DYNAMICS OF ARGON BUBBLES IN STEEL CONTINUOUS CASTING WITH A MAGNETIC FIELD

Allocation: Illinois/0.20 Mnh
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EXECUTIVE SUMMARY:

This project aims to mathematically model multiphase flow in 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 were conducted to investigate the dynamic motion of argon bubbles in the caster with different casting conditions such as electro-magnetic braking, in order to minimize inclusion particle entrapment. This work quantified how the oscillations of the shape and velocity of the rising bubbles can be damped with the application of a static external magnetic field. In addition, transient thermal stress models of the solidifying dendritic microstructure will be applied to investigate strain concentration and the formation of longitudinal cracks in order to understand how to avoid this problem.

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 In this process, fig. 1 shows how molten steel flows into the mold to solidify a thin shell against the walls that is withdrawn downward at the casting speed to support the liquid pool below the mold.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, one must understand the mechanisms of defect formation and 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 & RESULTS

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 was studied numerically using a volume-of-fluid (VOF) method implemented into the finite-difference fluid-flow program CUFLOW [2]. An improved algorithm for surface tension modeling, originally proposed by Wang and Tong [3], was applied to mitigate the spurious velocities generated in numerical simulation of multiphase flows with large density differences.

The computational domain of 6*d* × 6*d* (section) x 16*d* (long) contained 192 x 192 x 512 (about 19 million) cells (fig. 2a). A spherical argon bubble of diameter *d* was initially placed at the center of the container bottom. A uniform magnetic field was applied in the *x* direction. The dimensionless shape and velocity were tracked with dimensionless time $t^* = t\sqrt{g/d}$.

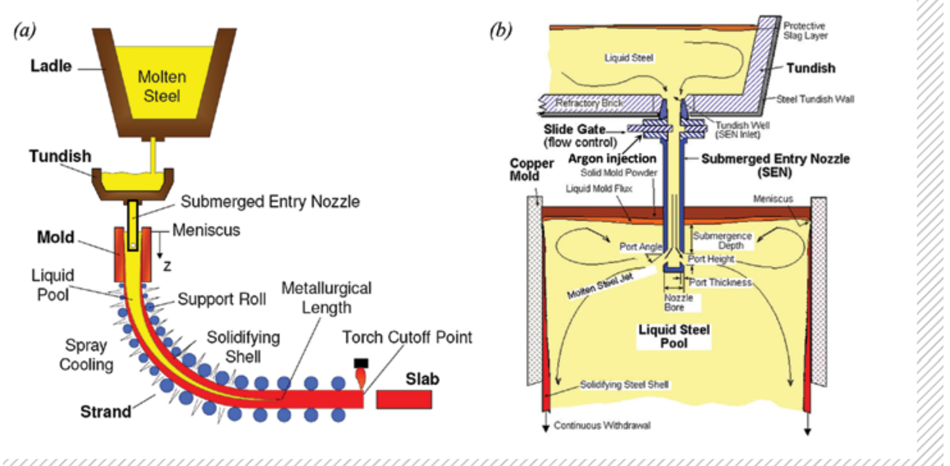

FIGURE 1:
(a) Schematic of the continuous-casting process and (b) close-up view into the mold region of the caster. Argon gas is injected near the slide gate.

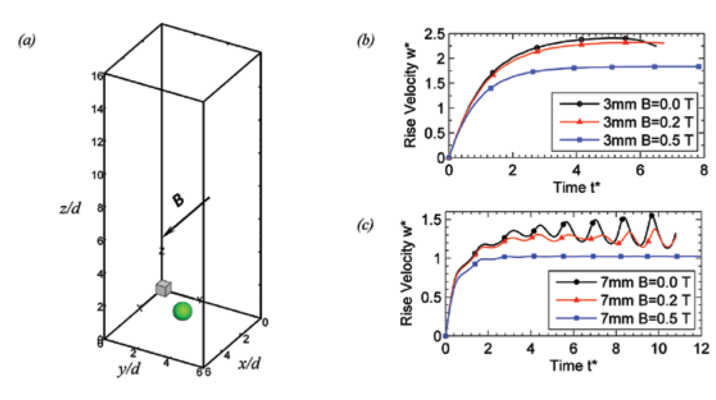

FIGURE 2:
(a) Computational domain and initial bubble location, (b) rise velocity of 3 mm argon bubble, and (c) rise velocity of 7 mm argon bubble. [4]

