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Mathematic and Physical Simulation of the Melt Flow at Roll Casting of Steel Bars

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Abstract
The publication deals with a fluid flow in the interroll space of twin-roll plant with a horizontal roll arrangement. In this connection, the new method has been developed and verified by physical simulation of the fluid flow under the mentioned conditions. A mathematical model describing the turbulent fluid flow between two rotating rolls in the test plant of a twin roll caster has been considered and implemented within the medium of Comsol software. The currently popular $k-\varepsilon$ model and the simplified model with an effective viscosity calculated by Prandtl formula have been used as the turbulence models. A good qualitative and quantitative coincidences of these models are observed if 1/4 of the width of the channel at the level of the fluid free surface is assumed as a mixing technique in the Prandtl formula or if the value of the effective viscosity of the studied liquid (water) is set more than 100 times above its molecular viscosity. The comparison has been carried out between the results of the fluid flow numerical calculation and the values of its speed measured at the test plant and are found consistent with the good qualitative and quantitative coincidences. The results of the conducted studies confirm the effectiveness of Comsol software package to be applied for molten metal flow simulation during the roll casting process and this allows reduction in the costs for the experimental research and the design of pilot plants of this type.
Keywords: roll metal casting, physical simulation, computer simulation, turbulence model, velocity field.

1. Introduction. Targeting competitive advantages, the enterprises try to achieve both the high performance of a twin roll caster and the high quality of its metal sheet products. In order to reach this aim it is necessary at the stages of twin roll caster design and manufacture to use the trustworthy mathematical model of hydrodynamic processes to determine the main processing characteristics and parameters of the caster [1, 2]. If we refer to such a model, it allows us to establish main predicted patterns of hydrodynamic processes occurring in the interroll space and hereon to improve the design features of the twin roll casters, including the metal feeding system. The truth of the mathematical model in this case can be confirmed by comparing the calculation results with the results obtained experimentally through the experimental model for the twin roll casters.

Further, we apply the mathematical simulation methods based on tenets of the similarity theory. The assessment criterion concerning the truth of the solutions made is their consistency with the results of physical simulation of the process under consideration.

The problem to be solved with the current research is the development of the mathematical and physical model to study the hydrodynamic processes of the liquid flow, which passes between two rotating rolls at the experimental plant of the twin roll caster, and to compare the results of the computer simulation with those of the experimental studies. We applied the computer simulation conducted by solving simultaneous Navier-Stokes equations with the virtue of the finite-element method, implemented in Comsol program [3] and by using the principal theory factors, stated in works [4–6] along.

2. Experimental Equipment and Mathematical Models.

2.1. Description of the Experimental Twin-Roll Plant.

The physical simulation has been carried out on the laboratory twin-roll plant for casting molten metal vertically feed (refer to Fig. 1 [7]). The parameters of the plant are given in table 1.

Table 1. Experimental Twin-Roll Plant Parameters

Performance specifications	Values
Roll Dimensions (mm) – Outer Diameter – Body Width	 300 200
Roll Material	Steel
Contact Angle between the Liquid and the Roll (degrees)	10, 20, 30, 40
Liquid Pouring Height (mm)	27, 53, 80, 110
Rotation Speed (m/min or m/s)	15.6 (0.26)

The industrial water has been used as a simulative liquid: the physical parameters of the molten metal and the simulative liquid are shown in table 2.

Table 2. Physical Parameters of the Molten Metal and Simulative Liquid

Parameter	Molten metal	Simulative liquid
	Steel	Water
Density (kg/m^3)	7000	1000
Surface Tension (N/m)	1.2	0.2
Dynamic Viscosity (Pa/s)	0.005…0.0085	0.00089
Kinematic Viscosity (m^2/s)	$6.3 \cdot 10^{-7}$	$9.0 \cdot 10^{-7}$

The visualization of the liquid flow has been performed by adding polystyrene balls or tracers with the diameter of 0.8…1.0 mm to the water. The balls have neutral buoyance. The direction and the velocities of the flows were registered by means of a web-camera and a USB interface serves for the record of flow patterns.

The observation area in the interroll space of the model with the transparent case has been determined by an obturating beam of light. The values of the fluid flows were obtained via the calculation of the relation between the measured lengths of tracks on the monitor screen and the exposure time, the scaling ratio was taken into account.

2.2. Mathematical Model of the Hydrodynamic Processes in the Experimental Plant.

For the development of the mathematical model, the following aspects and assumptions were considered:

- The rotating rolls do not deform;
- The melt is a Newtonian viscose incompressible liquid;
- Since that the ratio of the metal bar width to its thickness is big, then the effects occurring at the ends can be ignored; this allows us to assume that this task solution is in a two-dimensional model within the plane of Oxy Oxy cross-sectional view directly in the liquid;
- Due to the symmetry relatively to the central vertical plane of interroll space (or roll gap), 1/2 part of the volume of the liquid is considered;
- The processes are calculated in the steady regime without taking into account of the initial transient behavior, which is minor by duration;
- The thermal processes of liquid heating and cooling are not taken into account; the physical properties of the liquid (its density, its viscosity) are regarded as the ones that do not depend on temperature.

