EFFECT OF TEMPERATURE CHANGE ON THE STEEL FLOW IN THE FIVE-STRAND ASYMMETRIC TUNDISH USING NUMERICAL MODELLING

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Abstract

Numerical modelling is becoming an essential part of research in the field of steel metallurgy at present. In numerical modelling, the operating equipment is replaced by a mathematical model, which consists of a system of partial differential equations. Numerical modelling is used to display processes and results that cannot be monitored under operating conditions. From numerical modelling we can obtain the results of the flow field, we can monitor the change in temperature and monitor the wear of the refractory lining, etc. This paper deals with numerical modelling of steel flow in the tundish. The tundish is a very important part of continuous casting. It supplies liquid steel during the ladle change and distributes steel between casting strands. The tundishes are made of a welded steel shell and lined with a refractory material. During casting steel, the tundish is the last reactor where it is possible to influence the quality and purity of the cast steel. It is necessary to know the processes in the tundish. This presented paper compares the results obtained by flowing steel in the tundish at non-isothermal conditions. A five-strand asymmetric tundish for bloom casting was used for numerical simulations. The paper also provides an overview of the issues of numerical simulations and their applicability in practice. Fluent software, which is part of the ANSYS package, was used for numerical simulations.

Keywords: Numerical modelling, steel flow, tundish, temperature

1. INTRODUCTION

The tundish is a very important part of continuous casting. It supplies liquid steel and distributes steel between casting strands. The tundishes are made of a welded steel shell and lined with a refractory material. The steel flows into the tundish from the ladle through a ladle shroud made of ceramic material, which ensures the inlet flow conditions and prevents reoxidation of the melt. The surface of the steel melt in the tundish is covered with slag, which prevents reoxidation and heat loss of the melt. Another task of the slag is to ensure the ideal course of chemical reactions and the absorption of non-metallic inclusions from the melt. To control the flow of steel from the tundish, each casting strand is equipped with a stopper rod or a slide valve [1,2].

Optimum steel flow in the tundish is essential for continuous casting equipment. Impact pads, baffles, dams and weirs can be used to optimize the flow. The tundish is the last reactor where we can influence the final quality and purity of the steel. It is necessary to optimize the flow of steel in the tundish. Under operating conditions, monitoring the nature of the flow is very difficult. Numerical and physical modeling methods are used to monitor the flow behavior in the tundish. In the numerical model, the prototype is replaced by a mathematical model, which consists of a system of partial differential equations. In the case of physical modeling, the prototype is replaced by a physical model that has the same physical behavior [1,2].

Numerical modelling is suitable for optimizing the steel flow in the tundish. The main advantage of numerical modelling is the possibility of visualizing the steel casting process. In this paper, the behaviour of steel flow with changes in temperature will be assessed by numerical modelling [1,3,4]. The main objective of the present publication is to assess the effect of non-isothermal flow in the tundish.

2. PRINCIPLE OF NUMERICAL MODELLING

Numerical modeling is the process by which a prototype is replaced by a mathematical model. Partial differential equations of a mathematical model can describe, for example, heat transfer, liquid and gas flow or chemical reactions in the model. Processes in a mathematical model are described as a function of time [1,3].

The system of differential equations is solved in the mesh. The equations are solved for each cell of the mesh separately. Depending on the accuracy and fineness of the mesh, the number of equations that are solved in numerical modeling increases [1,3,4].

Fluid flow is an important process for ensuring the course of chemical reactions, removing non-metallic inclusions and homogenizing steel. It is essential to know the types of flows that can occur during steel casting. Flow can be divided into laminar or turbulent. Depending on the time, it can be stationary or non-stationary, where the quantities change in the time [5,6].

The Navier-Stokes equations together with the continuity equation and the so-called turbulence models are used to describe both flows (laminar and turbulent) [5,6,7].

2.1. Methods of numerical modelling

Finite difference method (FDM) - the essence is the conversion of the investigated system into a system of differential equations and subsequent solution within certain limits. The limits are determined by the boundary and initial conditions of the model. Derivatives at node points are replaced by differences [1,3,4,7,8,9].

Finite element method (FEM) - has the greatest importance among numerical methods. The essence lies in the division into the mesh of elements of finite number, which can be unstructured. The solution on each element has the shape of a quadratic polynomial or a linear function. [5-8].

Finite volume method (FVM) - when calculating the finite volume method, the object is first divided into a certain number of non-overlapping finite volumes. The calculation usually takes place at one point, which characterizes the given final volume. The representative point is located in the middle of the final volume. The method does not require too much hardware [1,3,5,6,7].

