Physical modeling was done to study the flow field in a cylindrical bath agitated by bottom purging, top lance blowing and a combination of both injection types. A particle image velocimetry (PIV) system has been used to capture the velocity field of all three cases mentioned above. Special attention was paid to the recirculation loop. Top blowing creates a re-circulation loop in a relatively small volume close to the surface, compared to bottom- and combined-blowing. Increasing bottom flow rate moves the center of the re-circulation loop downwards into the liquid. When top blowing is combined with bottom blowing the center of the re-circulation loop is moved downwards into the liquid with increasing top lance flow rate.

KEY WORDS: fluid flow; reactor; bottom purging; lance blowing.

1. Introduction

In metallurgical processes involving injection of gas, either from the top or from the bottom of the vessel, a good understanding of the flow field of the bath is desirable. This is important in order to increase the control of the process. Possible usages would be not only the obvious control of reactions in the vessel, but also control over refractory wear and the formation and removal of inclusions.

A large number of texts cover bottom blowing. Combined top and bottom blowing has been discussed by for instance Diaz-Cruz et al. and Koria. Iguchi et al. measured the mean velocity- and turbulence-distribution in a bottom blown bath. In another study by Iguchi et al., the bubble rising velocity, due to central bottom injection, was investigated when the bath was covered with silicone oil layer, acting as slag. In the same article the mixing time was evaluated. Iguchi et al. also investigated the establishment time of the bath during bottom blowing, as well as the bubble characteristics when the system was under low pressure. Bradshaw and Wakelin gave a relationship for the penetration depth on a bath surface caused by an impinging gas jet. Nordqvist et al. investigated the swirl motion in a bath induced by an impinging jet. Turkdogan studied the depression of the liquid surface during top blowing as well as the critical impact pressure at which the depression becomes unstable. Diaz-Cruz et al. investigated both the mixing time and the splashing characteristics in the top-, the bottom- and the combined-blowing cases. Koria studied the bath mixing intensity in combined blowing as well as top- and bottom blowing.

In this work a Particle Image Velocimetry (PIV) system has been used to capture the velocity field of all three cases mentioned above. The effects of the top jet on the combined case have been studied, especially compared to the bottom injection case. Data have been presented in such a way so that numerical analysis of the results should be simple. The bubbling jet has been left out of the presented data; instead the characteristics of the re-circulation region have been studied. The aim of this work was to investigate the effect of top blowing on the velocity field in the combined blowing case. In the first part of the paper the experimental setups as well as the experimental conditions are described. Thereafter, the theory for evaluating the experimental data is given. Finally, the results from the measurements are presented and discussed.

2. Experimental Setup

The flow field in the water was determined using a PIV system with model name Ultra CFR Nd: Yag laser. A schematic of the setup can be seen in Fig. 1. The PIV system gives information of the flow field of the liquid. It combines a double-pulsed laser with a video camera and tracer particles. First, the laser illuminates a sheet, of a plane, in the fluid and then the video camera records the positions of the added tracer particles. A fraction of a second later the laser illuminates the sheet again and the camera takes another recording. From the two sheet images, the software then calculates the flow field. In order to obtain more statistics this process is repeated a number of times (e.g. 50 or 100). The mean velocity can then be calculated.

De-ionized water was used in order to minimize the occurrence of erroneous readings. Also, special care was taken to remove bubbles at the walls of the experimental equipment. A black background was set at the far side of the camera. At the start of an experiment, the cylinder (ф200 mm) was filled with water to an initial height of 275 mm. Thereafter, the tip of the lance nozzle (ф2 mm)
was set to 50 mm above the undisturbed bath surface. Also, when used, the bottom nozzle (Ø2 mm) was placed in line with the center axis of the cylinder. The tracer substance used was a polymer from MCI GEL® with model name CHP2OP. It has a density of 1.03 g/cm³ and a diameter distribution of 75–150 μm. Before the tracer particles were added to the de-ionized water, they were subjected to Ethanol in order to remove trapped air inside the particles. This is important since trapped air causes unwanted buoyancy. Before each experiment there was a short time to let the flow field stabilize, this time was small, usually less than 5 min.

Three cases have been studied:
1. Top blowing
2. Bottom blowing
3. Combined top- and bottom blowing
Each case has a number of conditions set, which can be seen in Table 1.

