

# NUMERICAL STUDY OF HEAT AND MASS TRANSFER AT INOCULATIONS FILING TO THE SLAB CC MOLD

## ЧИСЛЕННЫЕ ИССЛЕДОВАНИЯ ТЕПЛО - И МАССООБМЕННЫХ ПРОЦЕССОВ ПРИ ВВОДЕ ИННОКУЛЯТОРОВ В КРИСТАЛЛИЗАТОР СЛЯБОВОЙ МНЛЗ

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**Abstract:** *Mathematical and numerical models for calculating heat- and mass transfer of metal bath in the mold of a slab CCM, that equipment the submerged nozzle with inclined discharge openings are developed. The thermal and hydrodynamic regularities of melt's behavior, including, in the feed to the mould inoculant in the form of a metal strip with a chemical composition different from the base, with possible oscillation.*

**KEYWORDS:** CONTINUOUS CASTING, SLAB, MOLD, MOLTEN METAL, MATHEMATICAL MODELING

### 1. Introduction

Today on the all over the world 2/3 continuous casting blanks are slabs. But in spite for that so big volume of output today we have many open problems connecting with slab quality simultaneously with increasing casting speed and decreasing the expenditure of energy and material cost.

One of advanced method of continuous casting is using different kinds of inoculators. For inoculators usually use the metallic materials with chemical composition similar to casting metal. Along with rare using methods inoculators input to the liquid pool in the mould that are pellets, water coolers, rods special attention deserve the using metallic band.

Most of continuous casting blank defects form in to the mould and connect with heat and mass transfer character and intensity. Because investigation the mould processes is very actual for continuous casting blank quality improving at the high casting speed.

This question is very urgent when we use additional materials inputting to the liquid pool in to the mould and only science-band recommendation can guarantee receiving products high quality.

**Investigation objectives** – development of mathematical and numerical models of heat and mass transfer of processes band's input in to slab CC mould.

This task can decide by methods of physical and mathematical modeling with following check and adaptation at the working environment. All decisions well be exclusive and can be use to special investigated type of CC and technological parameters. Mathematical modeling is most flexible method of investigation.

Most interesting investigation in this field are manuscripts [1, 2]. In manuscript [1] task decided for thin slabs casted at radial caster. Was used professional program packages for hydrodynamics and heat and mass transfer Fluent 5.5/Gambit 1.3 based on the RNG-k-ε turbulence model with accounting of liquid metal enthalpy changing. Model adequacy checked at physical model.

Joint two dimensional model of heat and mass transfer in the CC bloom mould with inert gas input to the metal stream decided in manuscript Joint two dimensional model of heat and mass transfer in to the CC bloom mould with inert gas input to the metal stream decided in manuscript [2].

The main disadvantage of that research works were impossibility to investigate speed and thermal fields in the mould with band feeding. But model from manuscript [2] that checked on the physical model and in the work environments can predict heat and mass transfer after inoculates feeding in to the liquid pool in the mould after model transformation from two dimensional to three dimensional.

### 2. Investigation methodic

1. The model created on the common approach basis to multi-phase systems [3, 4]. The basic model assumptions:

2. Basic metal with specified chemical composition cast to slab mould through one SEN with two unloaded inclined side openings.
3. Steel band with different from basic metal chemical composition feeding in to the mould straight down parallel mould wide side at the specified distance from SEN.
4. Metal meniscus is quiet, without waves and covered by slag. Therefore the accounting of free surface dynamics isn't required.
5. Heat removal conditions to mould and band depend from metal streams speeds and describe the border between solid metal and mushy zone.
6. The band feed straight down on the vertical mould axis at the specified distance from SEN.