2.2. Expected effect of non-isothermal flow

During the ladle change, the so-called non-isothermal flow occurs. Steel with a higher temperature than the steel in the tundish enters the tundish and a positive temperature difference is created. The change in temperature will also be reflected in the change in the nature of the flow, which will be a combination of forced convection and natural convection, as a result of which there are differences in melt densities and the resulting buoyancy forces. In this case, natural convection results in the formation of reverse flow [10,11].

Non-isothermal flow pattern persists until the temperature of the mixed existing and newly fed steel stabilizes and the conditions approach an isothermal steady state. Non-isothermal flow contributes to better separation of non-metallic inclusions into the cover slag. The resulting product at times of non-isothermal flow can achieve significantly higher homogeneity and purity [10,11].

3. EXPERIMENTAL CONDITIONS

All simulation preparations and calculations themselves took place in the Ansys Workbench software package, which includes for example the Ansys Fluent software for CFD (Computational Fluid Dynamics) simulation solutions.

3.1. Geometry

The 3D geometry of the five-strand tundish was constructed in the CAD system of the Ansys DesignModeler software. For numerical simulations, only the inner part of the tundish was constructed. The created geometry of the tundish is schematically shown in **Figure 1**.

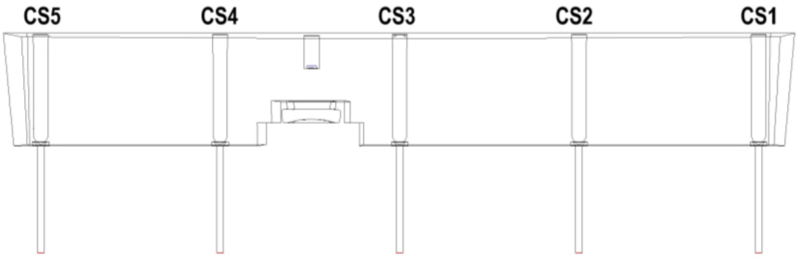


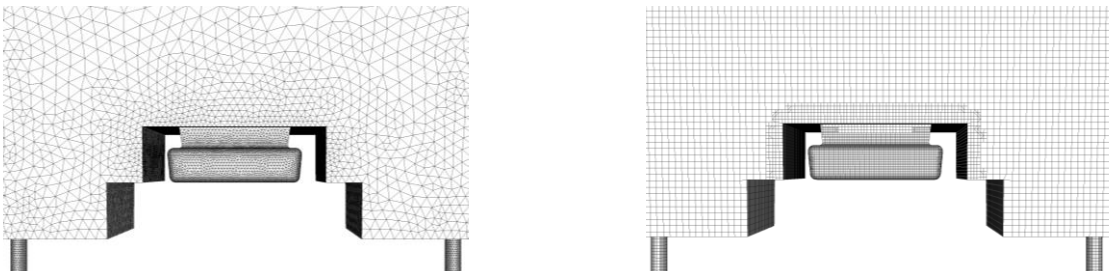
Figure 1 Geometry of the five-strand tundish

3.2. Computing mesh

As part of the preparation of the numerical model for the simulation, two different computing meshes were designed (see **Table 1**). For a computing mesh, it is important to follow the criteria of orthogonal quality and skewness. Orthogonal quality describes the quality of the created computing mesh, so it is necessary to achieve the highest possible value. In the case of the skewness criteria, it is an asymmetry that assesses the degree of cell deformation. In the case of skewness, it is necessary to reach the lowest possible value. Both criteria can take values in the range 0-1, we can also express them in percentages. Of the proposed variants, the mesh variant created using the CutCell method proved to be much better. With a significantly lower number of cells, a higher network quality was achieved and asymmetry was eliminated compared to the original tetrahedral mesh. With a lower number of cells, the calculation was significantly accelerated. Both variants are shown schematically in **Figure 2**.

Table 1 Variants of computing mesh

Computing mesh	Number of nodes	Number of cells	Orthogonal Quality	Skewness
Tetrahedral	248,977	1,331,930	0.7824	0.2162
CutCell	735,713	680,460	0.9827	0.0243



a) b)

Figure 2 Computing meshes: a) Tetrahedral; b) CutCell method

3.3. Model setting

Set boundary conditions for numerical simulations is shown in **Table 2**. The calculations were performed in SW Ansys Fluent and were solved by the finite volume method. Steel with a defined heat flux through the tundish walls and the steel surface was chosen as the material for the calculation. The steady flow for 1753.15 K was first calculated, then the temperature was raised to 1788.15 K and the change in flow was monitored. The material properties of the steel were set depending on the temperature [1].

