TURBULENT MULTIPHASE THERMAL FLOW MODELING OF DEFECT FORMATION MECHANISMS AND ELECTROMAGNETIC FORCE EFFECTS IN CONTINUOUS STEEL CASTING

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EXECUTIVE SUMMARY

Multiphysics models have been developed to quantify the formation mechanisms of various defects related to flow instability, particle transport and capture, superheat transport, surface depression, and cracking in continuous steel casting. To simulate these complex and interrelated phenomena more accurately, the research team implemented a commercial computational fluid dynamics program, ANSYS Fluent high-performance computing (HPC), and the multi-GPU-based in-house CUFLOW codes on Blue Waters' XE and XK nodes, respectively. Using these codes on Blue Waters' resources, various turbulent flow models including large-eddy simulations and Reynolds-averaged Navier–Stokes models have been coupled with the volume of fluid method, discrete phase model, particle capture models, and heat transfer models. Finally, the team is applying these models with magnetohydrodynamics (MHD) models to investigate the effects of electromagnetic systems (static or moving magnetic fields) on defect formation, such as longitudinal cracks and hooks, and to explore practical strategies for reducing defects in the process.

RESEARCH CHALLENGE

Continuous casting is the dominant process used to solidify over 96% of steel produced in the world [1]. Thus, even small improvements can have tremendous industrial impact. Many defects in final steel products originate in the mold region of the process owing to transient phenomena, which include turbulent multiphase flow, particle transport and capture, heat transfer, solidification, and thermal–mechanical behavior. To reduce defect formation, various electromagnetic (EM) systems are often employed to control the transient turbulent flow and accompanying phenomena, according to the varying process conditions in the production facility [2]. Experiments and measurements to quantify these phenomena are extremely limited owing to the harsh environment and huge size of the process as well as the many process parameters. Therefore, the development of high-resolution computational models is an important tool to more accurately simulate and understand the process phenomena and defect formation and to find more practical ways to reduce defects and improve the process. Thus, the research team conducted multiphysics simulations on the Blue Waters supercomputer in order to quantify turbulent multiphase flow, argon gas bubble interaction and size distribution, particle transport and capture, and superheat transport, and to simulate the effects of moving magnetic fields on these phenomena, in order to investigate ways to reduce defects.

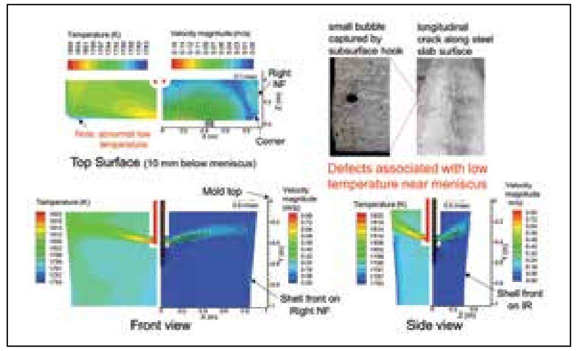

Figure 1: Mold flow pattern and resulting temperature distribution affect defect formation in continuous steel casting.

METHODS & CODES

The research team conducted large-eddy simulations (LES) coupled with the volume of fluid method to calculate transient behavior of three-dimensional surface slag/molten steel interface during continuous steel-slab casting [3]. The team used the hybrid multiphase turbulent flow model [4,5] that couples the Eulerian–Eulerian (EE) two-fluid model together with a discrete phase model (DPM) that was validated with lab-scale low-melting alloy experiments to simulate argon bubble interaction (gas pocket formation, gas expansion, breakup, and coalescence) and size distributions in a real slide-gate nozzle [6]. These models have been developed using a commercial computational fluid dynamics program, ANSYS Fluent HPC, on Blue Waters' XE nodes (AMD 6276 "Interlagos" processor). In addition, transport and capture of the argon bubbles were calculated using LES coupled with the DPM and advanced capture models [7], which were implemented on Blue Waters' XK nodes (NVIDIA GK110 "Kepler" accelerator) with the multi-GPU-based in-house code CUFLOW [8].

The team applied the magnetic-induction MHD model [2] together with the turbulent-flow models (LES/Reynolds-averaged Navier–Stokes models), the DPM of the transport and capture of inclusions and bubbles, and a heat transfer model, to investigate effects of moving magnetic fields, including EM level stabilizer, EM level accelerator, and mold EM stirring (M–EMS) [2] on the flow pattern and instability, gas bubble distribution, temperature distribution, and superheat at the shell solidification front in the slab mold during steady continuous casting.

RESULTS & IMPACT

Turbulent fluid flow, surface slag/molten steel interface instability, liquid-level fluctuations at the meniscus, slag entrainment, and entrapment were computed from the multiphysics model simulations. This allows understanding of slag defect formation mechanisms, especially the slag entrapment owing to sudden level drops near meniscus regions. From the validated EEDPM model [4,5] simulations, argon bubble behavior and size distributions in the turbulent molten-steel flow inside a slide-gate nozzle of the real caster [6] were revealed in detail. This calculation is expected to contribute to more accurate particle-capture results by being coupled with the advanced particle capture model [7].

In addition, the study investigated initial solidification-related defects such as meniscus freezing, hook formation [9,10], and longitudinal crack formation near the meniscus with the further aid of the coupled heat-transfer model. For example, in mega-thick slab casting, as shown in Fig. 1, the distribution of superheat flux around the mold perimeter was very nonuniform with the unoptimized mold flow pattern. In particular, superheat was unable to reach the meniscus corner, leading to deep hooks and/or longitudinal crack formation. In addition, the effect of the M–EMS on mold flow pattern, temperature, and superheat distribution was quantified from the magnetic-induction MHD model simulations. With M–EMS, the superheat flux at the shell front became more uniform owing to the rotating flow around the perimeter of the mold, resulting in higher superheat flux to the corners, as shown in Fig. 2. This effect is expected to lessen initial solidification defects, so long as the magnetic field strength is within an optimal range.

WHY BLUE WATERS

The high-resolution models used to more accurately simulate and better understand defect formation mechanisms in continuous steel casting are very computationally intensive. The many coupled governing equations need to be solved for turbulent flow, particle transport and capture, temperature, and MHD fields. Moreover, many computational cells are required to capture these complex and interrelated phenomena on micrometer and millisecond scale in the huge domain. Blue Waters enables such high-resolution simulations in a reasonable time frame by speeding up ANSYS Fluent HPC calculations by more than 3,000 times and CUFLOW calculations by 50 times. Furthermore, the Blue Waters parallel computing environment enables numerous cases to be calculated simultaneously with different process conditions for parametric studies essential to optimize this complex process. Thus, the Blue Waters supercomputer provides a great contribution to obtaining deep insights into complicated defect-related phenomena with high resolution in order to improve this important commercial process.

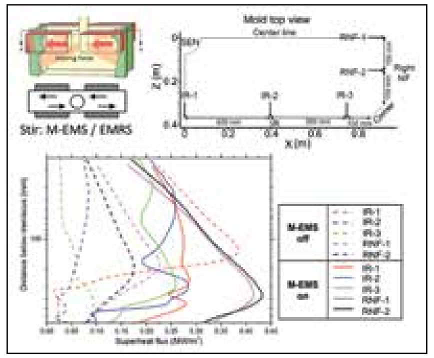

Figure 2: Effect of electromagnetic stirring on superheat flux profiles near the solidifying steel shell front around the perimeter of the mold.

PUBLICATIONS & DATA SETS

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