Mecánica Computacional Vol. XXI, pp. 2646–2654
S. R. Idelsohn, V. E. Sonzogni and A. Cardona (Eds.)
Santa Fe–Paraná, Argentina, October 2002

PHYSICAL AND NUMERICAL MODELLING OF A GAS STIRRED LADLE

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Key Words: Gas stirred ladle, multiphase flow, mixing time.

Abstract. *In order to improve refining processes in a gas stirred ladle, a good understanding of the flow conditions is almost crucial. For this reason, to get a better comprehension of the main effects that influence the flow, a scaled physical model was constructed, and numerical simulations of this system were made. The physical model is a 1:3 scaled industrial ladle, using water, air and kerosene to simulate molten metal, argon and slag respectively. Mixing times were determined injecting a salt solution and making conductivity measurements as a function of time. Numerical simulations were made using the commercial code CFX-4.4. This is a program for the prediction of laminar and turbulent flow, and heat transfer, which includes features like multi-phase flow, combustion, and particle transport. Flow calculations in this software are based on the resolution of the Navier-Stokes equations in either transient or stationary regimes. The code can solve free surface problems where the grid moves to fit the free surface depending upon an assumed boundary condition of constant pressure. An arbitrary number of phases may be specified. Phases are assumed to form an inter-penetrating continuum whereby each phase occupies a certain volume fraction of each control cell. Our results indicate that the assumption of a flat free surface is a good approximation for this class of systems. Furthermore, if we are interested not only in the velocity field of the continuous phase, but also in the velocity and distribution of the dispersed phases (gas or slag), the effect produced by forces others than drag cannot be neglected. The inclusion of the slag changes the pattern of the flow significantly. Therefore, if we want to obtain realistic values of the important variables in an industrial metallurgical ladle, the consideration of a three-phase system (gas, molten metal and slag) is unavoidable.*

INTRODUCTION

Gas injection is a common practice in metallurgical industries. In steelmaking ladles, gas stirring is used, for example, to enhance reaction rates and to eliminate thermal or composition gradients. For an optimization of these liquid-metal processing operations a good knowledge of the influence of operating variables on bath hydrodynamics is needed.

Due to operation conditions, many difficulties arise if measurements of flow characteristics have to be made directly in the ladle. For this reason, air-water physical models and computational simulations are frequently used to study the real system[1].

In this work we show experimental data obtained from a scaled physical model of an industrial ladle used in the SIDERAR plant. We also show results from numerical simulations using the commercial code CFX4. This is a code that allows us to include the main characteristics of the system like turbulence and multiphase flow.

PHYSICAL MODEL

In order to analyze the molten steel behavior during the refining process, a 1:3 scaled water-air model of a real ladle was constructed[2]. The industrial ladle that we modelled has two porous plugs. Nevertheless, in order to allow comparisons with numerical results, the scaled model has the possibility of working with either one axial centered or two eccentric porous plugs.

The stirring time is a very important factor in the ladle refining process[3]: if too long, steel can suffer reoxidation problems, while if too short it may not be enough to remove the inclusions. It would be desirable to establish an optimal stirring time in each particular case (see figure 1).

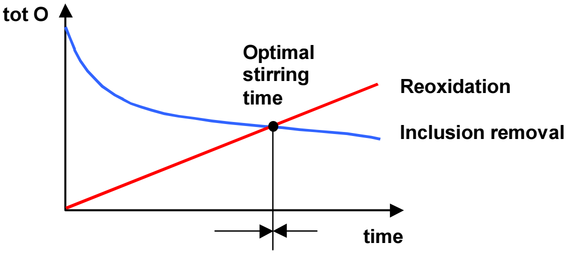

Figure 1: Optimal stirring time taking in consideration reoxidation and inclusion removal[3].

Typical flow values in each porous plug at the industrial plant are 200 l/min for the soft stirring case, and 750 l/min for the strong stirring condition. Following Refs. [4, 5], the corresponding values used for flow of air in the physical model are 40 l/min and 145 l/min respectively.

Simulations with one centered porous plug, used for comparison with numerical results, were made using 40 l/min and 80 l/min. Slag was simulated using kerosene and depending on the rate at which air is introduced, an open eye appears on the free surface over the plume. The open eye and the emulsification process can be seen in figures 2 and 3.

Figure 2: Emulsification with a central nozzle.

Figure 3: Upper view of the open eye.

An injection of a salt solution, followed by conductivity measurements to determine salt concentration, was made in order to obtain mixing times. Several configurations of the injection point as well as of probe position are proposed in the literature[6]. Different alternatives can be seen in figure 4, and figure 5 shows typical curves of salt concentration evolution for various injection and probe locations.

