UDC 621.746.62:669.189

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QUANTITATIVE RESEARCH OF BAND'S FEEDING IN THE ROUND MOULD

Introduction. Pipe industry is the leading consumer of tube stock. And so, in 2014 the world tube consumption made 165 mln. ton. China manufactures the greatest part of pipes (107 mln.ton in 2014) and has a stable growth trend.

At present hot rolled tubes are mainly produced from continuous casting square, bloom, and round (with diameter from 90mm to 800mm) billets. The investigations conducted in Germany, USA, Japan and CIS reveals that round casting billet use in comparison with continuous casting bloom application in the manufacture of tubes have certain advantages. First, the surface of round billet has better quality than square one (because round billet hasn't longitudinal and corner cracks). Second, high density of equiaxed structure in the axial zone of round billets provides the reduction of micro defects quantity. Third, the surface layer of round continuous casting ingot is more ductile and less exposed to ferrostatic pressure and internal strains if compare with rectangular billet.

But in round billet continuous casting, particularly at radial steel continuous casting plant, the degree of irregularity of solidifying billet surface layer in casting mold is increased which causes the formation of cross-section out-of-roundness. Except this, the pressing questions often arise on macrostructure quality that influences the life cycle of the internal surface of hot-rolled pipes.

One of the advanced methods of improvement of quality parameters is using different kinds input of inoculators [1-5]. The experience of steel band feeding into continuous casting mold liquid pool deserves special attention [6].

But steel band feeding into continuous casting mold has several specificities. Band parameters and its chemical composition, feeding speed, feeding place, and feeding angle, etc. in many respects predetermine final products quality. This question is very crucial when we use additional materials to the molten pool into the mold, and the only science-band recommendation can guarantee the receiving products with high quality.

Investigation objectives – development of quantitative and numerical models of heat and mass transfer of the band feeding into continuous cast (CC) round mold.

This task can be decided by the methods of physical and quantitative modeling with following check and adaptation in the working environment. All decisions will be exclusive and can be used to specially investigated type of CC and technological parameters. Quantitative modeling is a most flexible method of investigation.

Most interesting studies in this field are in the literature [7, 8]. Oler et al. [7] used professional program packages for hydrodynamics and heat & mass transfer Fluent 5.5/Gambit 1.3 based on the RNG–k–ε turbulence model with the accounting of liquid metal enthalpy changing for thin slabs cast at the radial caster. Model adequacy was checked at the physical model. Two-dimensional models of heat and mass transfer in the CC bloom mold with inert gas input to the metal stream were investigated [8].

The main disadvantage of those research works was an impossibility to study the speed and thermal fields in the mold with band feeding. However, the model of Hress and

Ogurtsov [9] can be checked on the physical model and in the work environments and can predict heat and mass transfer after inoculant feeding into the liquid pool in the mold after model transformation from two dimensional to three dimensional.

This model was used during the studying of heat and mass transfer in the slab continuous casting mold SCCP [10] and approved successfully at practice for continuous casting billets industrial production in China. It was this model taken as a basis of the developed one.

Results of the work. *Investigation method.* The model created on the standard approach basis to multiphase systems [8, 9]. The underlying model assumptions are:

1. Basic metal with specified chemical composition cast to round mold through one submerged entry nozzle (SEN) with the direct-flow outlet.
2. Steel band with different from basic metal chemical composition feeding into the mold straight vertical down, its plane perpendicularly mold diameter and located within a certain distance from SEN.
3. The metal meniscus is quiet, without waves and covered by slag. Therefore, the accounting of free surface dynamics is not required.
4. Heat removal conditions to mold and band depend on the metal streams speeds and describe the border between solid metal and mushy zone.

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:

$$(\vec{v}\,\nabla)\vec{v} = -vp + v\Delta\vec{v} + \vec{q}\,; \qquad (1)$$

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

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

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

The difficulty of boundary conditions representation of pronounced cylindrical system in Cartesian coordinates is a feature of the software implementation of this model. Inappropriate use of cylindrical coordinates is explained by the significant labor costs associated with the need of software methods using to put the flat tape into a cylindrical mold. The possible use of the conformal transformation apparatus is also not an easy decision. Therefore, we abandoned the use of a cylindrical coordinate system in this study.