Fig. 2 shows that rise velocity was smooth and non-oscillatory at early stages (t*<0.5), especially with small bubbles. Without a magnetic field, velocity increased to 2.5 and then decreased slightly due to the inclined motion of the 3 mm bubble. Applying a transverse magnetic field of *B*=0.2 T lowered the rise velocities by 4%. Increasing the field strength to 0.5 decreased the rise velocities by 24% to 1.83. For a 7 mm bubble with no magnetic field, the rise velocity became oscillatory after t* > 1.0 due to the varying drag force as the bubble shape expanded and contracted along different axes. With a magnetic field of 0.2 T, the oscillations eventually were dampened. Increasing the field to 0.5 T completely damped the oscillations, resulting in a steady rise velocity that was ~25% lower relative to no field.

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

In related work, large eddy simulations (LES) were applied to investigate the flow in a commercial caster. Figs. 4a and 4c show instantaneous velocity magnitude in top views

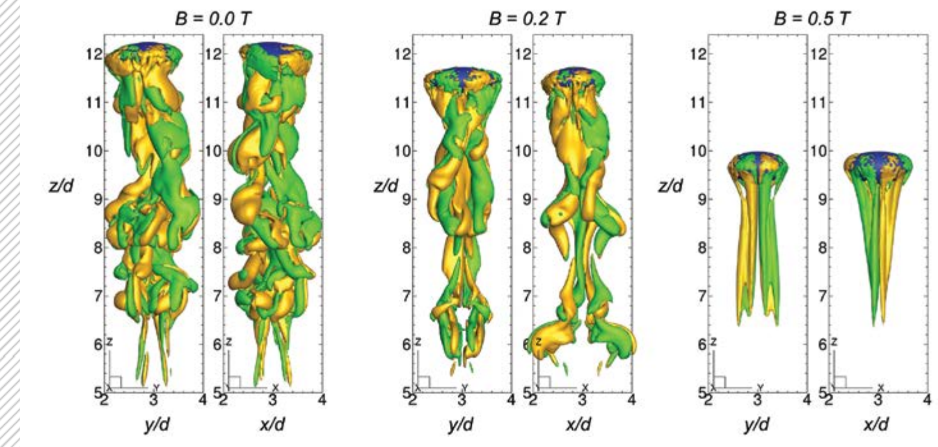

FIGURE 3:
Front and side views of the bubble (blue), isosurfaces of W_z^*= 1 (yellow) and W_z^*= -1 (green) at t* = 9 for 7 mm bubble. [4]

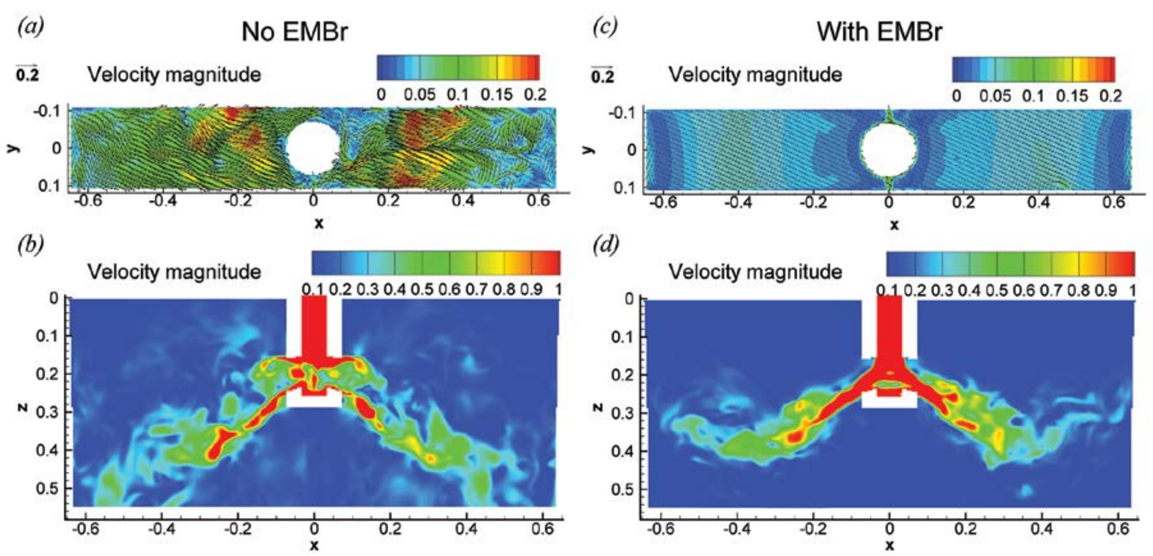

FIGURE 4: Predicted velocity in a horizontal plane near the top surface (top) and in the middle vertical plane of the caster mold (bottom) for cases without (left) and with (right) an external magnetic field.

