Dynamics of argon bubbles in steel continuous casting with a magnetic field

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Executive Summary

This project aims to mathematically model multiphase flow in the steel continuous casting in order to gain increased understanding and practical insights to improve this important commercial process. Specifically, Large Eddy Simulations of turbulent fluid flow are conducted to investigate the dynamic motion of argon bubbles in the caster with different casting conditions such as electro-magnetic braking (EMBr), in order to minimize inclusion entrapment. The present work quantifies how the oscillations of the shape and velocity of the rising bubbles can be damped with the application of a static external magnetic field.

Introduction

Continuous Casting (CC) is used to produce more than 95% of steel in the world [1] so even small improvements can have a large impact. In this process, Fig. 1 shows how molten steel flows into the mold, to solidify a thin shell against the walls that is withdrawn downward at the casting speed to support the liquid pool below the mold. Most defects arise in the mold region, due to the entrapment of inclusion particles into the solidifying shell, and crack formation in the newly-solidified steel shell. To improve steel products requires understanding the mechanisms of defect formation, and to find windows of safe operation. The harsh environment makes experiments difficult, so computer simulations are an important tool. Argon gas is often injected and affects defect formation in several ways, including the attachment of inclusions to the surface of rising argon gas bubbles, so it is important to understand the complex motion and dynamics of the bubbles. The shape and motion of the bubbles are modified by applying external magnetic fields. To simulate the complex motion of argon gas bubbles rising in turbulent molten steel and their interaction with inclusion particles and external magnetic fields requires advanced computational models and computing capabilities.

Methods

To better understand the behavior of argon bubbles and their interaction with inclusion particles during steel continuous casting, the motion of a single argon gas bubble rising in quiescent liquid steel under an external magnetic field is studied numerically using a Volume-of-Fluid (VOF) method implemented into the finite-difference fluid-flow program CUFLOW [2]. To mitigate the spurious velocities generated in numerical simulation of multiphase flows with large density differences, an improved algorithm for surface tension modeling, originally proposed by Wang and Tong [3] is applied.

The in-house multi-GPU code CUFLOW has been developed and tested on Blue Waters XK node, which has Nvidia K20x GPU as co-processors, and good speed up has been obtained. Figure 2 shows that less than 2 days are required for a 30s-LES simulation of flow in a caster domain with 14.1 million cells (based on 100 time step test run with average time step size Δt=0.0005s). Preliminary results show that ANSYS FLUENT also has good scaling on Blue Waters for this problem. To resolve turbulent flow in the real caster complete with thousands of bubbles is only feasible with petascale computing, such as Blue Waters.

As shown in Fig. 3(a) the computational domain of 6*d* × 6*d* (section) x 16*d (long)* contains 192 × 192 × 512 (about 19 million) cells. A spherical argon bubble of diameter d was initially centered at the center of the container bottom. A uniform magnetic field was applied in *x*. The dimensionless shape and velocity are tracked with dimensionless time $t^* = t\sqrt{g/d}$.

Results

Figure 3 shows that rise velocity is smooth and non-oscillatory at early stages (t*<0.5), especially with small bubbles. Without a magnetic field, velocity increases to 2.5 and then decreases slightly, due to the inclined motion of the 3mm bubble. Applying a transverse magnetic field of *B*=0.2 T, lowers the rise velocities by 4%. Increasing the field strength to 0.5 T, decreases the rise velocities by 24% to 1.83. For a 7 mm bubble, without no magnetic field, the rise velocity becomes oscillatory after t* > 1.0, due to the varying drag force, as the bubble shape expands and contracts along different axes. With a magnetic field of 0.2 T, the oscillations eventually are dampened. Increasing the field to 0.5 T completely damps the oscillations, resulting in a steady rise velocity, that is reduced by ~25%, relative to no field.