Well-known stationary Navier–Stokes equation, equations of liquid metal continuity and heat transmission in mold was the basis of moving and heat transfer mathematical model:

$$(\vec{v}\nabla)\vec{v} = -\nabla p + \nu\Delta\vec{v} + \vec{g}, \quad (1)$$

$$\nabla\vec{v} = 0, \quad (2)$$

$$\nabla(\vec{v}T) = \nabla(\lambda\nabla T) + Q, \quad (3)$$

where  $\vec{v}$  – velocity vector;  $p$  – pressure;  $\nu$  – coefficient of effective kinematic viscosity;  $\vec{g}$  – vector, taking in account the action of mass volume forces (acceleration of gravity etc);  $T$  – temperature,  $\lambda$  – metal thermal conductivity;  $Q$  – thermal volume source, taking in account heat of phase transition at the steel solidification process.

Taking in account the task character mould geometry was approximated by orthogonal non uniform net and in equations (1–3) used Cartesian coordinate system. In equation (1) used Boussinesq approximation on the first stage calculations that taking in account lifting force because liquid metal has different density at different temperatures. Density at kinetic momentum equations is constant. Stationary equations system solved by assignment method.

Hence velocity vector  $\vec{v}$  can divide to axis constituents OX, OY, OZ Normalized presser for equation (1) introduced for convenience decision.  $Q$  in equation (3) changed to effective heat capacity  $C_{ef}$ .  $C_{ef}$  taking in account crystallization heat release at the time of steel solidification in the temperature range liquidus  $T_L$  – solidus  $T_S$ . Introducing additional assumption about metal fluidity absence at temperature lower than  $T_L$ .

The penetration absence and free sliding are conditions for velocity boundary conditions on the symmetry axis and near solid surface

$$v_{\perp}|_S = 0, \vec{n} \cdot \vec{\nabla}_{\parallel}|_S = 0, \quad (4)$$

and free moving stream condition on the free surface and on the down side of calculated field:

$$v_{\perp}|_S = v_S, \vec{n} \cdot \vec{\nabla}_{\parallel}|_S = 0, \quad (5)$$

where  $\vec{n}$  – normal vector to surface.

$v_s$  accept velocity stream finish value at the SEM exit and is equal 0 at the other surface.

Solidified skin freezing was calculated on the basis of well-known Fourier thermal conductivity equation with near-equilibrium mushy zone approximation

$$C_{ef}(T) \cdot \rho \frac{\partial T}{\partial \tau} = -C_L \cdot \rho \vec{\nabla}(T\vec{v}) + \vec{\nabla}(\lambda \vec{\nabla}T), \quad (6)$$

where

$$C_{ef}(T) = \begin{cases} C_S, & T < T_S \\ C + \frac{L}{T_L - T_S}, & T_S \leq T \leq T_L \\ C_L, & T > T_L \end{cases} \quad (7)$$

For equation (7)  $T$ ,  $T_L$ ,  $T_S$  – current temperature for calculated field, liquidus and solidus temperatures accordingly;  $C_{ef}$  – effective thermal capacity depended from thermal capacity in the solid phase ( $C_S$ ), liquid phase ( $C_L$ ) and in mushy zone ( $C$ ). Thermal conductivity in mushy zone is equal:

$$C = (C_{liq} - C_{sol}) \frac{T}{T_L - T_S} + \frac{C_S T_L - C_L T_S}{T_L - T_S}. \quad (8)$$

This task can solve with natural variables by physical factor split method and can be realize in the form of three stage split schedule. This system is combination of physical factors split method to equation of hydrodynamics and recalculated difference scheme:

$$1. \quad \vec{v} = \vec{v} + \Delta\tau [-(\vec{v}^n \cdot \vec{\nabla})\vec{v}^n + \nu\Delta\vec{v}^n], \quad (9)$$

$$\vec{T} = T^n - \Delta\tau c \rho_l \vec{\nabla}(T^n \vec{v}^n). \quad (10)$$

$$2. \quad \Delta\vec{p}^{n+1} = \frac{\vec{\nabla} \cdot \vec{v}}{\Delta\tau}. \quad (11)$$

$$3. \quad \vec{v}^{n+1} = \vec{v} - \Delta\tau \vec{\nabla} \Delta\vec{p}^{n+1}, \quad (12)$$

$$T^{n+1} = T^n + \Delta\tau \vec{\nabla}(\lambda_l \vec{\nabla} \vec{T}). \quad (13)$$

where  $n$  – number of times layer;  $\tau$  – times pitch;  $\lambda_l, \rho_l$  – liquid metal thermal conductivity and density accordingly.