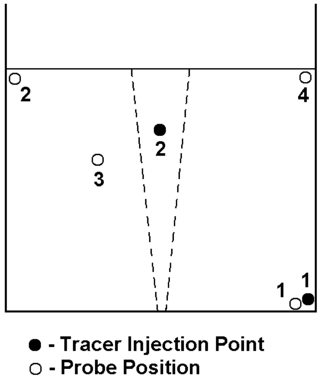

Figure 4: Several configurations of the tracer injection point and the probe position found in the literature[6].

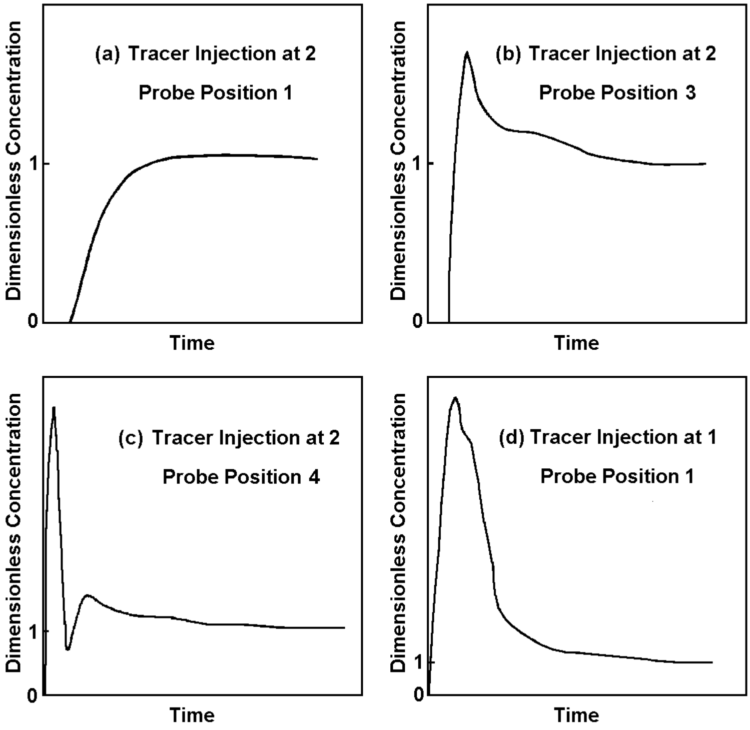

Figure 5: Typical concentration curves as a function of time[6] for different alternatives of salt injection and detection shown in figure 4.

Results using the configuration corresponding to figure 5(a) are shown in figure 6; i.e. the salt solution was injected in the plume and conductivity was measured at the bottom of the ladle near the wall. The curves obtained compare well with those of the literature and give us confidence in this kind of measurements to estimate the mixing time.

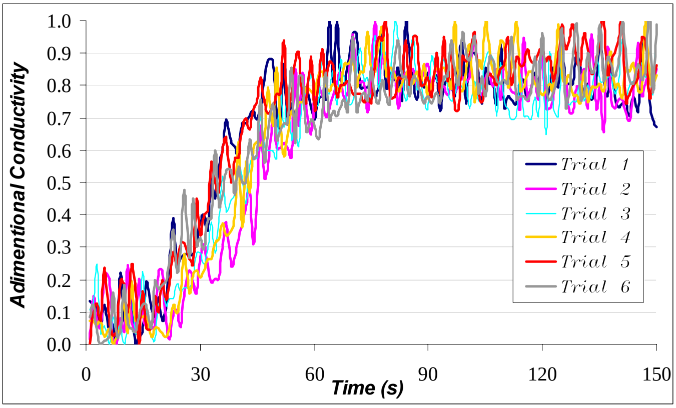

Figure 6: Mixing curves using a central nozzle. The tracer was injected in the plume and the detector was located at the bottom of the ladle near the wall

When two eccentric plugs were used, the open eyes were in contact with the wall of the ladle (figure 7). In this case a reduction of the emulsification and a growth of the mixing time was observed. These results can be attributed to the fact that the plumes are in contact with the wall and therefore, part of the kinetic energy that would be transferred to the liquid is lost.

Figure 7: Lateral view of the ladle when two plugs are used, where one of the open eyes in contact with the wall can be seen.

NUMERICAL SIMULATIONS

As we mentioned previously, numerical results were obtained using the commercial code CFX-4.4. Although the program allows the calculation of temperature distribution, the analysis in this work was limited to isothermal flow.