Figure 4 shows isosurfaces of *z* vorticity $\omega_z^* = \pm 1$ at $t^* = 9$ for the 7 mm bubble. The alternating patterns are more complex than those behind a 3 mm bubble. With a 0.2 T field, the isosurfaces elongate in the magnetic field (x) direction because the *y* and *z* velocities in the surrounding fluid are reduced, so the flow perpendicular to the magnetic field is dampened. The magnetic-field damping effect was studied previously [5] in a driven cavity. Increasing the field strength to 0.5 T makes complex wake structure almost disappear. The front isosurface is wider (in x) near the bubble, and bundled below, where the wake spreads (in *y*).

In related work, Large Eddy Simulations were applied to investigate the flow in a commercial caster. Figure 4(a) and (c) show instantaneous velocity magnitude in top views of the caster (casting speed 1.5 m/min). Applying an EMBr field greatly lowers the velocity near the top surface, which can lead to problems of meniscus freezing, where the steel around the 3-phase perimeter solidifies into detrimental hook structures which capture inclusions and bubbles. Figure 5(b) and (d) show velocity in side views. Applying EMBr deflects the jets upward, but the flow in the top region is reduced by the dampening effect of the field. The steel plant that was experiencing this problem lowered the field strength towards the top of the mold and increased the casting speed, which has improved quality.

References

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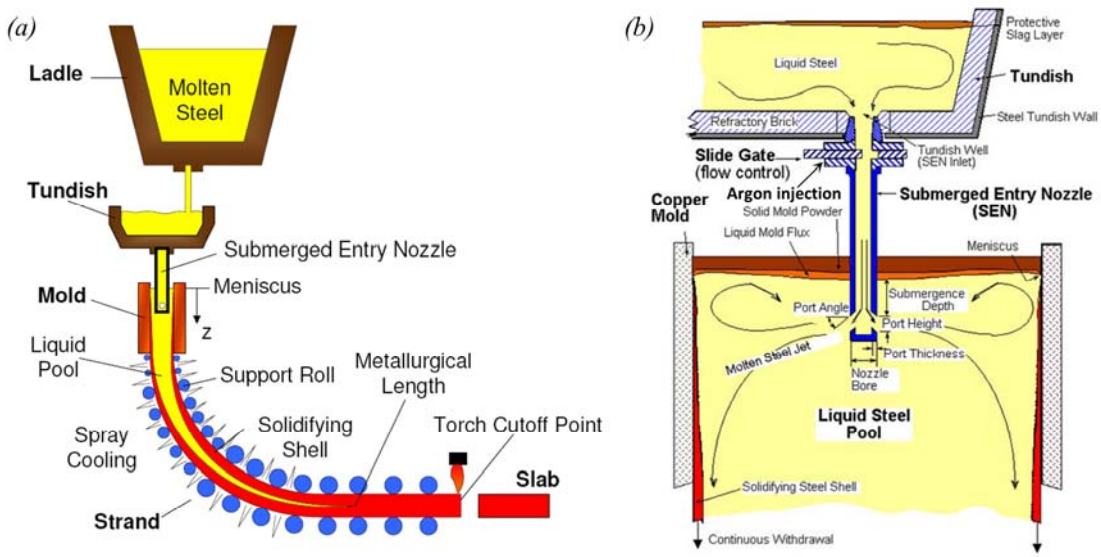

Figure 1. (a) Schematic of the continuous casting process and (b) Closeup view into the mold region of the caster. Argon gas is injected near the slide gate

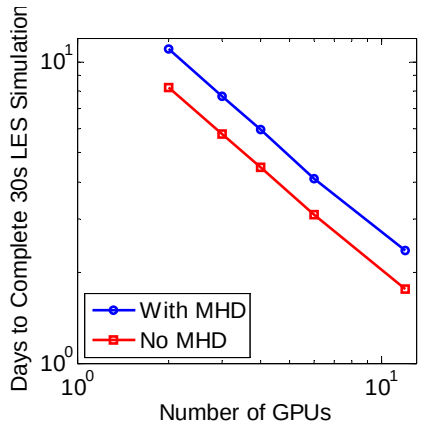

Figure 2. Estimated time for 30s LES simulation of caster with 14.1 million cells