From the comparison carried out with the Reynolds number for the liquid water flow in the channel of the plant under the studies, it follows that

$\mathrm{Re} = \frac{vl}{\nu} = 0.26 \cdot 0.1/10^{-6} = 26 \cdot 10^3$

reaches the values much bigger than the critical one ($\mathrm{Re}_{cr} = \backslash 20 \backslash 00$).

Therefore, the flow of the liquid within the channel of the experimental plant is turbulent. For the calculation of the Reynolds number, we took a distance between the rolls on the free surface of the liquid as the reference length and it equals 0.1 m while the linear speed on the surface of the rolls is assumed as the reference speed (0.26 m/s). The kinematic viscosity of the water applied for the plant is equal to $\nu = \backslash 1 \backslash 0^6 \nu = \backslash 1 \backslash 0^6$ m^2/s.

In order to simulate the turbulent flow of the liquid in the active zone of the plant, we have used $k-\varepsilon$ turbulence model as the principle model. The other simplified way to calculate the turbulent flow can be conducted by setting the turbulent viscosity effective value, which has been constant within the area, and has been calculated by the virtue of Prandtl formula.

Those hydrodynamic turbulent processes, which use $\mathbf{k-\varepsilon}$ $\mathbf{k-\varepsilon}$ turbulence model, can be calculated as based on of the Navier-Stokes equations and the continuity equation [4]:

$$\rho(u\cdot\nabla)u=\nabla\cdot\left[-pI+(\eta+\eta_T)\cdot(\nabla u+(\nabla\cdot u)^T)-\frac{2}{3(\eta+\eta_T)}\cdot(\nabla\cdot u)I-\frac{2}{3}\rho kI\right] \quad ,(1)$$

$$\nabla\cdot(\rho u)=\mathbf{0} \quad ,(2),$$

they are supplemented by two-equation turbulence model [8], consisting of the equation for turbulence kinetic energy of k type:

$$\rho(u\cdot\nabla)k=\nabla\cdot\left[\left(\eta+\frac{\eta_T}{\sigma_k}\right)\nabla k\right]+P_k-\backslash\rho\varepsilon \quad ,(3).$$

and the equation for dissipation rate of the turbulence kinetic energy (ε):

$$\rho(u\cdot\nabla)\varepsilon=\nabla\cdot\left[\left(\eta+\frac{\eta_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+C_{\varepsilon 1}\frac{\varepsilon}{k}P_k-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \quad .(4).$$

After determining the values of k and of ε, the turbulent dynamic viscosity has been defined by the following equation:

$$\eta_T=C_\mu\frac{k^2}{\varepsilon} \quad .(5).$$

In equations (1) and (2): u is the velocity vector of the molten metal; p is pressure; η is a dynamic molecular viscosity; ρ is a density of the liquid melt; I – identity tensor; the component of is a viscous stress tensor (Pa).

In equations (3) and (4), the value of P_k is equal $\eta(\nabla u+(\nabla\cdot u)^T)-\left(2^{\eta}/_{3}\right)(\nabla\cdot u)I$ to as follows:

and presents a turbulence generation rate.

There are indeterminates in equations (3)–(5), they are k which stands for turbulent kinetic $P_1k=\eta_1T$ $[(\nabla u:(\nabla u+(\nabla\cdot u)^{\dagger}T)-2/3(\nabla\cdot u)^{\dagger}2]-2/3\ \rho k\nabla\cdot u$ The conventional model issues are constant [8]: $C_{\varepsilon 1}$ = 1.44; $C_{\varepsilon 2}$ = 1.92; C_μ = 0.09; σ_k = 1.0; σ_ε = 1.3.

The boundary conditions of the hydrodynamic problem are as follows. On the surfaces of the symmetry, we set the condition for it: at the entrance – the speed of the metal outflow from the slot; at the exit – the liquid metal speed under conditions of the consumption equality; at the border with the roll – its rotation speed; on the adjacent edge surface along the bar width – the condition of the solid wall. For the variables of turbulence, we chose the condition of $k=\varepsilon=\mathbf{0}$ on all the boundaries of the calculation area.