Concerning the task characteristics, mold geometry was approximated by the orthogonal nonuniform net, and in equations (1)-(3) Cartesian coordinate system was used. In equation (1), Boussinesq approximation on the first stage calculations was used, that contains the lifting force because liquid metal has the different density at different temperatures. Density at kinetic momentum equations is constant. Stationary equations system was solved by assignment method.

Velocity vector can be divided into axis constituents OX, OY, OZ. Normalized pressure for equation (1) was introduced for convenience decision. Q in equation (3) was changed to effective heat capacity C_{ef}, that crystalizes heat release at the time of steel solidification in the temperature range (liquidus T_L – solidus T_S). The additional assumption about metal fluidity absence at the temperature lower than T_L was introduced.

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

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

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

$$v_{\perp}\big|_S = v_S\,, \qquad \vec{n}\cdot\vec{\nabla}_{\|}\,\big|_S = 0\,, \tag{5}$$

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

v_S accept velocity stream finish value at the SEM exit and is equal to 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

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

where

$$C_{ef}(T) = \begin{cases} C_S\,, T < T_S\,; \\ C + \dfrac{L}{T_L - T_S}\,, T_S \le T \le T_L\,. \\ C_L\,, T > T_L \end{cases} \tag{7}$$

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

$$C = (C_L - C_S)\frac{T}{T_L - T_S} + \frac{C_S T_L - C_L T_S}{T_L - T_S}\,. \tag{8}$$

It can be solved with natural variables by the physical factor split method and can be realized 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:

$$\vec{\tilde{v}} = \vec{v} + \Delta\tau\left[-(\vec{v}^{\,n}\cdot\vec{\nabla})\vec{v}^{\,n} + \nu\Delta\vec{v}^{\,n}\right]; \tag{9}$$

$$\tilde{T} = T^n - \Delta\tau\, c\, p_l\vec{\nabla}(T^n\vec{v}^{\,n}); \tag{10}$$

$$\Delta\tilde{p}^{n+1} = \frac{\vec{\nabla}\cdot\vec{\tilde{v}}}{\Delta\tau}; \tag{11}$$

$$\vec{v}^{\,n+1} = \vec{\tilde{v}} - \Delta\tau\vec{\nabla}\Delta\tilde{p}^{n+1}; \tag{12}$$

$$T^{n+1} = T^n + \Delta\tau\vec{\nabla}(\lambda_l\vec{\nabla}\tilde{T}), \tag{13}$$

where n – number of times layer; τ – times pitch; λ_l, p_l – liquid metal thermal conductivity and density accordingly.

Stage 2 was fulfilled only in the liquid phase.

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

The heat exchange on the model symmetry axis was set absent. Heat exchange on the ingot surface was set by means radiative and convection heat exchange. Specified superheat temperature was 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):

$$T_S = T_f + \left(T_i - T_f\right)^{1-\frac{V_c}{l_{cr}}}, \qquad R{=}0{,}95, \tag{14}$$

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

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

The net with variable pitch was used to decrease the calculation time because the bandwidth is low.

Presented model recognized by Delphi 7.0 medium. The band feeding modeling was fulfilled after heat and hydrodynamics conditions stabilized.

The model adequacy was checked by comparing the calculated data with physical modeling results and end–use measurements [11].

Discussion. Heat and mass transfer process on the mould with diameter 300mm (BAOSTEEL plant)1000mm length was investigated. Casting process of steel grade S355 with superheat 20°C at the mould entrance was modeled. The distance from direct-flow SEN diameter 85 mm unloaded openings axis to metal meniscus was 150mm. Casting speed was set to 1 m/min. The ingot surface temperature on the mold exit was 1150°C.

Metal band has chemical composition corresponded to steel grade 45. The band thickness was 1.5 mm and width was 60 mm. The distance from SEN axis to band end face was 85 mm. The inoculator feeding speed was 1.4 m/min for demonstrative calculations. Initial band temperature was equal to 20°C. Heat and mass transfer was investigated when 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 a metal stream of absolute velocities without inoculators input and after isosurfaces correspond here and after to 0.02; 0.04; 0.06; 0.12 m/s velocities can be seen in Fig.1 (3D). It appears that metal stream, flowing out of direct-flow SEN, spread vertically along continuous caster technological axis (Fig.1). The absolute stream velocities near the mold bottom don't exceed the amount by 0.02 m/s.

