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3-D CFD simulation of a vertical direct chill slab caster with a submerged nozzle and a porous filter delivery system

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ABSTRACT

A 3-D CFD model coupled with turbulent melt flow and heat transfer with solidification is developed to simulate an industrial-sized vertical direct chill (DC) slab caster for aluminum AA-1050 alloy. In a DC casting process, a melt distributor is used to feed melt to the mold to minimize the temperature gradient between the hottest and coldest areas. This study considered a new melt distributor which consisted of a submerged nozzle underneath of which there was a porous filter occupying the entire transverse cross-section of the caster. The whole assembly was placed inside the hot-top above the mold. Simulations were carried out by varying three different important parameters of the problem, namely, the casting speed from 40 to 100 mm/min, the effective heat transfer coefficient at the mold-metal contact region from 0.75 to 3.0 kW/(m^2 K), and the Darcy number of the porous filter from 10^{-6} to 10^{-3}. For all parametric cases, the inlet melt superheat was 32 °C and the porosity of the filter was taken as 0.4. Detail results in the form of velocity and temperature profiles, solid shell thickness, sump depth and local surface heat flux are predicted and compared.

1. Introduction

The vertical direct-chill (DC) casting of aluminum was invented during 1936–1938 almost simultaneously in Germany (W. Roth, VAW) and the USA (W.T. Ennor, ALCOA). Since the invention, this semi-continuous casting technique is being used exclusively to produce rolling ingots and extrusion billets owing to its robust nature and relative simplicity. Many non-ferrous alloys such as aluminum, magnesium and copper are nowadays cast through this technology [1]. Among non-ferrous metals, aluminum is widely preferred for its light weight, strength and corrosion resistance. It is used in numerous applications such as automotive, transport, packaging, construction and printing industry to name but a few. At present, the world production of aluminum using DC casting technology is approximately 25 million tons per annum [2]. Although this casting process is more than seventy-five years old and despite extensive research in this area, still today many major challenges the industry is facing during the production of the casts. The two major issues this industry is facing today are that, how the slabs or billets of various aluminum alloys of short, medium and long solidification ranges can be cast in the same machine economically and defects free.

In a DC casting process, the liquid metal is poured into a bottomless static water-cooled mould, which is initially enclosed partially at the bottom with a metallic block. At the beginning of this casting process, the bottom block is placed such that the top edge is about 20 to 35 mm inside the mould [3]. A metal feeding system feeds the superheated liquid aluminum into the cavity formed by the mold and the bottom block. The metal level above the bottom block is allowed to increase slowly as specified by the casting house practice, until the liquid metal reaches to a prescribed level. Once the liquid metal freezes on the metallic block and a solid shell is formed close to the mould walls, the metallic block is lowered slowly by means of a hydraulic ram towards the casting pit until a constant casting speed is reached. During this process the metal level in the mould is kept at a certain height by controlling the metal flow through a distributor system. At the beginning, the solid shell forms due to the heat extraction through the water-cooled mould (referred to as primary cooling) as well as through the bottom block. Now the outer part of the ingot is solid, but the inner core is still semi-solid/liquid. As the partially solidified ingot is lowered under the mold, further cooling of the ingot bulk is achieved by jetting chilled water from a series of holes at the mold base to get the temperature of the cast below the alloy solidus. This quenching of the strand is referred to as secondary cooling. During