Stage 2 fulfill in the liquid phase only.

Boundary conditions for pressure on calculated field was received by project (12) to surface normal.

The heat exchange on the model symmetry axis set absent. Heat exchange on the slag surface set by means radiative and convection heat exchange. Specified superheat temperature set on the place of stream entrance to the mould.

First kind boundary conditions on the mould surface set by means power law (statistical literature data manipulation):

$$T_s = T_f + (T_i - T_f)^{1 - \frac{\nu_c}{l_{cr}}}, R=0,95, \quad (18)$$

where  $T_i, T_f$  – initial input metal temperature to the mould and slab surface temperature on the exit of the mould accordingly;  $\nu_c$  – casting speed;  $l_{cr}$  – mould length;  $R$  – multiple correlation coefficient.

Third kind boundary conditions was set on the slab surface after mould.

The net with variable pitch used for decrease the calculation time because the band width is low.

Presented model realized by Delphi 7.0 medium. The band feeding modeling fulfill after heat and hydrodynamics conditions were stabilize.

The model adequacy was check by comparison calculated data with physical modeling results and end-use measurements [5].

### 3. Discussion

Heat and mass transfer process on the mould with dimensions 2300\*300mm and with 900mm length was investigated. Casting process of steel grade S355 with superheat 15°C at the mould entrance was modeling. The distance from SEN unloaded openings axis to metal meniscus was 150 mm. Unloaded openings inclination angle was 15° down. Casting speed set 0.9 m/min. The slab surface temperature on the mould exit was 1150°C.

Metal band has chemical composition correspond to steel grade 45. The band thickness was 1.5 mm and width was 400 mm. The distance from SEN axis to band end face was 200 mm. The inoculator feeding speed was 5 m/min to demonstrative calculations. Initial band temperature was equal 20°C. Heat and mass transfer investigated whet band feeding was in quiet mode and with transversal oscillation imposition to the band. The oscillation frequency was 150 Hz and amplitude was 2 mm.

Isosurfaces of metal stream absolute velocities without inoculators input you can see on fig.1. Here and after isosurfaces correspond 0.06; 0.15; 0.3; 0.55 m/s velocities. Obviously, two symmetric metal streams in this case arise in the metal volume around SEN with direction to mould narrow sides and down.

Flowing metal streams created enclose extended along withdrawal axis vortexes in the longitudinal sections. That streams intensity decries from mould axis to mould wide walls and have the tendency to SEN unloaded openings approaching. More difficult conditions we can see on the transversal sections. On the upper side of the mould streams go to SEN with some down angles. On the deep side streams change them direction and create enclosed and extended with different angles to vertical axis vortexes. It process promote flow out of SEN unloaded openings metal stream energy dissipation.

