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Mathematical modelling of single and multi-strand tundish for inclusion analysis

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ABSTRACT

In the present work a numerical study was carried out to investigate the inclusion behaviour in a four strand asymmetric billet caster tundish. A parameter called *separation efficiency* was used to compare inclusion behaviour quantitatively. An open source CFD code called OpenFOAM was used to model the inclusions through Lagrangian Particle Tracking approach. First, the Lagrangian particle class was defined in the existing *simpleFoam* solver of the OpenFOAM and the same customized solver was used to track particles in the already obtained velocity field. Inclusions were modelled as spheres and various forces acting were also considered. Present numerical results were validated using available experimental results and found to be in good agreement. Further, such inclusion behaviour was also extended for a real industrial case tundish. Inclusion flotation characteristics in thermally induced flow was analyzed in detail. This is, perhaps, for the first time such an exhaustive study on inclusion analysis being reported considering the forces acting on the inclusions particles and with OpenFOAM.

1. Introduction

With the rising demand for the better quality of steel, inclusions removal plays a very important role in the casting process. Tundish which is the integrated part of the steel making process is ideally used for continuous casting process in a steel industry. In the continuous casting process, tundish acts like a reservoir by holding sufficient quantity of steel and helping in ladle changeover without interrupting the casting process. Apart from this tundish plays a significant role in facilitating flotation in order to remove non-metallic inclusions from the molten steel. This has a direct effect on the cleanliness of steel produced. Thus the quality of steel produced also depends on the fluid flow phenomenon inside the tundish. Although complete elimination of these inclusions is a close to impossible task, a slight improvement in inclusion removal plays a greater role in determining the cleanliness of steel produced. Generally these inclusions which can be removed at the tundish stage will be in the order of micrometers.

Sahai and Ahuja [1] has postulated that to achieve maximum inclusion separation ratio, there should be a minimum spread of residence time, large ratio of plug to dead volume, relatively large ratio of plug to mixed volume, surface directed flow, and contained region of mixing.

The basic source of inclusions in tundish is in the carry over slag from the ladle (micro droplets form), tundish slag, eroded particles of refractory wall, various chemical/steel deoxidation reactions *etc.* Previous investigations [2–4], *etc.* showed that the basic tundish design, operating parameters (for example, throughput rate, bath depth, *etc.*), incorporations of various

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Nomenclature

C_D	drag coefficient
d_p	particle diameter
F_D	drag force
F_{AM}	added mass force
F_B	buoyancy force
F_{VM}	virtual mass force
k	turbulent kinetic energy
m_p	mass of the particle (inclusion)
Re_p	particle Reynolds number
u	velocity of the flow field
Greeks	
ρ	density of the fluid
μ	kinematic viscosity
μ_l	laminar viscosity
μ_t	turbulent viscosity
κ	thermal conductivity
σ_k	Prandtl number for turbulence kinetic energy
σ_ε	Prandtl number for dissipation rate of turbulent kinetic energy
τ_p	particle relaxation time
ρ_p	particle density
β	separation efficiency
ε	turbulent dissipation rate
Subscripts	
i, j, k	three perpendicular components along x, y, and z axes respectively
l	laminar component
t	turbulence component
f	fluid
p	particle

flow modifiers, as well as external electromagnetic forces *etc*. influence the amplitude of residence time distribution (*RTD*) in tundish. Such factors have considerable influence on the efficiency of inclusion separation as well as its floatation. Jha et al. [5] performed an extensive study on the effect of height and position of dams on inclusion removal in a multi strand tundish. This is well known fact that a tundish without any flow modifier do not satisfy the necessary requirements essential to the inclusion removal and consequently, critical to the production of clean steel. It should be mentioned here that specific conditions for removal of inclusions vary largely from one operating practice to another. The size of inclusions is the critical factor in determining the effectiveness of a given tundish design to separate and float out inclusions. Literature suggested [6,7] that inclusions with a large terminal velocity or larger particle diameter will readily float-up to the slag-metal interface provided appropriate flow modifiers are incorporated into the tundish geometry. To fulfill the steel maker's requirement the existing or basic tundish geometry cannot be frequently interchanged/revamped at the caster. Therefore, the insertion of the appropriate flow control devices in the tundish is the best option to create desirable flow pattern economically. Numerous studies [8,9], *etc*. have been reported in the literature on fluid flow and RTD in steelmaking tundish. Recently Sarkar et al. [10] studied flow and heat transfer phenomenon for multi strand asymmetric tundish. They showed the importance of proper tundish pre-heating practice on thermal stratifications of the liquid steel.

Apart from the inclusion analysis many researchers investigated fluid flow and heat transfer phenomenon in a single and double strand tundish (see [11–13], *etc*.). Several thermo-fluidic phenomena and associated heat transfer characteristics have been analysed at every nuances of the tundish geometry. In industrial tundish, the side wall inclination plays a major role in the fluid flow phenomenon inside the tundish domain. He and Sahai [14] reported the effect of tundish wall inclination on the fluid flow and mixing. The state of fluid motion in the tundish considerably influences the rate of heat and mass transfer controlled processes. As majority of the metallurgical operations are governed by heat and mass transfer, consequently, the nature of the fluid flow (*viz*. spatial velocity distribution, turbulent kinetic energy *etc*.) influences tundish performance considerably. The already present inclusions inside the tundish follow the fluid flow pattern and thus the interaction of these inclusions as particles with the fluid flow will be of more importance. Matsuura et al. [15] showed the classification of inclusions morphologies after the addition of Aluminium and Titanium to the molten steel.

In the above mentioned literatures and to the best of author's knowledge there is not much information available on the characteristics of inclusions in multi strand asymmetric tundish. Although some preliminary studies with similar objectives [16,17] have been reported, a systematic study on multi strand asymmetric tundish addressing this extremely significant