Table 2 Boundary conditions of model setting [1]

Parameter	Value
Casting speed – velocity inlet ($m \cdot s^{-1}$)	1.04
Casting temperature (K)	1,753.15 / 1,788.15
Gravity ($m \cdot s^{-2}$)	-9.81
Operating pressure (Pa)	101,325
Heat flux of free surface ($W \cdot m^{-2}$)	15,000
Heat flux of tundish walls ($W \cdot m^{-2}$)	2,500

4. RESULTS AND DISCUSSION

The basic result is residence time distribution (RTD) analysis. The residence time determines the time that a certain element of the melt spends in the tundish and is essential for further flow optimization. The result of the RTD analysis is shown in **Figure 3**. In numerical simulations, it was determined using a species model [5,9].

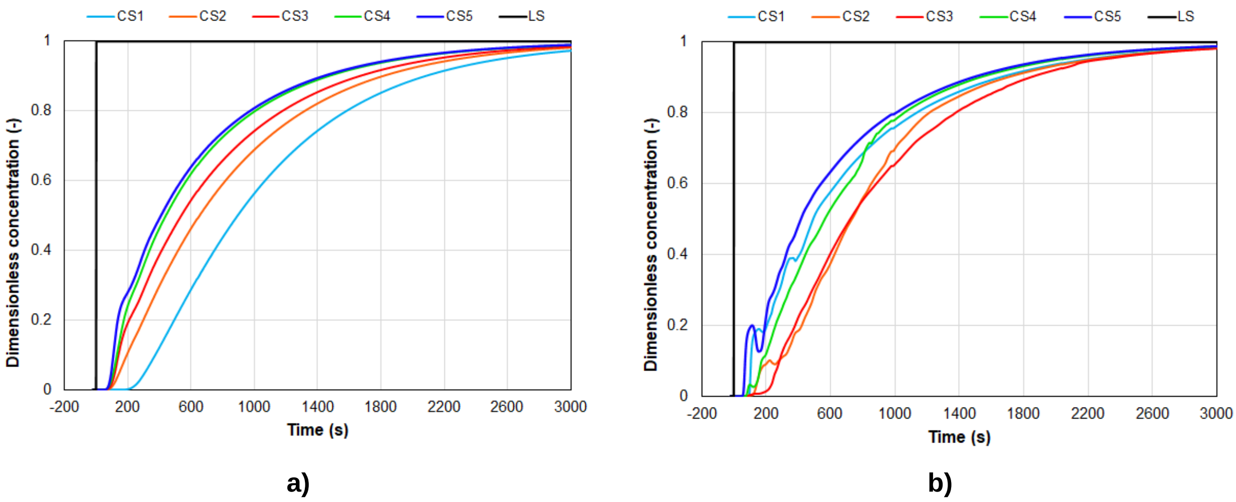


Figure 3 RTD analysis: a) Steady flow; b) Temperature change

A minimum retention time is necessary for flow optimization, which is determined as time until the first response on the strands [9,10].

The minimum retention time is shown in the **Table 3**. For optimization, it is necessary to increase the residence time on all casting strands and at the same time keep the variability low, which is expressed by the coefficient of variation.

The result shows that the residence times at the nearest nozzles (CS3, CS4) to the ladle shroud were increased after the temperature change. At the same time, low variability was obtained after the temperature change. Flow after temperature change achieves better results.

Table 3 Results of residence time distribution

Variant	Minimal residence time - τ_{min}					
	CS1 (s)	**CS2 (s)**	**CS3 (s)**	**CS4 (s)**	**CS5 (s)**	**v (%)**
Steady flow	180	68	58	52	56	66
Temperature change	93	82	68	63	52	22

Figure 4 shows the flow velocity vectors of the tundish in steady flow and 100 seconds after the temperature change. The highest velocity is seen at the entrance to the tundish around the ladle shroud. Around the first casting strand, the flow is significantly slowed down. There are obvious zones in which steel circulates. After the temperature changes, the newly supplied warmer steel flows due to the density mainly at the surface. The stagnant flow zone near the CS1 is gradually removed.

a)

b)