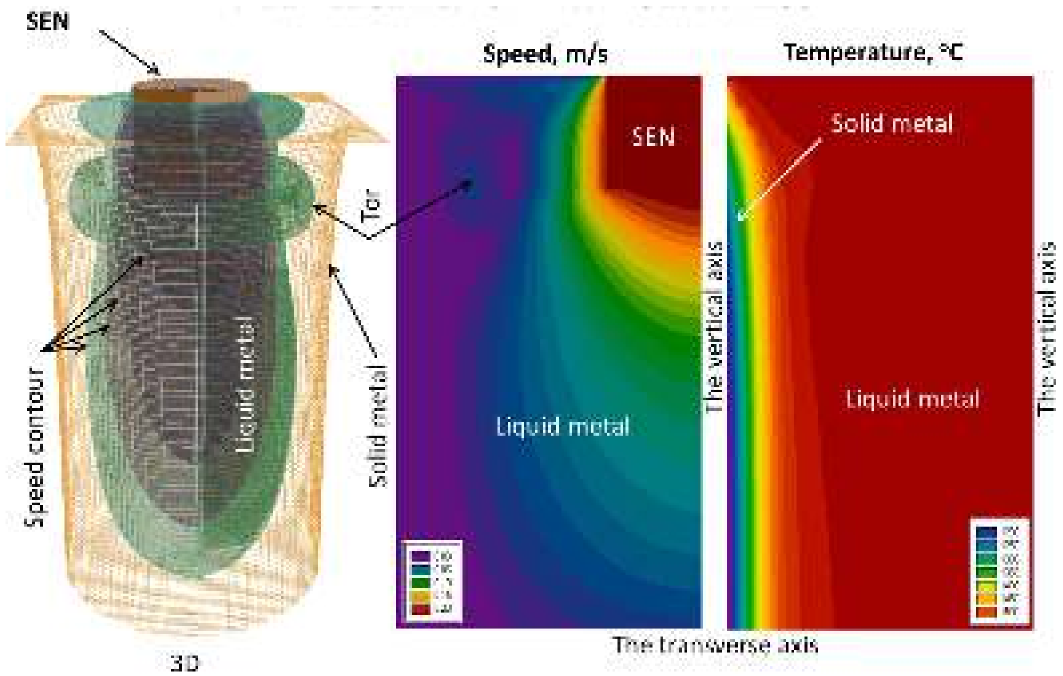

Figure 1 – The hydrodynamicand heat setting of metal in the mould without band feeding

Steady toroid-shape vortex with 150mm height and ≈30-40mm width arise in the upper part of the mold on the depth of ≈50 mm from the metal meniscus and on the distance 80mm from mold axis. In the upper part of the vortex metal stream is directed to the SEN and in the bottom part it is oppositely directed. Hot metal portion inflow to the billet solidifying skin, their passing upward along crystallization front with simultaneous cooling cause the non-uniform distribution of liquid metal layers temperature along vertical billet skin. In particular, isotemperature layers of molten metal near from upper edge of toroid-shape vortex, has the thickness two times more than layers near bottom vortex edge.

In the upper part of the toroid-shape vortex the liquid streams are divided into two differently directed ones. One of them extends along metal meniscus to billet skin and forms a small toroid-shape vortex around billet perimeter near the metal surface. This vortex increases heat exchange intensity between the mother melt and the inner mold surface. After that skin growing speed in this liquid pool part increases and skin thickness around perimeter becomes stable. Another stream with growing velocity caused by catching influence of main stream from SEN is directed along metal meniscus to SEN. Later it sinks along SEN external surface. This stream promotes more intensive heating and melting of bottom layers of slag-forming compound.

On the whole, thermal and hydrodynamic situation becomes stabilized very fast and doesn't cause the non-uniformity of thermal and velocity fields at strict SEN and mold coaxiality.

The band feeding without oscillation changes substantially the hydrodynamic and thermal situation in the cylindrical mold. At the time of band feeding start, as in the previous case, pronounced closed toroid-shape vortex occur with the sizes similar to the last case. However, as the band submerges into the mold pool, the main tor is disintegrated into two parts in the form of a crescent with different intensity. (Fig.2). More intensive streams are located in the mold part free from the band and lower streams - between band and billet skin. The main stream form is also changed because band repels the stream.

