Mixing and Settling in Continuous Metal Production

Progress Report

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ABSTRACT

Modern metallurgical converters are operated in the horizontal mode to permit staging of bath oxygen potential by utilizing bottom-blowing of oxygen and fuel. The submerged injectors must provide sufficient turbulence to maximize heat and mass transfer in the bath but must be selectively localized so as to provide adequate phase separation zones between the active turbulent zones.

A test facility has been built to study gas injection into a bath simulating such a converter and instrumentation such as flow meters and a Laser Doppler Velocimeter were installed. Further instrumentation such as a resistivity probe to measure void fraction is under construction. First experimental results are available and numerical modelling of the simplest case were completed successfully.

Introduction

Tonnage oxygen is now employed to increase the process efficiency in a great variety of ferrous and nonferrous smelting and refining operations. Bottom-blowing of oxygen was first employed in OBM/QBOP steel converters. The QSL oxygen reactor produces now lead bullion continuously in a simple, elongated, horizontal, countercurrent flow reactor, utilizing bottom-blown oxygen and coal and thus creating a staged oxygen potential along the reactor. This process is also planned for copper production and can be modified for continuous steelmaking.

Oxygen and fuel is injected into the molten bath of such a pyrometallurgical reactor at velocities and quantities required for heating, mixing and chemical reaction purposes. There must be sufficient turbulence in the bath to maximize heat and mass transfer by maximizing the gas-liquid-solid contact areas and minimizing the extent of reactant diffusion layers. However, the desired bath turbulence is opposite to the requirement of bath phase separation into slag and metal. Therefore, the stirring effect by bottom-blowing must be localized so as to provide active turbulent zones and adequate settling zones along the reactor. The behavior of gas and particulates in the liquids must be well understood for appropriate reactor design, i.e., jetting, formation and size of bubbles, travel of the bubble plume, the amount and location of liquid entrainment into the jet and plume and the liquid separation from the plume. However, submerged gas injection is also of generic interest to other smelting processes.

Work is going on to study gas injection through submerged injectors into a liquid bath consisting of two immiscible liquids having approximately the same viscosities and density ratios as the slag and matte or metal, respectively.

Experimental Facility and Instrumentation

In the first six months of the contract period we built a new test facility, which is shown in Figure 1. The test section consisting of plexiglass is 2.44 m (8 ft) long, 1.22 m (4 ft) high and its width can be varied from 0.025 m (1") to 0.91 m (3 ft). If necessary, the length of the test section can be doubled. Air is injected through a nozzle at the bottom in the center of the test section. The pressure and flow rate of the injected air is metered. A "Coherent Innova" 12W Argon Laser with a TSI 9100 Laser Doppler Velocimeter (LDV) is mounted on an optical table which has a range of travel to permit flow measurements throughout the test section. The optics in the Laser Doppler Velocimeter can be rotated by 90° and thus two velocity components perpendicular to each other can be measured in the bath. The signals from the LDV are sent to a frequency analyzer (LDV input conditioner) and the results are stored in a PC and can be displayed. Figure 2 shows the set up.

Preliminary choice for the two liquids in the test channel were salt water and soybean oil. The density of the salt water can be increased by adding more NaCl. Thus, the density ratio between oil and water can be varied. Soybean oil and water are in the correct viscosity range. Both liquids have the added advantage that they are nontoxic. Oil and water can be separated with an Alfa-Laval oil-water separation centrifuge which was installed recently and tested successfully.

Experimental Results and Analysis

First experiments were run with water only in the test section which has a width of 1". The water depth was approximately 52 cm. Air was injected into the bath and the liquid velocities caused by the bubble plume were measured. Results of these measurements are shown in Figure 3.

In parallel, analytical efforts are under way to predict such behavior. We have used the FLUENT computer code and specified an air bubble size to be injected through the nozzle. Since the test section was very narrow in these first experiments, wall effects are important. Thus, a three-dimensional finite element method was necessary. The trace of the calculated bubble trajectories can be seen in Figure 4. Note that the computer solution shows a symmetry line in the center of the nozzle. Figure 5 is a long-time exposure photograph of the bubble trajectories. At least qualitative agreement of the computed and observed trajectories can be established. Also, the measured and computed velocities in the center of the channel are in relatively good agreement (see Figures 3 and 6). Even the center of the circulation is predicted correctly. It is noteworthy that the whole bath is set in motion by the bubble plume, but surface waves cannot be calculated by this computer program. However, these are only preliminary considerations and the task at hand is to measure, analyze and model the circulation caused by the bubble plume when there are two liquids of different density and viscosity, respectively, and to find the subsequent separation of these fluids.