The basis of the simplified model of the turbulent liquid flow is the equations of Navier-Stokes system:

$$\rho(u\cdot\nabla)u=\nabla\cdot\left[-pI+\eta_{\text{eff}}(\nabla u+(\nabla\cdot u)^T)-\left(2^{\eta}/_{3}\right)(\nabla\cdot u)I\right] \quad ,(6)$$

$$\nabla\cdot u=\mathbf{0} \quad ,(7),$$

wherein we use the effective value of the turbulent viscosity, calculated by the virtue of Prandtl formula [9, 10] as shown:

$$\eta_{\text{eff}}=\rho\,c\,l^2\left(\partial^u/_{\partial y}\right) \quad .(8),$$

where **cc** – an empirical constant (in some cases its value is assumes as equal to $c=K^2$, with K =0.41 (Karman constant); l – typical scale of turbulence (according to Prandtl is named «the mixing way», and the other name is «hypothesis of turbulent way of mixing»). The coordinate of y in (8) is directed transversely to the direction of the liquid flow.

In order to access viscosity of η_{eff} in (8), we use the following values: $\rho=$ 10^3 kg/m^3, k =0.41^2=0.17, $l=$ 0.1/4 m. That width of the channel, which is at the level of the liquid free surface with the pouring height of 110 mm, has not been neglected and equals 0.1 m. If the derivative value is $\partial^u/_{\partial} l=$ 0.26/0.05=5.2 s^{-1}. then for the efficient viscosity we obtain η_{eff} =1.1 Pa·s.

3. Analysis of the Experiment Outcomes and Computer Calculations.

On the ground of the recorded parameters of tracers movement in the physical model we build vectorial field of velocity (Fig. 2*a*), which shows the formation of two vortex structures in the liquid, attracted by two rolls, that rotate in the opposite directions. The obtained data show that the highest speed of the liquid flow is near the surface of the rolls, which pump the liquid into the roll gap. The reverse flow occurs in that point where the surface liquid flows meet each other. It passes along the central axis of the interroller space and moves with significantly lower speed.

The calculations performed by the turbulent model at the initial data are stated in table 1 and table 2 (the height of the liquid pouring is 110 mm). This corresponds to the conditions of the experiment and has showed a good qualitative coincidence with the experimental observations of the velocity field and the occurring circulation zones (see Fig. 2b).

In Fig. 3, we set the results of the numerical matching of the computation data with the experiment outcomes. Here we show isopleths of the velocity modulus, which are obtained by the computation method on the ground of $k-\varepsilon$ model, described by equations (1)–(5) (the velocity values are shown at ruptures of lines). The points in Fig. 3 are the depictions of the speed values of the tracers (measured at the experimental model with the liquid pouring level as high as 110 mm and the linear speed of the rotating rolls is as fast as 0.26 m/s). As we can see, the results of the numerical calculation and the experimental data are in good agreement with each other.

Utilizing our experience of theoretical calculations, we know that if the calculations for the hydrodynamic processes of the liquid movement are based on $k-\varepsilon$ turbulent model, it involves the heavy spending on the computer time, especially when the solutions of three-dimensional problems. In order to simplify this, we have performed the velocity field calculations by solving equations (6)–(7) with the efficient viscosity value, identified from expression (8) and the constant set in all the calculation area. Further, we carried out comparison of the obtained data with the results of the calculation with the specified $k-\varepsilon$ model for turbulence.

The computer calculations were performed with different values of the efficient dynamic viscosity, namely η_{eff} =0.001 Pa, 0.01 Pa and 0.1 Pa. The results of the numerical simulation in the form of the vector fields and the isopleths of the velocity modulus are shown in Fig. 4.

On the ground of the calculation data matching, we can conclude that in order to obtain a real-life image of a liquid flow in the considered experimental plant, we need to make sure that the efficient viscosity exceeds the molecular viscosity (equal to 10^{-3} Pa·s for water) more than 100 times. We should note that these data are coherent with the value assessment of η_{eff} carried out through formula (8) (η_{eff} = 1.1 Pa·s). More clearly this fact is demonstrated by the virtue of the distribution diagrams of the velocity vertical component for the considered examples, presented in Fig. 5.

Outcomes and Conclusions.

The new method for the liquid in the interroller space of the twin-roll plant with the horizontal arrangement of the rolls has been developed and its physical simulation has been performed. Moreover, for the mentioned issue, the mathematical model has been developed, it describes the turbulent flow of the liquid between the two rotating rolls and it has been implemented in Comsol computer program.

The results of the numerical calculation for the liquid have been compared with the values of velocity measured at the experimental plant. We obtained their good qualitative and numerical coincidence.

With our research, we have shown that for the turbulent flow calculations, one can use a simplified laminar model with the efficient viscosity, calculated by Prandtl formula, in which the value of the efficient viscosity of the simulative liquid of water is set above 100 times more than its molecular viscosity.

The results of the performed researches prove the efficiency of Comsol program package for the molten metal flow simulation in the process of roller casting that allows reducing both expenditures on any experimental studies and those on the development of the pilot plant equipment.

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