### Table 1. Experimental conditions during the PIV measurements.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Q_{b,top} [cm³/s]</th>
<th>Q_{b,bottom} [cm³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>283</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>283</td>
<td>16.7</td>
</tr>
<tr>
<td>3</td>
<td>283</td>
<td>27.1</td>
</tr>
<tr>
<td>4</td>
<td>333</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>333</td>
<td>16.7</td>
</tr>
<tr>
<td>6</td>
<td>333</td>
<td>27.1</td>
</tr>
<tr>
<td>7</td>
<td>333</td>
<td>49.5</td>
</tr>
<tr>
<td>8</td>
<td>417</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>417</td>
<td>16.7</td>
</tr>
<tr>
<td>10</td>
<td>417</td>
<td>27.1</td>
</tr>
<tr>
<td>11</td>
<td>417</td>
<td>49.5</td>
</tr>
<tr>
<td>12</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>700</td>
<td>16.7</td>
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<td>14</td>
<td>700</td>
<td>27.1</td>
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<tr>
<td>15</td>
<td>700</td>
<td>49.5</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>16.7</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>49.5</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>92.0</td>
</tr>
</tbody>
</table>

3. Equations Used

Cylindrical coordinates are used in order to describe the system, where \( u, v \) and \( w \) are the velocity components in the radial, azimuthal and axial \((r, \theta, z)\) directions respectively. Only the axial and the radial velocity components were registered in the experiments. The mean velocities; \( U, W \) are calculated as follows:

\[
\overline{u} = U = \frac{1}{N-1} \sum_{i=1}^{N} u_i \quad (1)
\]

\[
\overline{w} = W = \frac{1}{N-1} \sum_{i=1}^{N} w_i \quad (2)
\]

where \( N \) corresponds to the number of data samples.

4. Results

Since the bubbling jet affects the laser the readings on the left side of the axis are less accurate (see Fig. 1 for the setup). Accordingly, the right side of the flow field has been the main viewpoint. The flow field in the bath can be classified as having a number of regions \( i.e. \), the momentum-, the transition-, the buoyancy- and the surface-region as well as the re-circulation region.\(^7\) The first four regions describe the bubbling jet and the re-circulation region is outside the bubbling jet.

4.1. Fluid Flow

Figure 2 shows a vector plot of the mean velocity in a two-dimensional plane where the symmetry plane is on the left side. Data are presented for a case when only bottom purging was used and the follow gas flow rates, \( Q_b \): (a) 16.7 cm³/s, (b) 49.5 cm³/s and (c) 92.0 cm³/s.

![Fig. 1. Schematic of experimental setup when using the PIV system.](image)

![Fig. 2. Mean velocity distribution in a two-dimensional plane where the symmetry plane is on the left side. Data are presented for a case when only bottom purging was used and the follow gas flow rates, \( Q_b \): (a) 16.7 cm³/s, (b) 49.5 cm³/s and (c) 92.0 cm³/s.](image)
49.5 cm$^3$/s and (c) 92.0 cm$^3$/s. As can be seen the water is lifted up towards the surface due to buoyancy forces resulting from the gas that is injected. Thereafter, the flow is directed towards the wall and further downwards towards the bottom of the vessel. This gives rise to a recirculation loop. The higher the gas flow rate the more the main recirculation loop is moved downwards into the bath close to the wall.

In Fig. 3 data for both top blowing and combined top and bottom blowing are shown. The flow rate in the top lance was 283 cm$^3$/s and the flow rates in the bottom located nozzle were as follows: (a) 0 cm$^3$/s, (b) 16.7 cm$^3$/s and (c) 27.1 cm$^3$/s. When gas is injected only through the top lance (Fig. 3(a)), it is seen that only the top part of the fluid is affected. Also, if the results in Fig. 2(a) and Fig. 3(b), for the same bottom purging rate, are compared it can be seen that the main re-circulation loop is closer to the surface for the case when combined blowing is used compared to when only bottom purging is used. It seems like the axial momentum from the gas jet at the liquid surface counteracts the axial momentum from the rising liquid. Thus, the overall fluid flow pattern is changed.

Figure 4 also represents data from experiments using both top blowing and combined top and bottom blowing. The flow rate in the top lance was 333 cm$^3$/s and the flow rates in the bottom located nozzle were as follows: (a) 0 cm$^3$/s, (b) 16.7 cm$^3$/s, (c) 27.1 cm$^3$/s and (d) 49.5 cm$^3$/s. Similar to what was seen in Fig. 3, use of only top blowing will only affect the fluid flow in the upper part of the vessel despite the increase in flow rate from 283 to 333 cm$^3$/s. By comparing the results in Figs. 3 and 4 it can also be seen that for the same gas-purging rate an increased gas injection through the top lance will move the location of the main re-circulation loop downwards. Also, an increased gas-purging rate will move the center of the main re-circulation loop downwards. However, note that for the experiment using a 283 cm$^3$/s gas flow rate in the top lance and a 16.7 cm$^3$/s flow rate in the bottom located nozzle, the recirculation loop only moves downwards slightly.