Such redistribution of liquid streams hydrodynamics leads to the expected changing of the thermal situation inside the mold. The absence of high intensive liquid metal streams between band and billet skin decreases the non-uniformity of temperature distribution along the vertical billet skin and accelerates solid skin growing velocity and increases the thickness of a frozen metal layer on the band surface of mother melt. Simultaneously, the changing of main stream torch from cylindrical to semi-oval predetermines hot metal layers inflow into mold parts free from the band. Uneven temperatures around the perimeter of round billet appear and increase hot longitudinal surface cracks origin probability. At the same time, the intensification of liquid hydrodynamics between SEN and band slow down liquid metal freezing on the band surface. This effect decreases the molten steel superheat inside the mold.

It was discovered that the band thickness and width changing dynamically depend on liquid streams velocity and temperature and haven't steady type. So, some molten metal freezes from all sides of the band on the upper part of the mold. Later skin growing velocity on the band surface decreases up to zero on the upper level of toroid-shape vortexes because melting temperature on the top part of the mold is high.

The freezing growing velocity drastically increases in toroid-shaped vortexes zone with decreased temperature, and when the band passed it, the growing velocity decreases because the thermic resistance of freezing layer increases and temperature gradient inside freezing layer decreases. This effect is more intensive in zones between band and billet skin where liquid speed is substantially less than it is between band and SEN.

As the band sinks into the liquid pool, its base heats and melts. The band melting mainly prevails from band edges. End band melting, as the depth of submergence into the mold increases, provides freer penetration of high- temperature liquid layers to the billet skin and equalizing the temperature across perimeter. Simultaneously solidification speed increases due to the overheat removing across billet perimeter.

We found that on the referred above parameters of casting process and band feeding, the band depth of submergence to complete melting was near 640mm for casting above parameters. (The depth of melting was showed on the Fig.2 subject to the pouring out effect).

The investigation of the hydrodynamic and thermal situation with other band feeding parameters without elastic oscillation mode shows particular type for every case if the basic law conditions of the process are satisfied.