The main characteristics of the numerical model are:

- Two dimensional with axial symmetry.
- Grid of 40×25, 80×50 and 160×100 rectangular elements.
- Isothermal and incompressible flow.
- Liquid phase (water) continuum and turbulent (k–ε model).
- Gas phase (air) disperse and laminar that can flow through the free surface.
- Each phase has its own set of variables (multi-fluid model).
- Drag as well as non-drag forces are included
- Deformable free surface.

Although phases are assumed mixed on length scales larger than molecular length scales, they are also assumed mixed on scales smaller than that we wish to solve. Thus, each phase is treated as an interpenetrating continuum. That is, each phase is assumed present in each control volume, and is assigned a volume fraction equal to the fraction of the control volume occupied by that phase.

In the multi-phase flow context, we used a multi-fluid model. In this model, there is a separate solution field for each phase, and transported quantities interact via inter-phase transfer terms. For example, two phases may have different velocities, but they will have a tendency to equalize because of inter-phase forces.

The main interaction between phases is due to drag forces that act in the direction opposite to the relative movement. However, not only drag forces but also non-drag forces can influence the flow. The non-drag forces that we considered are the virtual mass force, the lift force, and the turbulent dispersion force. Details of the balance equation used and the way in which the different non-drag effects are implemented can be found in Ref. [8].

Sometimes some of these forces are neglected in the literature, but if our interest is not only in the liquid phase but also in the dispersed phase (gas or slag) these forces cannot be neglected[8].

To validate the model we started with an air-water system and compared the results with the experimental measurements of Ref. [7]. Streak lines representing the water velocity field and the air volume fraction are shown in figure 8, where can be seen the recirculating flow induced by the gas injection.

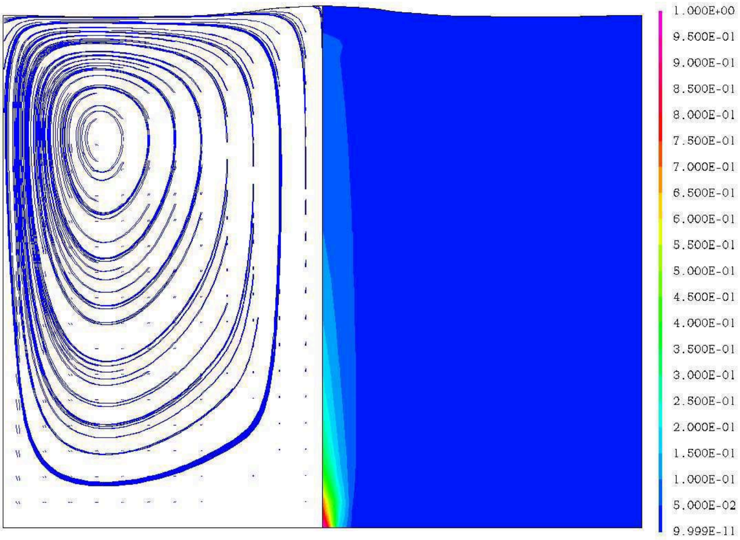

Figure 8: Streak lines corresponding to the water phase (left) and volume fraction of the air phase (right)

The volume fraction of the air on the symmetry axis of the cylinder as a function of height is shown in figure 9. It is worth to note that comparison with experimental results is fairly good not only taking into account the values of the volume fraction (figure 9(a)), but also its functional dependency with height. The latest is emphasized in figure 9(b) where a log-log plot is shown.

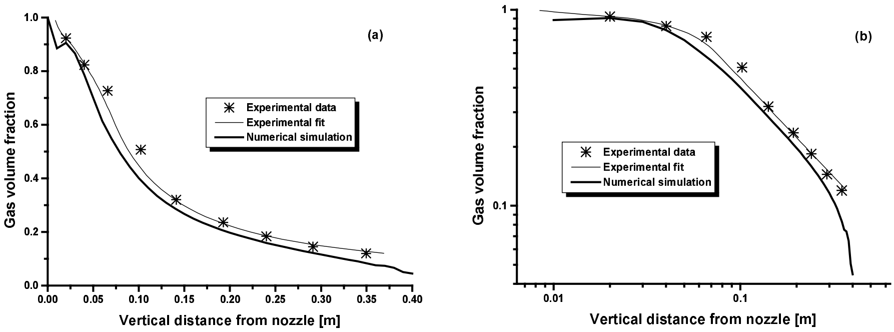

Figure 9: Volume fraction of the air phase on the symmetry axis of the ladle in (a) linear and (b) log-log graphics

The consideration of the deformability of the free surface does not change substantially the results and the curves obtained are practically the same as those of figure 9.