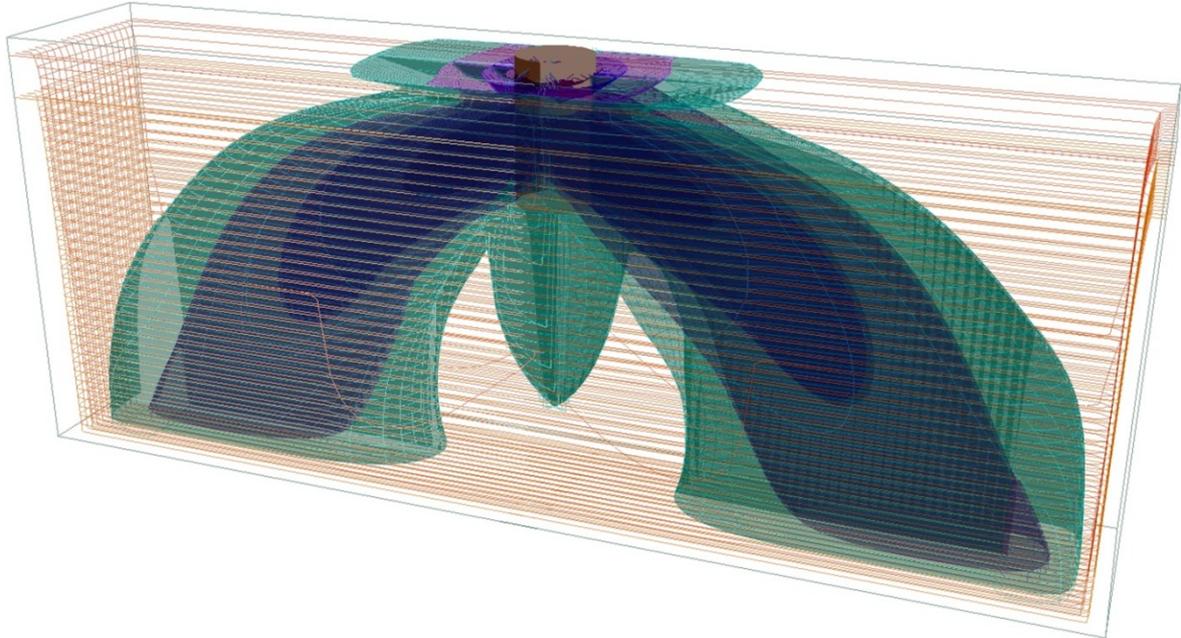
Metal streams direct to mould narrow walls on the level below SEN unloaded openings except narrow walls neighboring fields. Short enclosed vortexes form near SEN body and promote solidification rate decrease in wide walls local zones. After some times that vortexes intensity and temperature decrease and solidification rate in that local zones increase and solidified shell thickness along mould perimeter become level. Metal motion become laminar and short enclosed vortexes remain in mould corners only.

Solid and liquid phases behavior in the case of band feeding without oscillation superposition you can see on the fig 2. The band thickness increased artificially for better visual clearness (here and after).

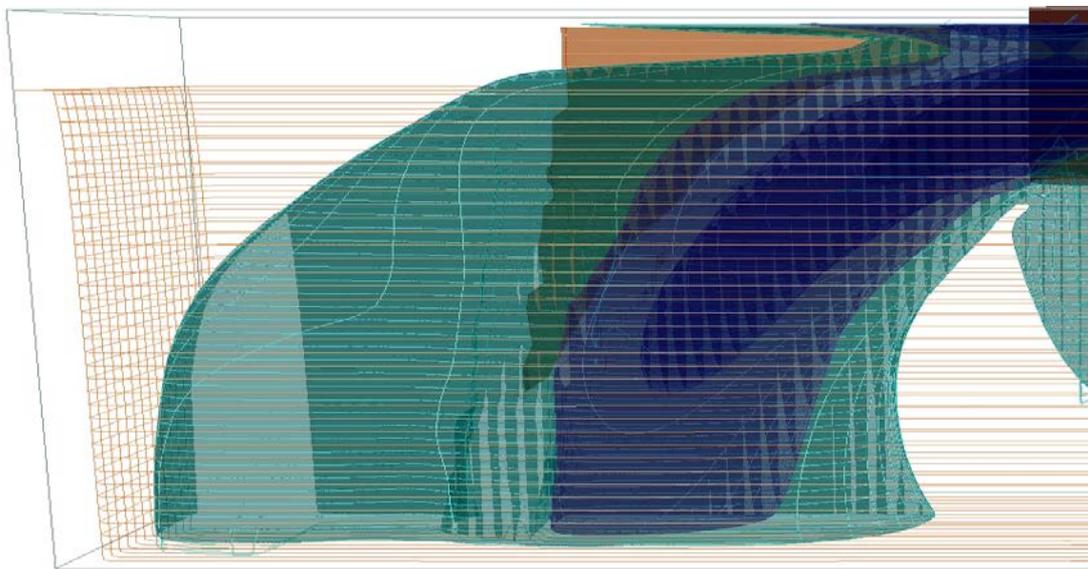
Liquid metal stream divide in two symmetric parts with vortexes between band and SEN similar previous case. High stream speeds and temperatures lead band near axis fields submelting with phase borders creation. Basic chemical composition solid shell on the band surfaces from steel meniscus deep down created due to band material cooling effect. The shell thickness increase from meniscus up to 0.3m depth and after that the band thickness decrease up to 0. Together with this process dual phase not mobile indelible layer of basic metal and inoculators material creates on the band surface The thickness of this layer increase along all mould length by exponential dependence. The band thickness initially increase and after decrease up to 0 in the direction normal to big mould axis. All this phenomena create liquid streams reorganization and change them direction to mould wide walls and more intensive streams influence to solidified layers. The solidified rate in that zones slightly decrease if compare with previous case. The solid shell thickness at the mould exit is high if use special coolers – inoculators.