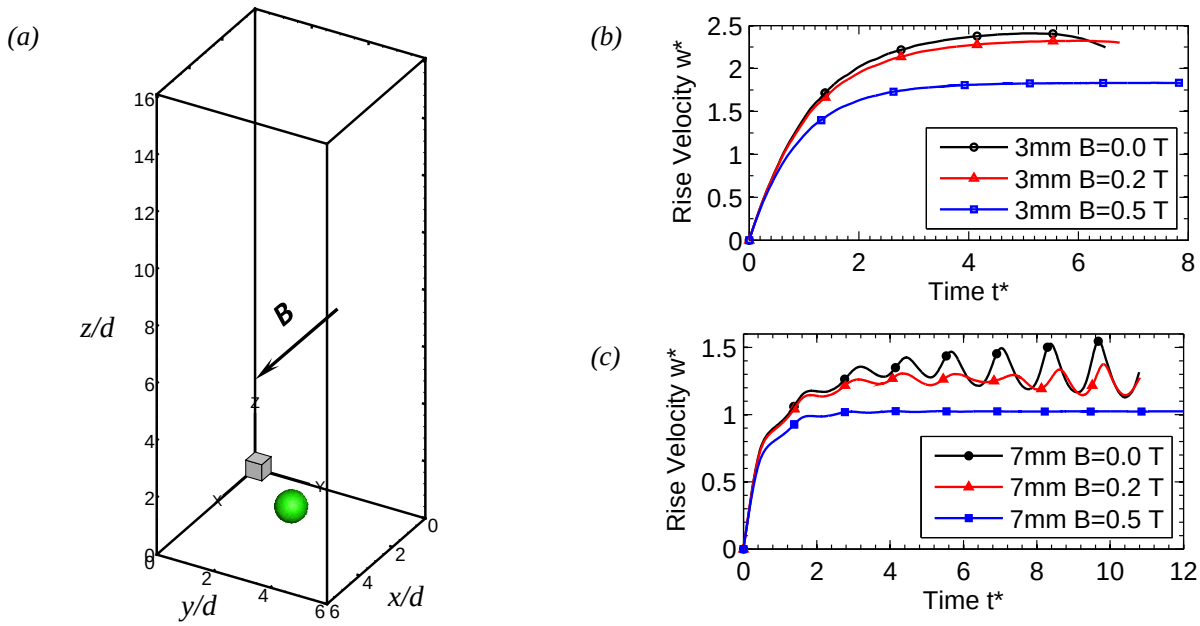

Figure 3. (a) Computational domain and initial bubble location (b) Rise velocity of 3 mm argon bubble and (c) Rise velocity of 7 mm argon bubble [4]