of the caster (casting speed 1.5 m/min). Applying an EMBr field greatly lowered the velocity near the top surface, which can lead to problems of meniscus freezing in which the steel around the three-phase perimeter solidifies into detrimental hook structures that capture inclusions and bubbles. Figs. 4b and 4d show velocity in side views. Applying EMBr deflected the jets upward, but the flow in the top region was reduced by the dampening effect of the field. The steel plant that was experiencing this problem improved quality by lowering the field strength towards the top of the mold and increasing the casting speed.

WHY BLUE WATERS?

The in-house multi-GPU code CUFLOW was developed and tested on Blue Waters XK nodes and good speed-up was obtained. Less than two days were required for a 30 s LES simulation of flow in a caster domain with 14.1 million cells (based on a 100-time-step test run with an average time step size $\Delta t=0.0005$ s). Preliminary results showed that ANSYS-FLUENT also scales well 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 another part of this project, transient thermal-stress models of the solidifying dendritic microstructure will be applied to investigate strain concentration and the formation of longitudinal cracks in order to understand how to avoid cracks.

PUBLICATIONS

Jin K., S. P. Vanka, and B. G. Thomas, Three-dimensional flow in a driven cavity subjected to an external magnetic field. *J. Fluids Engineer.*, 137 (2015), 071104, doi:10.1115/1.4029731.

LATTICE QCD ON BLUE WATERS

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EXECUTIVE SUMMARY:

Project goals include developing highly optimized code for the study of quantum chromodynamics (QCD) to carry out calculations that will have a major impact on high-energy and nuclear physics. We have optimized and used Chroma for the simulation of Clover quarks and MILC for the simulation of HISQ quarks. Our long-term objectives with HISQ quarks are to generate gauge configurations with physical-mass up, down, strange, and charm quarks, to use these configurations to calculate fundamental parameters of the standard model of high-energy physics, and to make precise tests of the standard model. The objective of our Clover fermion program is the determination of the excited mass spectrum of strongly interacting particles (hadrons) within QCD.

INTRODUCTION

The standard model of high-energy physics encompasses our current knowledge of the fundamental interactions of subatomic physics. It has successfully explained a wealth of data from accelerator and cosmic ray experiments over the past 40 years. However, it has been difficult to extract many of the most interesting predictions of quantum chromodynamics (QCD), those that depend on the strong coupling regime of the theory. The only way, from first principles and with controlled errors, is through large-scale numerical simulations. These simulations are needed to obtain a quantitative understanding of the physical phenomena controlled by the strong interactions, determine a number of the fundamental parameters of the standard model, and make precise tests of the standard model. Despite the successes of the standard model, high-energy and nuclear physicists believe that a more general theory will be required to understand physics at the shortest distances. Thus, QCD simulations play an important role in efforts to obtain a deeper understanding of the fundamental laws of physics.

METHODS & RESULTS

Our objective is to perform calculations of QCD, the theory of the strong interactions of subatomic physics, to the precision needed to support large experimental programs in high-energy and nuclear physics. We are using two formulations of lattice quarks. The highly improved staggered quarks (HISQ) formulation is being used to calculate fundamental parameters of the standard model, our current set of theories of subatomic physics, and to make precise tests of the standard model. In particular, the HISQ formulation is being used to calculate the masses of quarks, which are the fundamental building blocks of strongly interacting matter, and to determine elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, which are the weak interaction transition couplings between quarks. The CKM matrix elements and the quark masses are fundamental parameters of the standard model and therefore of great interest. Furthermore, a major line of research within high-energy physics has been to determine the same CKM matrix element through different processes to look for inconsistencies that would signal a breakdown in the standard model. Until now, uncertainties in the lattice calculations have limited the precision of these tests. We aim to match the precision of our calculations to that of experiments.

Our first objective with the Clover formulation of lattice quarks is to perform a calculation of the mass spectrum of strongly interacting particles (hadrons). The determination of the excited-state spectrum of hadrons within QCD is a major objective for experiments and is a focus of the $310 million upgrade of Jefferson Laboratory. In particular, the GlueX experiment at Jefferson Laboratory will search for “exotic” mesons. These particles are a signature for new states of matter, specifically the presence of gluonic