Direct numerical simulation of mass transfer at the oil water interface in a model metallurgical laddle

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We investigate mass transfer between liquid steel and slag during a metallurgical secondary refinement process through a reduced scale water experiment which reproduces the dynamics seen in an argon-gas bottom-blown ladle. The three-phase flow modelling includes a container filled by water, modelling the molten metal, topped by a thin layer of oil, modelling the slag. The system is agitated by the injection of air at the bottom, creating a bubble plume that merges into the air on top of the system (Figure 1). A tracer material, dissolved in the water, acts as a passive scalar that is progressively absorbed into the oil layer. The numerical results obtained for the hydrodynamics and the mass transfer properties of the system are then compared with theoretical and experimental studies for two differently shaped ladles: a cubical ladle as investigated by Joubert et al. [1, 2] and a truncated cone ladle as in the experiments by Kim et al. [3].

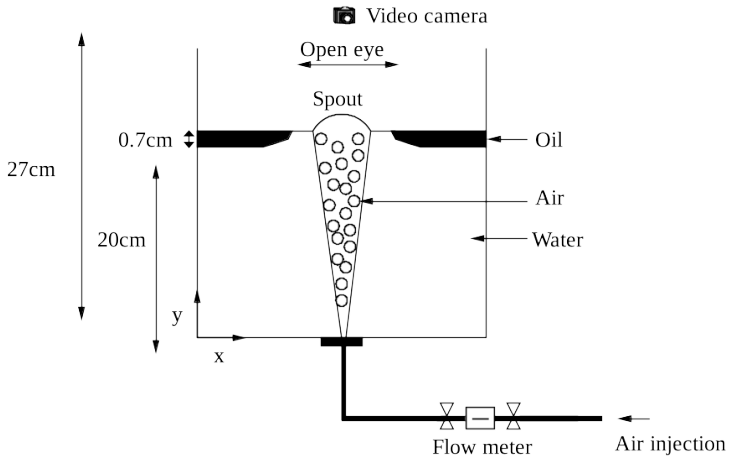


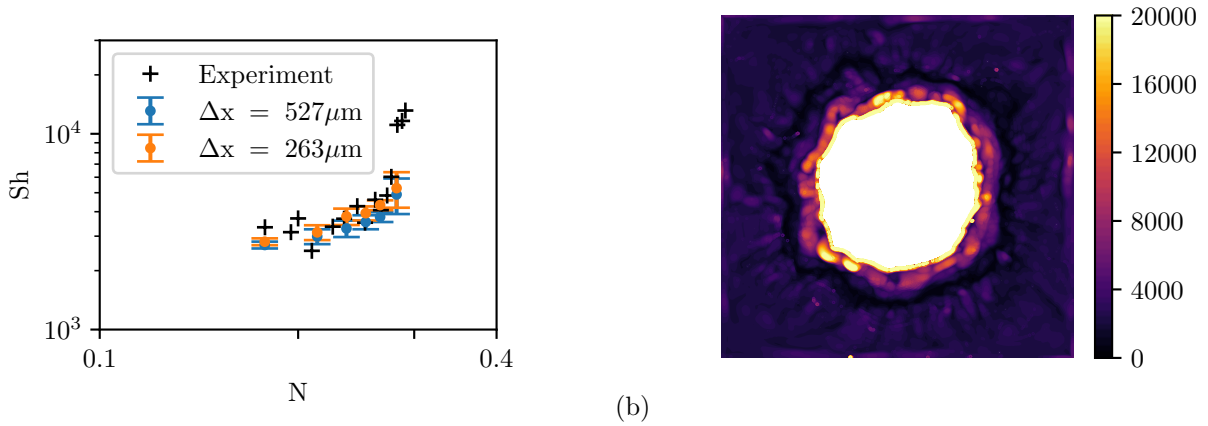
Figure 1: Schematic representation of the cubic ladle experiment .

The numerical study of the ladles is made difficult by the very large values of the Peclet number $Pe = U_0 h_w / D_w$ involved, where U_0 is the typical large scale velocity in the water, h_w is the height of the water layer and D_w is the diffusion coefficient of the tracer. Peclet numbers of the order of 10^6 - 10^7 are obtained even at the lowest flow rates in the experiment, leading to extremely thin boundary layers of size $\delta \sim h_w Pe^{-n}$, with n between 1/3 and 1/2. Such small boundary layers require numbers of grid points that are prohibitive even with advanced octree simulation methods.

To circumvent this difficulty we proceed in two steps. First, the hydrodynamics of the flow is investigated, then in a second step we analyze how the resulting momentum boundary layers drive concentration boundary layers. For the hydrodynamics the numerical results recover two regimes: a laminar regime at low flow rate Q in which the oil-water interface remains relatively quiescent and an atomizing regime at large flow rate Q where the oil layer starts to shed ligaments and droplets. The numerical results in a range of relatively small Peclet numbers are extrapolated to large Peclet numbers using a theory of the boundary layer with shear and the final result is in agreement with the experiments at low values of the flow rate.

In Figure 2, the efficiency of the mass transfer in the experiments and simulations are compared, for the

cubic ladle case, by means of the Sherwood number Sh that represents the ratio between the convective and diffusive mass transfers. In Figure 2(a) the average Sherwood number is plotted against the Froude number N, that compares the flow inertia to the external gravitational field, for the experiment and for two simulations at different minimum grid size. Figure 2(b) shows instead the instantaneous local Sherwood number on the oil water interface, showing how the majority of mass transfer occurs in an annulus surrounding the open eye.



(a) (b)

Figure 2: (a) Numerical and experimental Sherwood number for different Froude numbers. (b) Instantaneous Local Sherwood Number on the oil water interface for a flow rate of 0.6L/min.

References

[1] Nelson Joubert. *Liquid-liquid mass transfer characterization applied to metallurgical process*. PhD thesis, Sorbonne université, 2021.

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[3] Seon-Hyo Kim and RJ Fruehan. Physical modeling of liquid/liquid mass transfer in gas stirred ladles. *Metallurgical transactions B*, 18:381–390, 1987.