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Research Progress on Bubble Behavior During Bottom Blowing in Ladles

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Abstract. Bottom-blown argon stirring is widely applied in ladle refining to improve the uniformity of steel temperature and composition, enhance steel–slag reactions, and promote inclusion flotation. Its refining performance is closely associated with bubble dynamics in the molten steel. Bubbles generated at the bottom undergo expansion, rising, deformation, breakup, and coalescence, driving the circulation of the surrounding liquid. The resulting bubble plume and gas–steel–slag interfacial behavior are therefore strongly affected by these processes. However, measurements in industrial ladles remain difficult because molten steel is opaque and operates at extremely high temperatures, while interactions among different phases further complicate direct observation. Numerical simulation, usually combined with physical experiments, has consequently become an important means of studying bubble behavior. This review summarizes recent studies of bubbles in ladles, with attention given to Eulerian–Eulerian, Eulerian–Lagrangian, and multiscale modeling approaches. Relevant water-model experiments and measurement techniques are also reviewed. Current limitations and future research needs are considered with respect to model coupling, quantitative experimental validation, and the application of numerical and laboratory findings to industrial ladle refining.

Keywords: ladle refining, bottom argon blowing, bubble behavior, numerical simulation, physical modeling

1. Introduction

The effect of bottom blowing is transmitted to the molten bath through argon bubbles. Once released from a porous plug, a bubble expands as the hydrostatic pressure decreases and may deform, fragment, or merge with neighboring bubbles while rising through the steel. Its motion and interaction with the slag layer and suspended inclusions establish the plume geometry and drive circulation in the surrounding liquid. Consequently, bubble evolution affects slag-eye behavior, bath mixing, and the probability that inclusions reach and enter the slag. A mechanistic description of these events is therefore needed to connect operating conditions at the plug with the macroscopic refining response.

Studies that resolve bubble generation, ascent, and population changes help explain how gas stirring transfers momentum to the bath. The resulting knowledge also supports the selection of argon-flow conditions that shorten homogenization time and improve refining performance [1-3].

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2. Numerical modeling studies

2.1. Eulerian-Eulerian models and the PBM approach

An Eulerian-Eulerian formulation represents both molten steel and the dispersed gas as interpenetrating continua. Separate mass and momentum balances are solved for each phase, while bubble or inclusion size classes are commonly described through a coupled population balance model (PBM) [4-7]. Because individual particles are not tracked, this framework can accommodate industrial vessels and broad size distributions at a comparatively moderate computational cost. The same averaging that gives the method its efficiency, however, limits its ability to describe individual trajectories, bubble deformation, and localized encounters with inclusions or interfaces [8-12].

Among the earlier contributions, Bellot et al. [13-15] applied an Eulerian two-fluid formulation to gas-stirred ladles and included momentum exchange between the phases. Lou [16] subsequently evaluated alternative interphase-force closures against experimental observations and introduced a modified force expression into the momentum source terms. Eulerian-Eulerian flow calculations were later combined with PBM equations and mass-source formulations by Lou [16, 17], Chen [10], Qu [18], Geng [19, 20], and other researchers to predict the size distribution, transport, and removal of large inclusion populations. These engineering models provide useful process-level information, although many treat the steel-slag boundary as a flat free-slip surface and consequently omit part of the coupling between slag motion, interfacial deformation, flow, and reaction. For RH refining, Chen [21] incorporated initial bubble size, nonequilibrium expansion, and several interphase forces into an Eulerian two-fluid model. Its predictions of circulation, mixing, and flow agreed reasonably with measurements and showed that pressure-driven bubble expansion must be retained.

2.2. Eulerian-Lagrangian models and multiscale methods

In the Eulerian-Lagrangian method, the continuous molten-steel phase is solved in an Eulerian framework, whereas bubbles are tracked as discrete particles in a Lagrangian framework. Johnson [22] and Guo [23] were among the first to use this method to track argon bubbles in bottom-blown ladles. Cloete [24] coupled Lagrangian tracking of the dispersed gas with a volume-of-fluid (VOF) description of the bath surface. A difficulty arises because a ladle contains interfaces large enough to resolve on the mesh together with bubbles that remain smaller than a grid cell. Li [25-29] treated these scales separately: resolved interfaces were retained on the grid, subgrid bubbles were advanced as Lagrangian entities, and large-eddy simulation (LES) supplied the turbulent flow field. This arrangement captures bubble ascent, collision-driven coalescence, breakup, and transient slag-eye motion without forcing all interfacial features onto a single numerical scale.

Mohammadi [30] applied Eulerian-Lagrangian calculations to the gas-stirred bath and used the predicted flow to examine the decay of thermal stratification. Cao [31] extended this framework by allowing bubbles to expand in response to both pressure and temperature, then compared the resulting ladle flow with an Eulerian-Eulerian solution. Discrete tracking becomes more demanding when collisions lead to rebound, coalescence, or fragmentation. Yang et al. [32-35] represented these events with user-defined functions (UDFs). Their applications concerned continuous-casting molds, but the collision and breakup algorithms can be transferred to ladle calculations after the relevant flow and material properties are adjusted.