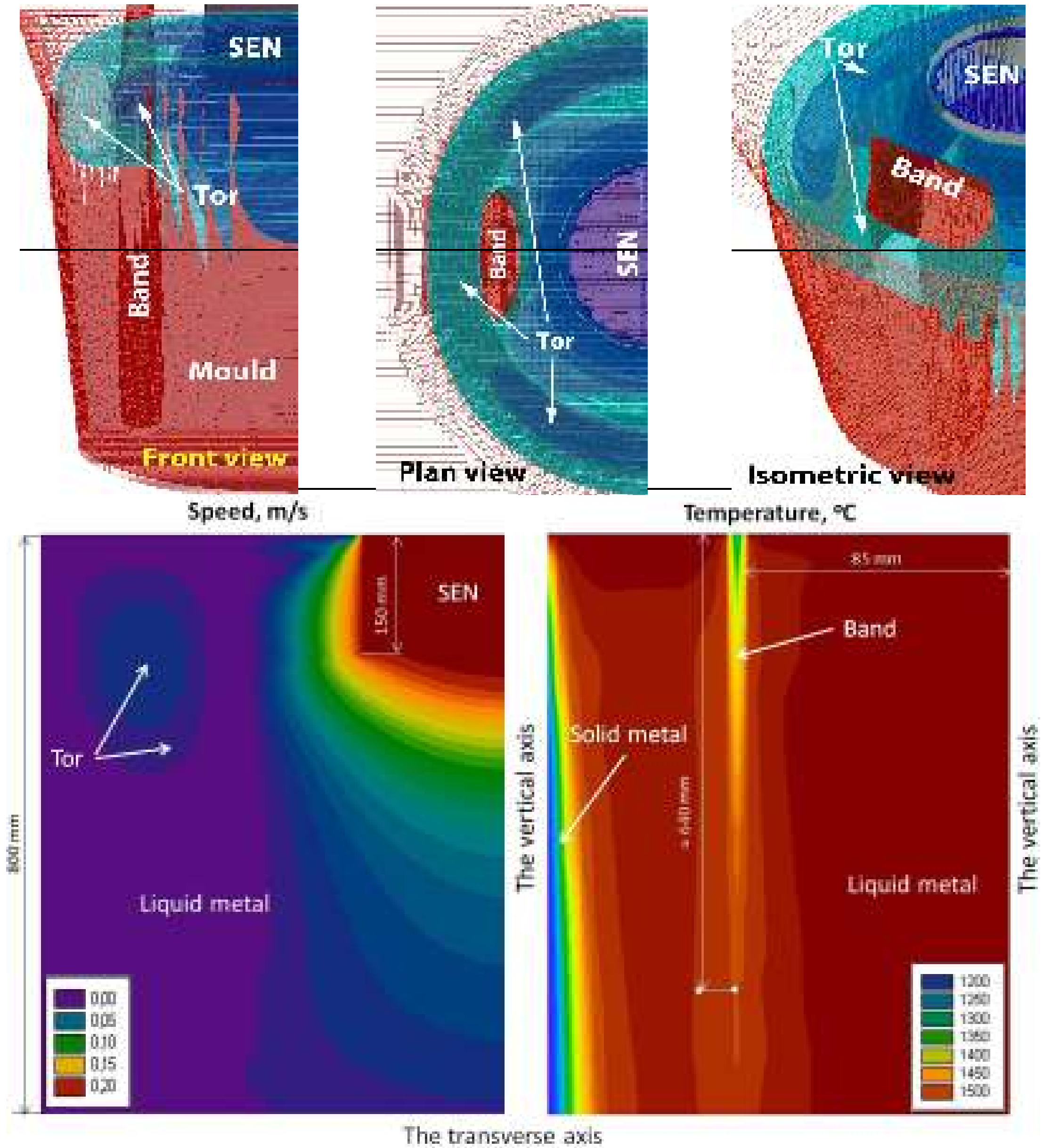

Figure 2 – Temperature and speed fields in the mould with band input

Hydrodynamic and thermal situation in the mold changes still more when using oscillation mode to the band feeding into the mold (Fig.3), but common thermal laws remain for band feeding start and metal liquid behavior.

Metallic band transversal oscillation induced by a special device mounted on the casting flow give rise to the origin of additional hydrodynamic streams. These additional streams influence the thermal situation inside the mold positively. In particular, we detected that hydrodynamic streams intensity around the band increase up to 1.35 times. Accordingly, heat transfer conditions between the band and liquid melt intensify substantially, which causes band melting acceleration and superheat decreasing.

We defined that in contrast to the technology without oscillation mode, in this case melting speed from the ends is substantially less because of crosswise direction of force application of simulated oscillation towards the band surface and corresponding essential increase of speed characteristics of liquid metal streams in these zones. We discovered that cone-and-plate part of melting band with elastic oscillation mode (in other equal conditions) is 10.4 times less compared to the band feeding without oscillation. Therefore, the bottom band end is similar to plane form. Hot liquid streams feeding toroid-shape vortexes between band and billet skin also promote this situation.