Further experiments were performed with a relatively thin layer of oil on top of the water. A typical short-time exposure photograph is shown in Figure 7. Qualitatively the following observations can be made:

- If the oil layer is thin, the bubble plume drags mostly the heavier liquid (water) to the surface. Thus, there is little contact between the gas and the oil.
- Gravity is important. The heavier liquid is flowing downward from the top of the plume entraining oil droplets, which subsequently rise back into the oil layer.
- With two immiscible liquids of different density and viscosity the circulation of the bath is limited to the vicinity of the plume.

Figures 8 to 11 show the results of flow velocity measurements in the vicinity of the bubble plume. The only difference from one figure to the next is that the density of the salt water is increased. Thus, the density ratio between the liquids gets larger, while the overall bath depths of oil and water and the gas velocity is kept approximately constant. One result is that the center of the circulation moves closer towards the bubble plume with increase in density ratio. Another result is that the maximum liquid velocity changes very little for a given gas injection volume (the center of circulation is indicated with a *). The distribution of oil in a certain instant of time during the experiment is shaded in the diagrams. The oil layer seems to be thicker than at the beginning of the test since an oil-water emulsion forms at the oil-water interface.

The wall effect in the narrow channel is probably very important, but repetition of these particular experiments in a wider channel will indicate how important the wall effect is. The narrow channel is like a two-dimensional slice out of a three-dimensional plume. Thus it allows excellent opportunity to observe the formation and breakup of bubbles, the interfacial behavior between gas and the two liquids, droplet formation of oil or water and their motion without obstruction due to radial gradients in the bubble plume.

Progress to Date

The experimental facility has been completed and experimentation is under way. The test section will be widened in the next weeks. A resistivity probe is being built at the present time with the help of one undergraduate student and a temporary graduate student.

The analytical work is not as far in its development as the principal investigator would desire since we were unable to attract a capable graduate student last fall. However, for the coming fall we will have a second master's student. He has experience in fluid mechanics and numerical modelling. The principal investigator will spend most of this summer working on the analytical task.

Personnel

Professor Horst Richter spent 10% of his time in the last nine months on this project. This summer the principal investigator plans to spend two months working on analytical portions of the project. During the contract, Jaan Laaspere, a master's student, was working on the project as well.

TOP VIEW

FRONT VIEW

Figure 1: Top and Front View of the Test Facility

Figure 2: Test Facility with Laser Doppler Velocimeter

Figure 3: Submerged gas injection into water only. Laser Doppler Velocity measurements in the vicinity of the plume. Gas injection flow rate $1.3 \cdot 10^{-4} \text{ m}^3/\text{s}$.

Figure 4: Calculated Bubble Trajectory

Figure 5: Trace of Bubble Trajectories

Maximum Velocity 0.52 m/s

Figure 6: Calculated Velocity Vectors in the Test Section for Water as the Only Liquid

Figure 7: Bubbles Rising Through Two Layers of Immiscible Liquids

Figure 8: Submerged gas injection into two immiscible liquids, a 15 cm oil layer on top of a 39 cm water layer (density ratio of the liquids 1.065) Laser Doppler Velocity measurements in the vicinity of the bubble plume. Gas injection flow rate $1.3 \cdot 10^{-4} \text{ m}^3/\text{s}$.

Figure 9: Submerged gas injection into two immiscible liquids, a 12 cm oil layer on top of a 45 cm salt water layer (density ratio of the liquids 1.12) Laser Doppler Velocity measurements in the vicinity of the bubble plume. Gas injection flow rate $1.3 \cdot 10^{-4} \text{ m}^3/\text{s}$.

Figure 10: Submerged gas injection into two immiscible liquids, a 12 cm oil layer on top of a 45 cm salt water layer (density ratio of the liquids 1.17) Laser Doppler Velocity measurements in the vicinity of the bubble plume. Gas injection flow rate $1.3 \cdot 10^{-4} \text{ m}^3/\text{s}$.

Figure 11: Submerged gas injection into two immiscible liquids, a 12 cm oil layer on top of a 45 cm salt water layer (density ratio of the liquids 1.25) Laser Doppler Velocity measurements in the vicinity of the bubble plume. Gas injection flow rate $1.3 \cdot 10^{-4} \text{ m}^3/\text{s}$.

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