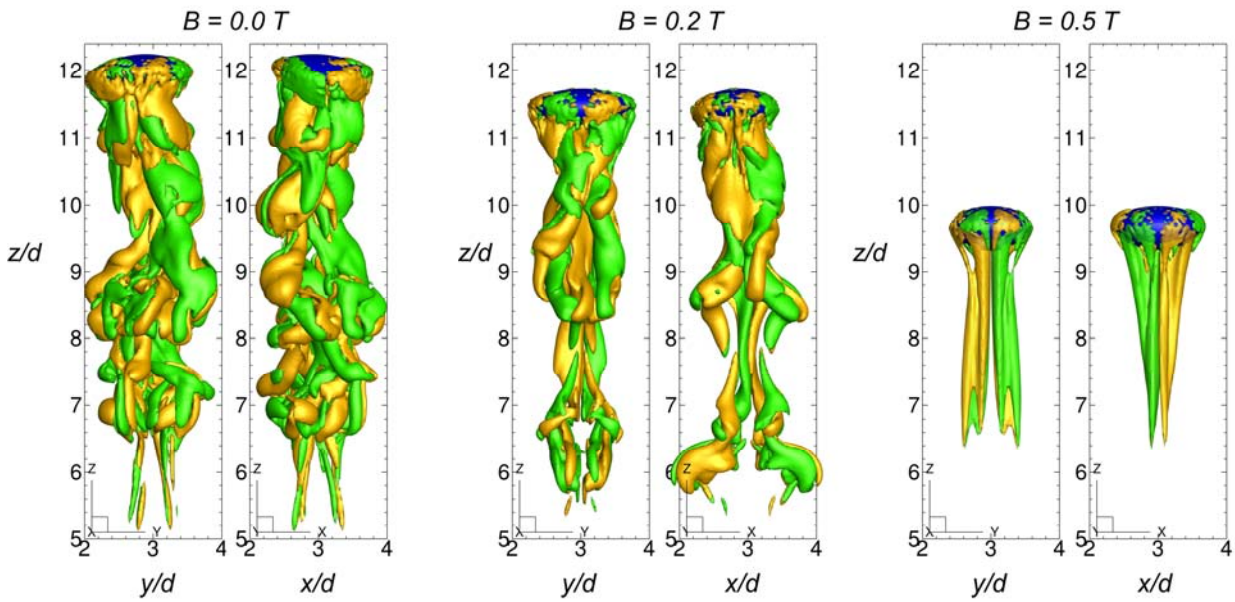

Figure 4. Front and side views of the bubble (blue), isosurfaces of ω_z*= 1 (yellow) and ω_z*= −1 (green) at t* = 9 for 7 mm bubble [4]

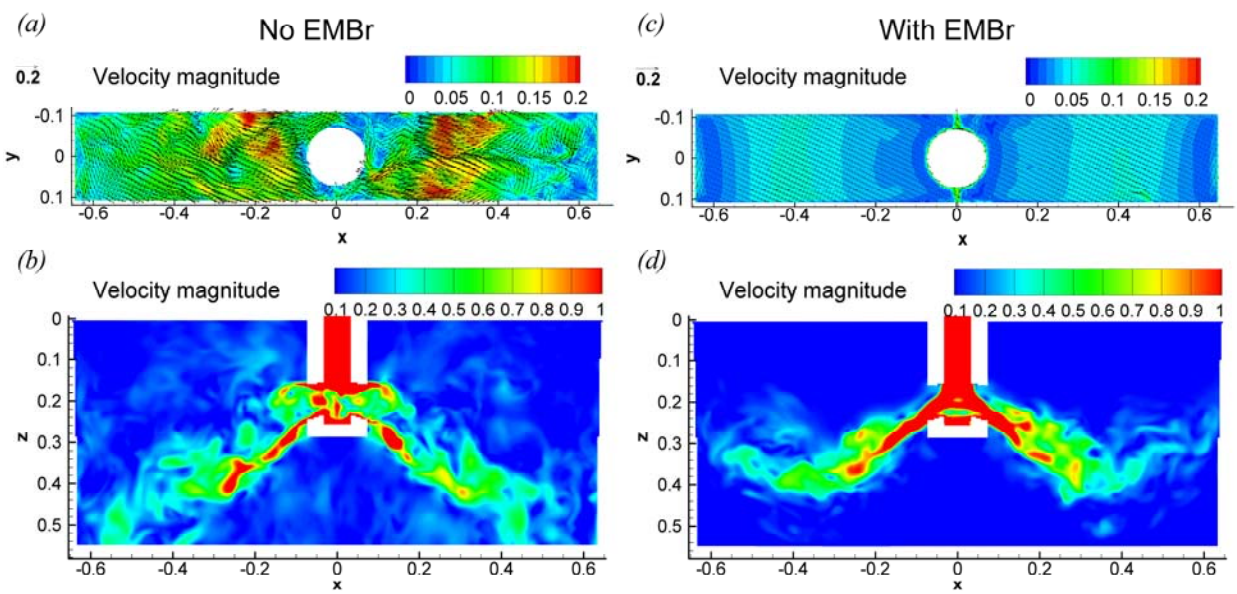

Figure 5. Predicted velocity in horizontal plane near top surface (top) and in the middle vertical plane of the caster mold (bottom) for cases without (left) and with (right) an external magnetic field