In Fig. 5, data for both top blowing and combined top and bottom blowing are shown. The flow rate in the top lance was 417 cm$^3$/s and the flow rates in the bottom located nozzle were as follows: (a) 0 cm$^3$/s, (b) 16.7 cm$^3$/s, (c) 27.1 cm$^3$/s and (d) 49.5 cm$^3$/s. When comparing the results in Fig. 5(a) with those in Fig. 4(a) it is seen that the increase in flow rate from 333 to 417 cm$^3$/s results in a more obvious radial movement of the fluid from the gas plume towards the wall. Also, when comparing the results in Fig. 4(c) with those in Fig. 5(c) it is seen that the increased injection rate of gas through the top lance will move the center of the main re-circulation loop downwards. However when examining 4(b) and 5(b) it seems that the center of the recirculation loop has roughly the same position.

Figure 6 also represents data from experiments using both top blowing and combined top and bottom blowing. The flow rate in the top lance was 700 cm$^3$/s and the flow rates in the bottom located nozzle were as follows: (a)
0 cm$^3$/s, (b) 16.7 cm$^3$/s, (c) 27.1 cm$^3$/s and (d) 49.5 cm$^3$/s. It is seen in Fig. 6(a) that for this high gas injection rate the momentum from the gas jet is so high that the fluid flow in approximately half of the cylinder is affected. When comparing the results in Figs. 5 and 6 it is also seen that the higher gas injection rate through the top lance will have such a high momentum so it will dramatically counteract the momentum from the rising liquid. Thus, the fluid flow pattern in Fig. 6 becomes more complicated than in Fig. 5. It is also more difficult to define clear main recirculation loops in the results for the higher gas flow rate data.

4.2. The Re-circulation Loop

Here a study how parameters in the vortex, i.e. the main re-circulation loop, change for the different experimental conditions is presented. A crosshair was placed over the center of each vortex, as illustrated in Fig. 7. The center was determined, first visually, and then by using the PIV data to locate the position with the lowest velocity magnitude. From the measuring points contained in the crosshair the mean axial velocities are plotted in Figs. 8–10. Note, that the axial locations of the crosshairs are different for the different experiments in the following figures.

Figure 8 shows a plot of the axial velocity as a function of the radial distance from the symmetry plane. Data are shown for a case where only bottom blowing has been used and for flow rates of 16.7 to 92.0 cm$^3$/s. As expected the highest axial velocities are found at the center of the vessel close to the plume, where gas is injected. The axial mean velocities decrease with radial distance from the center of the vessel. In general, the effect of an increased gas-purging rate on the mean velocity is relatively small. Close to the wall the difference between downward directed axial velocities for the different purging rates is larger than for the data closer to the plume. This is mainly due to that the overall fluid flow change as discussed earlier in the paper.

In Fig. 9 the axial mean velocity distribution as a function of the radial distance, through each center of the vortex, is shown for experiments using combined top-lance blowing and gas purging. The flow rate in the top lance is
283 cm$^3$/s and the bottom flow rate, $Q_b$, varies as indicated in the figure. When gas is injected only through the top lance the axial mean velocity profile is much flatter than when combined blowing is used. More specifically, the axial mean velocity only varies between 0.016 m/s close to the plume and $-0.016$ m/s (downwards) close to the wall.

For the experiments using combined blowing the axial mean velocities are as high as 0.044 m/s close to the plume and $-0.062$ m/s (downwards) close to the wall. The results for the two different gas-purging rates are very similar except for close to the wall. Similar to what was said regarding the results in Fig. 8, the change of the stirring conditions mainly has an effect on the overall fluid flow in the region close to the wall.