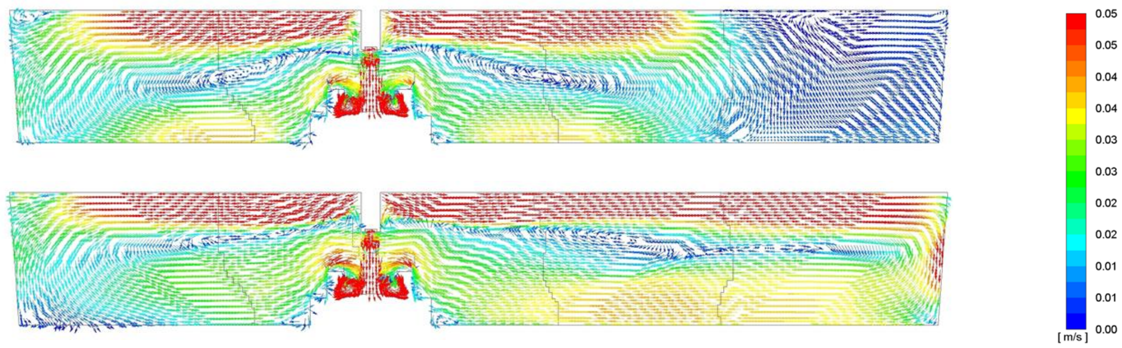


Figure 4 Velocity vectors in the tundish: a) Steady flow; b) Temperature change (100 secs)

From the flow of steel in the tundish, it is also possible to predict places prone to lining wear. A wall shear stress model was used. The model is based on velocity vectors. **Figure 5** shows the results of steady flow and flow 100 seconds after the temperature change. The biggest problems in the steady flow occur between CS4 and CS5 and also between CS2 and CS3. After the temperature change, the problem area is shifted to the side walls of the tundish until it is completely removed.

a)

b)

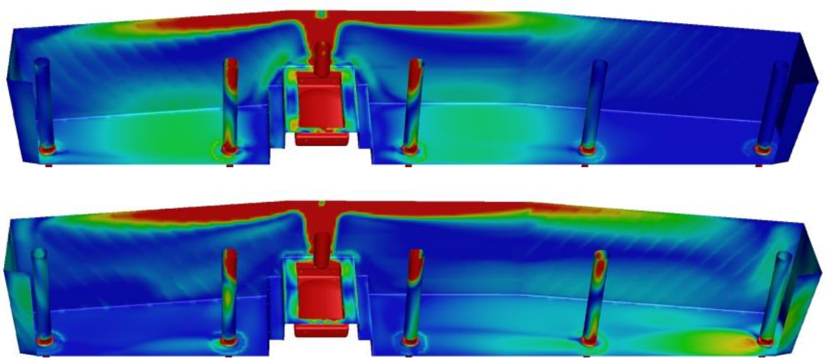


Figure 5 Wall shear stress: **a)** Steady flow; **b)** Temperature change (100 secs)

Another result is the temperature field in the tundish. From the front and side view. **Figure 6** shows the results 100 seconds after the temperature increased from 1753.15 K to 1788.15 K. From the temperature field we see the removal of stagnant flow around CS1. Warmer steel flows near the surface.

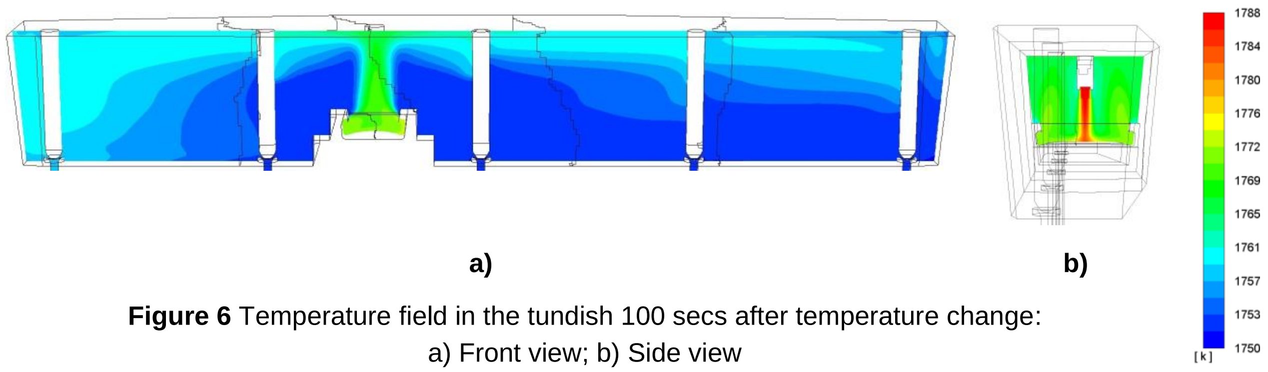


Figure 6 Temperature field in the tundish 100 secs after temperature change:
a) Front view; b) Side view

CONCLUSION

In this paper were compared steady and unsteady flow after temperature change. Temperature change is a process that always accompanies the continuous casting of steel during ladle change. In several cases, the flow was better after the temperature change. Especially when removing stagnant flow. An increase in casting temperature affects the flow and has a positive effect on the wear of the lining. Based on RTD analysis, low flow variability was achieved after temperature change, leading to better product homogeneity.

