ABSTRACT

Producing good quality steel at higher production rates is the objective of every steel industry. Continuous casting has been the most widely used process of producing steel products from molten steel in various basic shapes which undergo subsequent operations to reach final shapes. The successful implementation of the continuous casting process in the latter half of the 19th century has seen numerous developments in casting technology, model developments, and its application for producing a wide range of end products. The thin slab continuous casting process is the most widely implemented Near net shape casting process and a very promising sustainable technology due to the use of lesser finishing operations and economic viability. The thin slab continuous casting process involves very high casting speeds to produce the castings with a smaller thickness, which results in higher productivity with less cost. To obtain high productivity, this process experiences severe drawbacks such as meniscus instability, free surface fluctuations, mould flux entrapment, etc. which are more acute as compared to the conventional continuous slab casting.

The continuous casting process is a solidification process in which liquid metal undergoes solidification and converts into liquid. The initial solidification of the liquid metal takes place in the mould. During the solidification process, the material undergoes a phase change process and shrinkage of the material takes place which causes the formation of a gap between mould walls and the solidifying metal which is in contact with the mould walls. Various approaches are proposed in the literature to address this gap effect by considering several assumptions. The first objective of this thesis develops a mathematical model to study the three-dimensional non-linear thermal resistance offered by the gap. The mathematical formulation is developed based on the principle of conservation of mass and shrinkage of the material. The expression for the thermal resistance majorly depends on the solidified shell thickness and effective thermal conductivity of the gaseous medium present at the mould-strand interface. A user-defined function (UDF) is formulated to determine the 3D variation of the solidified shell thickness along the mould length and the conservation of energy principle is used to determine the effective thermal conductivity of the gaseous medium present at the mould-strand interface. The three-dimensional fluid flow, heat transfer and solidification model along with the specially formulated boundary condition able to capture the non-linear thermal resistance. Heat transfer at the corner regions is automatically adjusted as per the

shrinkage of the material without any manual adjustments. The shell thickness obtained at the face centre near the mould exit is close to the industrial observations.

Prior knowledge of the conventional continuous casting process need not be useful to solve the problems of the thin slab continuous casting process (TSCC). Continuous deformation of solidified shell thickness due to funnel-shaped mould used in this process is the prime reason for this discrimination. Though the physics involved in both the process is the same, the TSCC is completely different in terms of geometry (aspect ratio of the thin slab, funnel shape mould, design of the nozzle, cooling water design), operating conditions (casting speed, water flow rates, cooling water velocity), magnetic equipment used for applying EMBr effect, type of mould lubrication, size of air gap formation, stability at the meniscus, cracks formations, etc. It can be understood from the literature that the heat flux empirical relations available for billet and slab casting processes cannot apply to the TSCC. The second objective of this thesis considers the interfacial heat flux profile which is determined based on the industrial plant data to study the turbulent flow, heat transfer and solidification of the solidifying thin slab in a funnel shape mould. High velocities and recirculation flow in the upper and lower regions of the mould lead to several issues like non-uniform heat transfer and hindrance in the growth of the solidified shell, etc. The high speed of the molten metal emanating from the submerged entry nozzle impinges on the narrow face at high speeds, causing remelting of the solidified shell and a thinner shell at the mould exit.

TSCC faces severe challenges towards quality control due to high casting speeds within a very narrow region, which is even more acute in funnel-shaped moulds having wide face transition from a curvilinear geometry to a linear geometry. The formation of complex recirculation flows inside the mould region are observed to be chaotic which create adverse effects such as remelting of the solidified shell and longitudinal surface defects. The third objective of this thesis is focused on controlling these complex turbulence flows to improve the thermal characteristics of the solidifying strand in TSCC.

Since the liquid metal used in the solidification process has electrical conductivity and magnetic permeability, generating strong electromagnetic forces inside the mould effectively alters the shape and size of the strong recirculation flow formations inside the mould. Hence, the method of applying the electromagnetic brake with the help of a vertical electromagnetic brake (V-EMBr) system is applied in TSCC which uses a funnel-shaped mould. Lorentz force due to the static electromagnetic field is a very effective solution to control the flow behaviour within the mould. The V-EMBr significantly changes the flow near the narrow face and

downward flow direction of liquid metal travelling towards the mould outlet. The dominating effects on surface velocities and temperatures are observed close to the narrow face since the location of V-EMBr is confined close to the narrow face. Improvement in the shell thickness and reduction of remelting effect are the major contributions of applying V-EMBr. From the observations of pathlines of fluid particles, velocity profiles near the meniscus region, growth of solidified shell at the face centre and corner region, etc., it is observed that the application of V-EMBr is succeded in improving the thermal characteristics of the solidifying strand in TSCC.

The temperature of the liquid metal entering the mould is more than 1800 K. When the mould is subjected to continuous exposure to the high-temperature liquid metal for more than one week of duration, stresses and strains generate inside the mould. The response of the mould when it is subjected to thermal and mechanical interactions needs to be studied since they alter the shape of the mould. While studying the mechanical behaviour of the mould, creep effects have a significant contribution and is more than the elastic and plastic behaviour of the mould. The rigidity of the waterbox attached to the mould offers an additional constraint to the free deformation of the mould. The fourth objective of the thesis develops a 3D thermomechanical model using non-linear isotropic and kinematic plasticity models along with the creep model and calculate the distortion of the mould, residual stress and elastic-plastic-creep strains in an assembly of funnel-shaped mould and waterbox. Most of the funnel transition regions of the mould are accumulated with higher temperatures and hence, displacements and strain distributions are maximum in that region. Distortion of the narrow face is majorly affected by the mechanical boundary condition. It is observed that excluding the creep model highly overestimates the mechanical behaviour of the mould.

Keywords: Continuous casting; Computational Fluid Dynamics (CFD); Turbulence; Heat Transfer; Solidification; Interfacial thermal resistance; Jet impingement; Magnetohydrodynamics; Thermomechanical model; Elastic-plastic-creep model; Distortion.