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3. Experimental studies

3.1. Water-model experiments and zoning of the bubble plume

Argon or nitrogen introduced through porous plugs supplies the momentum that circulates molten steel in a ladle. Buoyancy carries the injected gas upward, and the associated plume produces turbulence and large recirculation loops in the liquid [36]. This motion redistributes heat and solute and increases the frequency with which nonmetallic inclusions are transported toward the slag. Measurements inside a production ladle remain scarce because the vessel is enclosed, the temperature is extreme, and neither the steel nor the refractory shell permits optical access. Investigators therefore reproduce the principal flow features in transparent water models or, when closer thermophysical similarity is required, in low-melting-point-metal systems. Visualization is often supplemented by electro-resistivity probes that quantify gas holdup, bubble passage frequency, and rise velocity [37-40]. These measurements provide benchmarks for numerical models and evidence for the selection of operating conditions.

Visual observations of gas injection commonly distinguish three parts of the two-phase zone: a primary region immediately above the injector, a free-bubble region, and the developed plume. Most of the gas-liquid volume belongs to the plume, whereas the two regions closest to the nozzle are comparatively small. Injection momentum and nozzle geometry strongly affect bubble behavior near the gas entry. Farther upward, the bubble-size distribution and mean rise velocity become less dependent on the details of the injector [41, 42]. Measurements by Sheng and Irons [39, 43] showed little variation in axial bubble velocity with height, which indicates that conditions at the orifice do not set the velocity throughout the developed plume. Sahai [44] reached a similar conclusion in bottom-blown water-model experiments. By balancing the energy delivered by buoyant bubbles against turbulent dissipation in the vessel, that study estimated the mean plume velocity while assigning only a secondary role to the initial nozzle-scale bubble parameters.

3.2. Measurement techniques and representative experimental results

Alexiadis [45] observed three distinct dispersion patterns in a bottom-blown ladle as the gas flow rate was raised. Changes in the balance between bubble breakup and coalescence produced the transitions among these regimes, which conventional computational fluid dynamics (CFD) did not reproduce reliably. The calculated turbulent kinetic-energy dissipation was also below the measured level because wake-generated turbulence was not represented explicitly. To address this discrepancy, the study introduced a spot-turbulence treatment that adds the enhanced dissipation associated with bubble wakes to the flow model.

Johansen [46] injected gas at the center of a ladle water model and used a laser Doppler system to measure the mean radial and axial fluid velocities and their fluctuations near the bottom, at mid-height, and close to the free surface. The results showed a low-velocity recirculation zone near the ladle bottom and higher velocities near the free surface. Taniguchi [47] likewise combined laser Doppler velocimetry with numerical calculations to determine the time-averaged liquid velocity, fluctuating velocity, and gas-liquid relative velocity. Li [48] established a 1:4-scale ladle water-model facility containing water, oil, and gas phases. Nitrogen was injected through a diffuse porous plug at different flow rates, the Sauter mean diameter of rising bubbles was measured, and the resulting data were used to validate a mathematical model of multiphase flow. Wang [49] focused on the motion of a single bubble and interactions between two bubbles. Bubble generation and rise, coalescence of coaxial bubbles, and bouncing of side-by-side bubbles were observed in both air-

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water and argon-steel systems. Bubble shapes gradually evolved from nearly spherical to spherical-cap, ellipsoidal, wobbling, or ellipsoidal-cap forms, and coalescence did not occur in some interaction processes.

Direct experiments on bubble motion and jet characteristics in liquid metals [50-52] show that the initial bubble diameter is generally much larger when liquid metal is used to simulate molten steel than under water-model conditions. Water models offer low cost, high controllability, and direct visualization, and they generally yield reliable qualitative trends. Nevertheless, they cannot fully represent industrial molten-steel systems and must be further corrected and supplemented using liquid-metal experiments, numerical simulations, and plant data.

At present, a considerable proportion of gas-liquid two-phase-flow experiments are conducted in small cylindrical or rectangular vessels. Results from these vessels cannot be transferred directly to an industrial ladle because confinement and vessel dimensions alter bubble paths and the surrounding circulation. Most ladle-model studies therefore report either a global flow pattern or velocities measured within selected regions of the plume. Measurements that reconstruct the plume-scale velocity from the motion of individual bubbles remain uncommon. More data are needed to determine whether such local observations are statistically representative and sufficiently accurate for validating full-scale calculations.

4. Conclusions and outlook

The available literature shows that no single numerical framework resolves every relevant scale in a bottom-blown ladle. Eulerian-Eulerian calculations are efficient for bath-scale circulation and polydisperse bubble populations, while Eulerian-Lagrangian calculations retain the trajectories and local interactions of individual bubbles. Coupled multiscale formulations bridge these descriptions by linking bubble-population changes to the evolving bulk flow. In experimental studies, water models, electro-resistivity probes, laser velocimetry, high-speed imaging, and low-melting-point-metal experiments have provided important data on bubble-plume structure, gas holdup, liquid-phase velocity, and bubble-shape evolution.

Future research should strengthen three areas. First, multiscale coupled models that account for both engineering and bubble scales should be developed to improve predictions of bubble breakup, coalescence, expansion, and slag-eye fluctuations. Second, quantitative validation of numerical models against experimental data should be reinforced, particularly for bubble-size distributions, gas holdup, local turbulence, and interfacial behavior. Third, gas-liquid two-phase flow should be coupled with inclusion removal, steel-slag reactions, temperature uniformity, and optimization of industrial bottom-blowing practices so that modeling results can more directly support refining-process design.

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