Visualization of calculated data for band feeding process with oscillation give on fig.3.

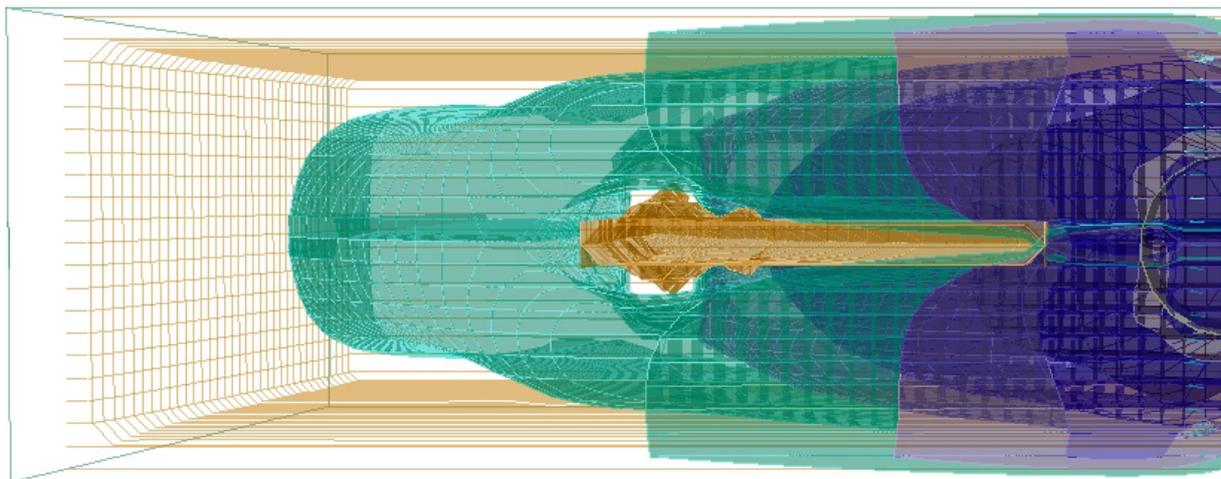
The oscillation superposition to the band change heat and mass transfer in the mould. In particular steel streams arise on the surface steel layers directed to mould narrow sides. In this case cooling rate increase and solidified skin decrease from behind more high heat emission.



