
<td>265.97</td>
<td>338.80</td>
<td>412.58</td>
<td>458.66</td>
<td>556.53</td>
<td>23.21</td>
<td>33.23</td>
<td>44.02</td>
</tr>
<tr>
<td>5</td>
<td>216.91</td>
<td>255.09</td>
<td>322.04</td>
<td>390.25</td>
<td>435.51</td>
<td>531.03</td>
<td>23.05</td>
<td>32.82</td>
<td>43.15</td>
</tr>
<tr>
<td>6</td>
<td>211.63</td>
<td>247.58</td>
<td>310.02</td>
<td>373.16</td>
<td>414.89</td>
<td>504.44</td>
<td>22.97</td>
<td>32.59</td>
<td>42.65</td>
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<tr>
<td>7</td>
<td>208.06</td>
<td>242.40</td>
<td>301.49</td>
<td>360.78</td>
<td>399.78</td>
<td>483.24</td>
<td>22.91</td>
<td>32.44</td>
<td>42.36</td>
</tr>
</tbody>
</table>

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REFERENCES