Figure 10 shows the axial mean velocity distribution as a function of the radial distance from the center of the cylinder at the axial location where the center of the vortex is located. The flow rate in the top lance is 333 cm$^3$/s and the bottom flow rate, $Q_b$, varies as indicated in the figure. When comparing the data in Figs. 9 and 10 for the experiments using only top blowing it is seen that the axial velocity is very similar for both gas flow rates. For the experiments using combined blowing the axial mean velocities for the three different gas-purging rates are very similar close to the plume. However, close to the wall the data differ, which is due to that the flow conditions are changed when the purging rate is changed, as also mentioned earlier. It should also be mentioned that exactly the same trends were found when plotting a similar plot as in Fig. 10, but changing the flow rate through the top lance from 333 to 417 cm$^3$/s.

Figure 11 shows the position of the center of the vortex in the bath. Different top lance flow rates are compared as well as different bottom purging rates. From the figure it is clear that increasing bottom purging lowers the center of the re-circulation loop if comparing trials 16–18. Top blowing only (trials 1, 4 and 8) follows the same pattern, with the center of the re-circulation loop moving further down into the liquid with increasing flow rate. When combined blowing is used the general trend is that increasing top blowing will push the center of the re-circulation loop downwards, compared to bottom blowing only, as can be seen when comparing trials 2 and 5 with 16 or when comparing 7 with 17. Also, at a constant bottom purging rate of 16.7 cm$^3$/s trials 3, 6 and 10, this trend is well shown.
5. Discussion

Inspection of Figs. 2–6 reveals that an increase in bottom flow rate changes the position of the re-circulation loop. Top blowing has, as expected, a relatively low impact on the bath re-circulation loop compared to bottom blowing, however when combined with bottom blowing it changes the overall flow field of the bath. By comparing Fig. 2(a) with Figs. 3(b)–6(b) this change in the flow field can be seen. With higher flow rates from the top lance, the center of the re-circulation loop is, in most cases, moved downwards into the bath.

In comparing the results in Figs. 3–6 it is also clear that at the highest gas flow rate of 700 cm$^3$/s, Fig. 6, the effect of the top lance injection on the overall fluid flow is suddenly quite large. One explanation for that can be due to an increased effect of the momentum from the gas on the liquid.

The axial momentum flux of the gas immediately after exiting the nozzle can be calculated as follows:

\[ M_{\text{jet}} = \rho_g v_{z,\text{max}}^2 \] ..........................(3)

where $\rho_g$ is the density of the gas, in present experiments the gas is air, and $v_{z,\text{max}}$ is the velocity of the gas exiting the nozzle calculated as:

\[ v_{z,\text{max}} = \frac{Q}{\pi \cdot r^2} \] ..........................(4)

where $Q$ is the gas flow rate and $r$ is the inner radius of the nozzle. It can be seen from Eqs. (3) and (4) that the axial momentum flux increases with the power two of the gas flow rate. The increased momentum flux will, of course, give a larger effect on the liquid surface as well as on the fluid flow in the vessel.

It can be seen that the bottom blown cases yields higher velocities than those cases where only a top jet was employed, and that an increasing bottom flow rate has a relatively small impact on the magnitude of the velocity field. When combined blowing is used relatively small differences in velocity magnitude in the flow field between different cases, including bottom blowing only, can be seen.

Instead the position and shape of the vortex’ are changed.

One important aspect, that can have a large impact on the results, is that the PIV measures the flow field in a 2-dimensional cross-section of the bath. Since no flow field present in all experimental setups is truly axisymmetric, the 2-dimensional flow field produced by the PIV is insufficient to describe all aspects of the flow. For instance, Fig. 5(d) shows a rather unexpected result where the increased bottom purging does not lower the center of the re-circulation loop, but instead pushes it upwards. This might be due to the deficiency in a 2-dimensional view, where the entire motion of the fluid is not captured. The experiments might experience large differences in the motion in the $\theta$ direction that is not captured.

6. Conclusions

A study of the flow field in a cylindrical bath agitated by bottom injection, top lance injection and a combination of both injection types have been performed using a PIV system. To summarize the findings of each independent case:

(1) Top blowing creates a re-circulation loop in a relatively small area close to the surface. This re-circulation extends further down into the liquid with increasing flow rate. At higher flow rates the flow field becomes increasingly unstable and a clear re-circulation loop becomes difficult to distinguish.

(2) Increasing bottom flow rate moves the center of the re-circulation loop downwards into the liquid.

(3) When top blowing is combined with bottom blowing the center of the re-circulation loop is moved downwards into the liquid with increasing top lance flow rate. However, as stated above, at high top lance flow rates the flow pattern becomes more difficult to distinguish.

Acknowledgement

The authors would like to thank Prof. Shinichiro Yokoya of Nippon Institute of Technology for his support to this study.

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