*Fig. 1. The hydrodynamic of metal in the mould without band feeding*

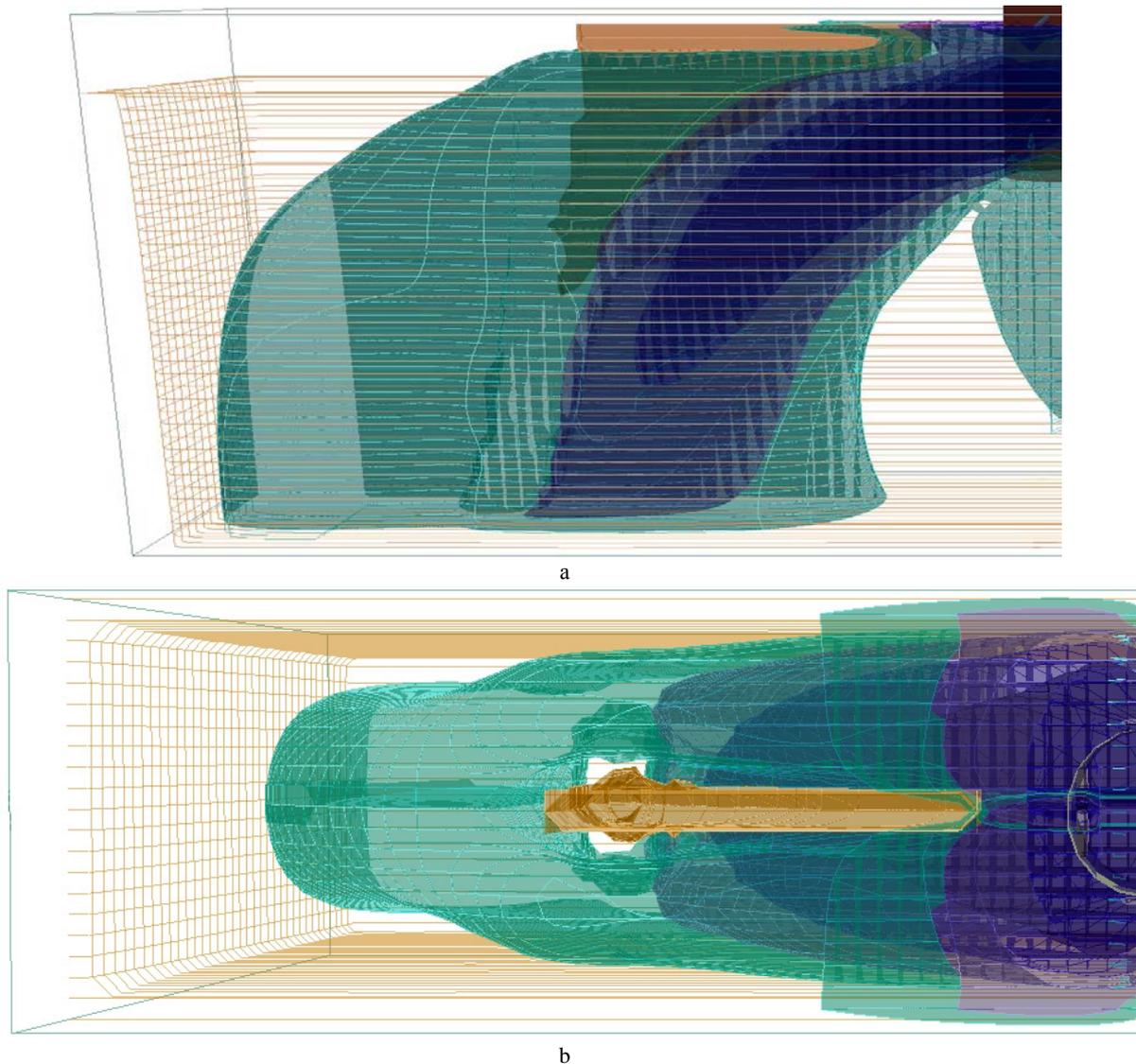


a



b

*Fig. 2. The hydrodynamic of metal and solid phase location in the mould with band feeding and without band oscillation a – frontal view ; b – plan view*



**Fig. 3.** The hydrodynamic of metal and solid phase location in the mould with oscillated band feeding (half of the mould) a – frontal view ; b – plan view

The decreasing of freezing skin thickness on the band surface after heat transfer increasing permit metal hot portion penetrate to the mould narrow sides and stabilize the mould heat conditions. Except that skin growth rate increase and even along perimeter. Feeding band melting rate increase up to 35% at the band oscillation superposition mode.

#### 4. Conclusions

With assistance developed mathematical and numerical models of slab continuous casting was investigated heat and mass transfer processes in to the mould with submerging nozzle equipped inclined unloading openings and with inoculator (band) feeding device with band oscillation. Was defined that band with given thickness and chemical composition and oscillation mode improve liquid pool heat and hydrodynamics conditions with simultaneous thickness skin increasing on the mould exit. The model can use for any slab dimensions and steel grades.

#### 5. Literature

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