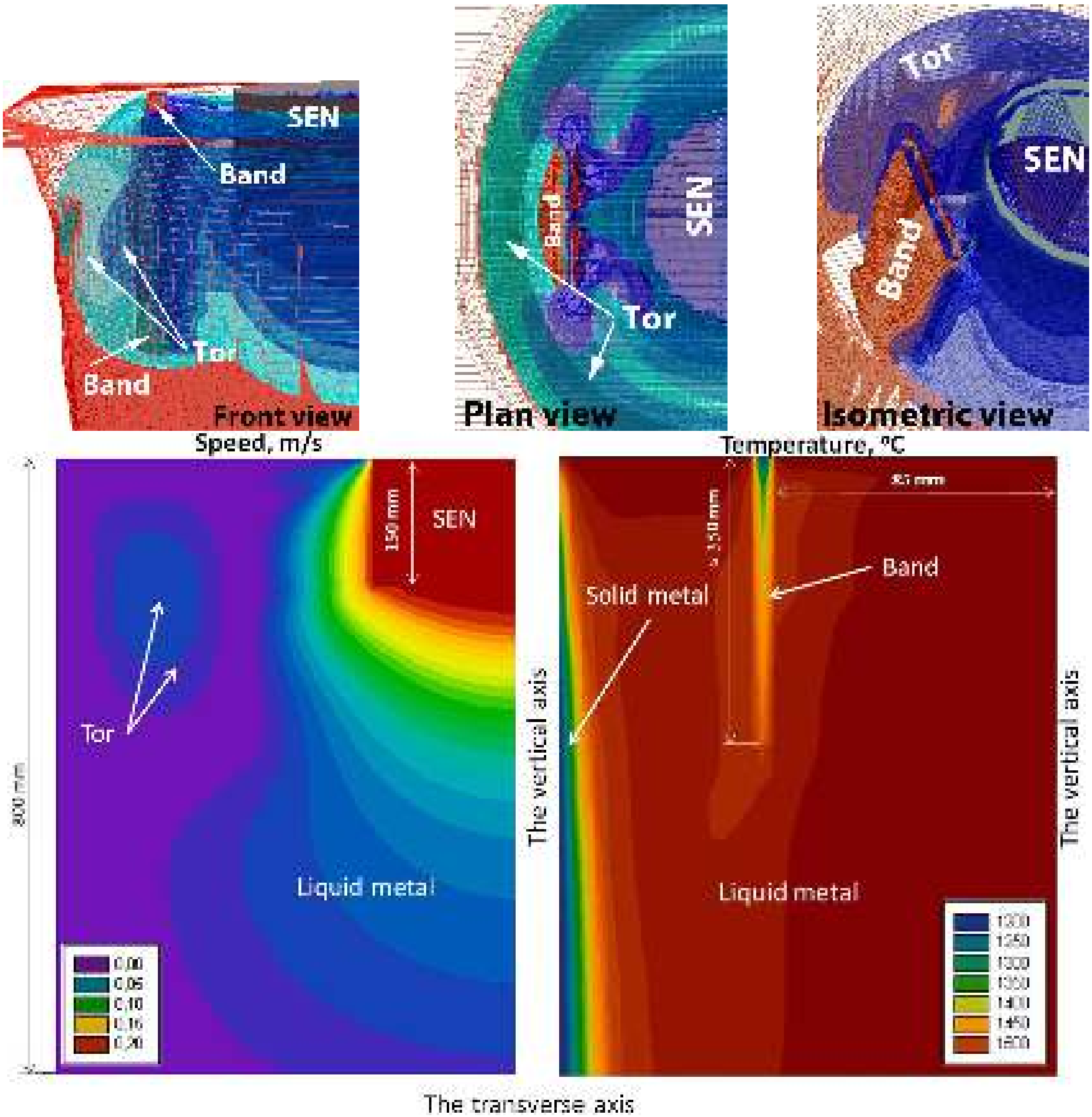

Figure 3 – Temperature and speed fields in the mould with oscillated band input

Critical analysis of other investigated variants of band feeding with oscillation mode into cylindrical molds using exclusive quantity parameters didn't give essential quantity differences for the thermal and hydrodynamic situation.

Conclusions. Developed mathematical and numerical models for heat and mass transfer and the hydrodynamic situation in the cylindrical mold CCM, including inoculator in the form of plain steel band, with composition different from matric melt and with possibility of elastic oscillation mode feeding, allowed us to investigate this process in details and qualitatively. Quantity parameters of investigated processes have an exclusive type and depend on the band geometry, its properties, band feeding velocity and technological parameters of continuous casting.

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Надійшла до редколегії 31.10.2016.

УДК 669.296

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АНАЛІЗ ПРОМИСЛОВИХ МЕТОДІВ ВІДНОВЛЕННЯ СПОЛУК ЦИРКОНІЮ ДО МЕТАЛУ ЯДЕРНОЇ ЧИСТОТИ

Вступ. Чистий цирконій за механічними властивостями легко піддається механічній обробці: прокатці, штамповці тощо. Високими є його корозійна стійкість та температура плавлення, малий перетин захоплення теплових нейтронів – 0,18 барн. Вода, соляна, азотна та розведена сірчана кислоти майже не діють на цирконій, навіть при нагріванні. Але він легко взаємодіє з плавиковою кислотою (HF), царською горілкою та розчиненими лугами. Все це зробило цирконій незамінним матеріалом в промисловості.

Основними галузями споживання металевого цирконію є: атомна енергетика (використовується у якості оболонки паливних елементів і канальних труб у ядерних реакторах), виробництво хіміко-технологічного устаткування та аерокосмічна промисловість, чорна металургія та виробництво різноманітних сплавів.

Атомна енергетика в теперішній час залишається провідною галуззю економіки України. На сьогоднішній день в Україні експлуатуються 4 атомні електростанції загальною встановленою потужністю 13835 МВт (вироблення електроенергії здійснюють 15 енергоблоків). Україна входить у першу десятку країн у світі за загальним виробництвом енергії на АЕС [1].

У промисловості застосовуються різні сплави цирконію. Одні з них, наприклад, сплави на основі міді, магнію та цирконію виробляються, тому що добавлення до них