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REFERENCES

[1] TKADLEČKOVÁ, M., WALEK, J., MICHALEK, K., HUCZALA, T. Numerical Analysis of RTD Curves and Inclusions Removal in a Multi-Strand Asymmetric Tundish with Different Configuration of Impact Pad. *Metals* [online]. 2020, vol. 10, no. 7 [viewed: 2022-04-23]. Avalible from: http://doi.org/10.3390/met10070849.

[2] WALEK, J., MICHALEK, K., TKADLEČKOVÁ, M., SATERNUS, M. Modelling of Technological Parameters of Aluminium Melt Refining in the Ladle by Blowing of Inert Gas through the Rotating Impeller. *Metals* [online]. 2021, vol. 11, no. 2 [viewed: 2022-04-23]. Avalible from: http://doi.org/10.3390/met11020284

[3] SUJATA, D., RAJEEV, K. S., AMITAVA, P. Role of Tundish Argon Diffuser in Steelmaking Tundish to Improve Inclusion Flotation with CFD and Water Modelling Studies. *International Journal of Engineering Research and Technology* [online]. 2015, vol. 4, no. 8, p. 213-218. [viewed: 2022-04-23] Avalible from: http://doi.org/10.17577/IJERTV4IS080223. ISSN 2278-0181.

[4] ZHANG, J., YANG, S., LI, J., TANG, H. JIANG, Z. The Effect of a Dissipative Ladle Shroud on Mixing in Tundish: Mathematical and Experimental Modelling. *High Temperature Materials and Processes* [online]. 2018, vol. 37, no. 1, p. 25-32. [viewed: 2022-04-23] Avalible from: http://doi.org/10.1515/htmp-2016-0093.

[5] HARNSIHACACHA, A., PIYAPANEEKOON, A., KOWITWARANGKUL, P. Physical water model and CFD studies of fluid flow in a single strand tundish. *Materials Today: Proceedings* [online]. 2018, vol. 5, no. 3, p. 9220-9228. [viewed: 2022-04-23]. Avalible from (DOI): <http://doi.org/:10.1016/j.matpr.2017.10.093. ISSN 2214-7853.

[6] ZHENG, S., ZHU, M. Optimization of flow control devices in a ten-strand billet caster tundish. *China Foundry* [online]. 2016, vol. 13, no. 6, p. 414-421. [viewed: 2022-04-23] Avalible from: http://doi.org/10.1007/s41230-016-6082-y. ISSN 1672-6421.

[7] MENTER, F., HÜPPE, A., MATYUSHENKO, A., KOLMOGOROV, D. An Overview of Hybrid RANS–LES Models Developed for Industrial CFD. *Applied sciences* [online]. 2021, vol. 11, no. 6 [viewed: 2022-04-25]. Avalible from http://doi.org/10.3390/app11062459

[8] CWUDZIŃSKI, A. Mathematical simulation and water modelling of liquid steel interaction with an argon bubble curtain in a one-strand continuous casting tundish. *Journal of the Southern African Institute of Mining and Metallurgy* [online]. 2018, vol. 118, no. 5, p. 545-554. [viewed: 2022-04-25] Avalible from: http://doi.org/10.17159/2411-9717/2018/v118n5a11. ISSN 22256253.

[9] BUĽKO, B., PRIESOL, I., DEMETER, P., GAŠPAROVIČ, P., BARICOVÁ, D., HRUBOVČAKOVÁ, M. Geometric Modification of the Tundish Impact Point. *Metals* [online]. 2018, vol. 8, no. 11. [viewed: 2022-04-25]. Avalible from: http://doi.org/10.3390/met8110944. ISSN 2075-4701.

[10] ALIZADEH, M., EDRIS, H., SHAFYEI, A. Fluid Flow and Mixing in Non-Isothermal Water Model of Continuous Casting Tundish. *Journal of iron and steel research, international*. 2008, vol. 15, no. 2, p. 7-13. [viewed: 2022-04-26]. Avalible from: https://doi.org/10.1016/S1006-706X(08)60022-9.

[11] CHATTOPADHYAY, K., ISAC, M., GUTHRIE, R. I. L. Modelling of Non-isothermal Melt Flows in a Four Strand Delta Shaped Billet Caster Tundish Validated by Water Model Experiments. *ISIJ International* [online]. 2012, vol. 52, no. 11, p. 2026-2035. [viewed: 2022-04-26]. Avalible from: http://doi.org/10.2355/isijinternational.52.2026. ISSN 0915-1559.