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Nomenclature

A	Darcy coefficient
a_p, a_{nb}, b	coefficients in the discretized governing equations
c_1, c_2, c_μ	empirical constants for low Reynolds number model
c_p	specific heat
C	morphology constant
D	nozzle hydraulic diameter
D_k	extra dissipation term in k-equation
Da	Darcy number
E_ε	extra generation term in ε-equation
f_1, f_2, f_μ	empirical constants used in low-Re version of k–ε models
f_l	liquid fraction
f_s	solid fraction
G	production term in turbulent kinetic energy equation
Gr	Grashof number
Gr_m	modified Grashof number = Gr/Ste
g_x	gravitational acceleration in the x-direction
h	sensible heat
H	total heat (sensible and latent)
K'	permeability of porous media associated with mushy region
K	permeability of porous media associated with filter
k	turbulent kinetic energy
k_l	thermal conductivity of the liquid
k_s	thermal conductivity of the solid
k_{ps}	thermal conductivity of the porous structure
P	hydrodynamic pressure
Pe	Peclet number
Pr	laminar Prandtl number
q	heat flux
Re	Reynolds number
Re_P	pore Reynolds number = Re/ϕ
Re_t	turbulent Reynolds number based on the turbulent quantities
S	source term
S_Φ	source term associated with Φ
Sc	Schmidt number
Sc_t	turbulent Schmidt number
S_{k^*}	source term associated with buoyancy term in k-equation
S_{ε^*}	source term associated with buoyancy term in ε-equation
Ste	Stefan number
T	temperature
T'	fluctuation of temperature
T_{in}	inlet temperature
T_l	liquidus temperature
T_s	solidus temperature
T_{surf}	slab surface temperature
u_i	velocity component in the ith direction; corresponding to u
$\bar{u}_i$	time-average velocity component in the ith direction
u'_i	fluctuation of velocity in the ith direction
u_{in}	inlet velocity
u_s	casting speed
U, V, W	non-dimensional form of the u, v and w velocities
U_s	non-dimensional form of u_s
x	axial direction
y	horizontal direction parallel to the wide face
z	horizontal direction parallel to the narrow face
X, Y, Z	non-dimensional form of x, y, z

Greek symbols

ΔH	nodal latent heat
ΔH_f	latent heat of solidification
Γ_Φ	diffusion coefficient associated with Φ
ρ	alloy density
φ	generalized dependent variable
μ_e	effective viscosity equal to $\mu_t + \mu_l$
μ_l	laminar viscosity
μ_t	turbulent viscosity or eddy diffusivity
Φ	generalized dependent variable
β_T	thermal expansion coefficient
Γ_{eff}	effective diffusivity
ε	rate of energy dissipation
ε_{in}	inlet rate of energy dissipation
γ	effective convective heat transfer coefficient
σ_k, σ_ε	turbulence model constants
σ_t	turbulent Prandtl number
ϕ	porosity of filter

Superscripts

*	non-dimensional variables
–	time-averaged variables
′	fluctuation of variables

the steady state operation of a DC casting process, typically around 80–95% of the total heat content in the metal is removed by secondary cooling [4] while about 5 to 20% is extracted through the primary cooling zone. The DC casting process is actually semi-continuous because of the fact that after achieving a desired cast length, the process is stopped and then the cast is lifted away from the casting pit. The casting is restarted when the metal and machinery are ready for the next new cast.

In a DC slab casting process, after slabs are cast they are usually rolled to make the final products. During the rolling process, if a large number of inclusions are present there, they may create a number of unwanted defects, namely, edge cracking, pinholes, and foil breaks [5]. To minimize the number of inclusions, in a DC-casting process, the melt is filtered before it is transferred to the launder and casting table. After filtration the melt can pick-up inclusions in the latter two facilities and can end-up in the cast if an appropriate removal scheme is not implemented before the melt enters the mold. Once the melt enters the mold, the oxide inclusions and oxide scale that develop at the top free surface of the caster due to oxidation, may be picked-up by the strong turbulent flow generated by the melt delivery system. These inclusions will also invariably end-up in the cast if they are not removed. The strong turbulent flow at the free top surface of the caster will influence strongly the inclusion content and distribution in the final cast [6,7]. Recently, Jaradeh and Carlberg [8] investigated experimentally the distribution of inclusions in vertical DC-slab casts. They have found that mostly oxide inclusions, which are larger and more harmful, appear at the slab surface, while the smaller inclusions remain in a significant pattern in the interior of the slab. They have concluded that the non-uniform distribution of inclusion is mainly due to the fluid flow conditions during solidification. The number of inclusions in the cast can be minimized by filtering the melt before it enters the mold using a filter of fine pore size.

Current standard practice in DC casting industry is to use a hot top mold with a combo bag melt distribution system. Usually, in industry the combo bag is made of fiberglass and it is placed only