The injection of a tracer to calculate mixing times was also simulated in this system. Numerical results using the four configurations of figure 5 can be seen in figure 10. Although the curves are not exactly the same as the curves of figure 5, the time dependency of the salt concentration is qualitatively similar.

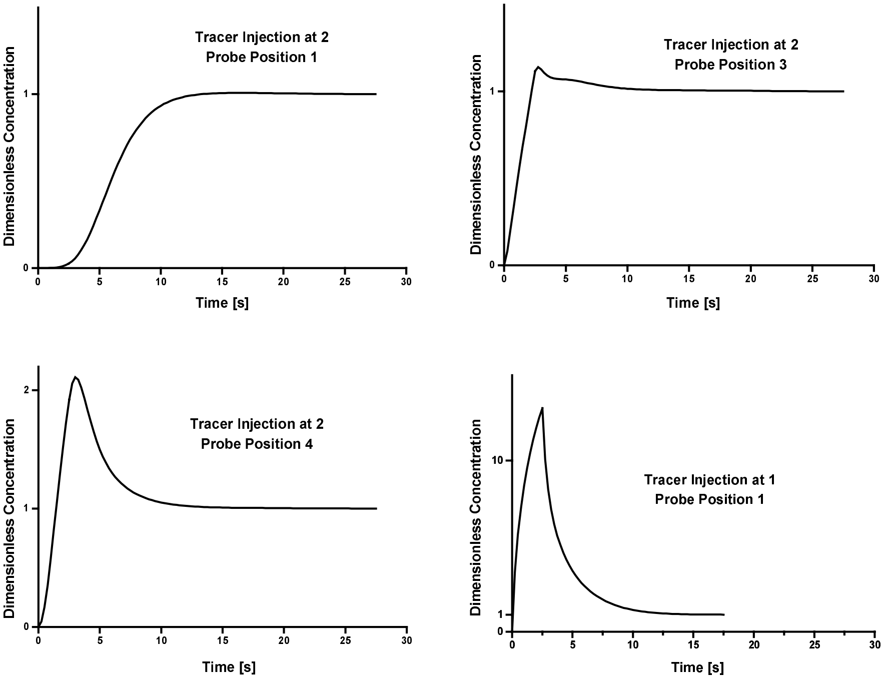

Figure 10: Concentration of a tracer injected on the plume and detected in the bottom of the ladle near the wall.

In figure 11 numerical results in the three-phases system are presented. An open eye can be observed and comparing with figure 8 it can be seen how the presence of the kerosene (simulating the slag) modifies considerably the velocity field of the water. Thus, when a real metallurgical ladle is modelled, the presence of the slag cannot be neglected.

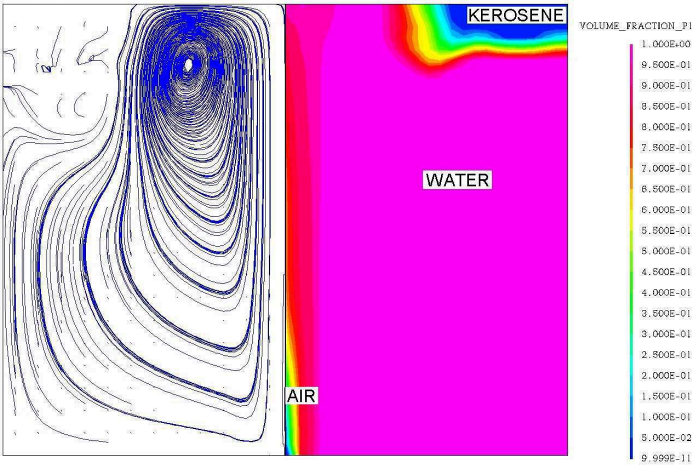

Figure 11: Streak lines (left) and volume fraction (right) corresponding to the water phase when coexisting with the kerosene and the air phases.

CONCLUSIONS

A scaled physical model of water was constructed to study a metallurgical ladle. With this model, several important processes that occur in refining operations, e.g., emulsification, mixing, and influence of the number and position of the porous plugs, can be analyzed. In particular, we showed mixing time results and the influence of the number of plugs.

A numerical model was also developed and the results obtained compare very well with experimental measurements. Mixing time curves were qualitatively reproduced and the calculated gas volume fraction is in very good agreement with experiments. When the free surface is considered as deformable, results are not affected significantly; but, when the slag is included, modifications of the velocity field are important.

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