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A. CWUDZIŃSKI*

NUMERICAL SIMULATION OF BEHAVIOUR A NON-METALLIC INCLUSIONS IN AN ONE-STRAND SLAB TUNDISH WITH STEEL FLOW CONTROLL DEVICES

NUMERYCZNA SYMULACJA ZACHOWANIA SIĘ WTRĄCEŃ NIEMETALICZNYCH W JEDNOWYLEWOWEJ KADZI POŚREDNIEJ WYPOSAŻONEJ W URZĄDZENIA STERUJĄCE PRZEPŁYWEM

An effective refining of liquid steel can be carried out either in a tundish or in the mould of a CSC machine. Being a flow reactor, the tundish performs the function of a link between the steelmaking ladle and the mould. Owing to this fact, the liquid steel resides in the tundish for a specific time, which enables the tundish to be used for refining purposes. For modification of tundish internal working space, two types of flow control device (FCD), namely a ceramic gas-permeable barrier and a subflux turbulence controller (STC), were proposed. For simulation of movement of gas phase and non-metallic inclusions, a discrete phase model was used. The obtained results unambiguously indicate which of the proposed tundish equipment configurations will be more advantageous for intensifying the process of liquid steel refining from NMIs.

Keywords: numerical simulation, tundish, steel flow, flow control devices, non-metallic inclusions

Skuteczną rafinację ciekłego metalu można prowadzić zarówno w kadzi pośredniej jak i w krystalizatorze urządzenia COS. Kadź pośrednia będąc reaktorem przepływowym pełni funkcję łącznika pomiędzy kadzią stalowniczą a krystalizatorem. W związku z tym faktem ciekła stal przebywa w kadzi pośredniej przez określony czas co umożliwia jej zastosowanie do procesów rafinacyjnych. Modernizacja kadzi pośredniej polegała na przebudowie jej wewnętrznej przestrzeni roboczej. W tym celu zaproponowano dwa typy urządzeń sterujących przepływem (USP) tj. ceramiczną przegrodę gazo-przepuszczalną i podstrumieniowy regulator turbulencji (PRT). Do opisu ruchu fazy gazowej i wtrąceń niemetalicznych użyto modelu fazy dyskretnej. Otrzymane wyniki jednoznacznie wskazują, która z proponowanych konfiguracji zabudowy kadzi pośredniej będzie korzystniejsza dla intensyfikacji procesu rafinacji ciekłej stali z WN.

1. Introduction

The manufacture of steel products involves the processes of pig-iron smelting, steel scrap preparation, smelting, ladle treatment, and continuous casting of steel, followed by the plastic working of the steel product. Each of the above stages of the production cycle is a crucial link in the production chain, therefore the techniques and technologies related to the metallurgical processes mentioned above are continuously improved and developed. For some decades, the improvement of processes related to the refining of liquid steel with removal of non-metallic inclusions (NMI) has been the subject of studies conducted by numerous scientific centres around the world. These studies concern, *inter alia*, the refining of liquid steel conducted during the continuous steel casting (CSC) process. An effective refining of liquid steel can be carried out either in a tundish or in the mould of a CSC machine. Being a flow reactor, the tundish performs the function of a link between the steelmaking ladle and the mould. Owing to this fact, the liquid steel resides in the tundish for a specific time, which enables the tundish to be used for refining purposes. For the assessment and prediction of tundish operation, physical and mathematical modelling methods are successfully used. By employing both research methods [1-7], RTD curves can be successfully determined, thus establishing the hydrodynamic conditions prevailing in the facility under examination. In addition, the model medium used in physical tundish models, which is water, lends itself perfectly to the description of the behaviour of the free surface and emulsification of slag drops in the liquid steel [1] and the observation of gas bubble behaviour in the case of using argon curtains in the

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* DEPARTMENT OF METALS EXTRACTION AND RECIRCULATION, FACULTY OF MATERIALS PROCESSING TECHNOLOGY AND APPLIED PHYSICS, CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, 42-200 CZĘSTOCHOWA, 19 ARMII KRAJOWEJ AVE, POLAND

tundish [2]. A milestone in model studies related to the analysis of tundish operation has been the development of numerical methods. Thanks to numerical procedures, it became possible to solve mathematical models enabling the determination of flow fields [5], temperature fields [6], and turbulence kinetic energy and turbulence intensity fields [7], for a medium of the liquid steel type in the newly designed working spaces of tundishes. As a result, some useful information about the behaviour of liquid steel was obtained, and the tundish was started to be perceived as a device possible to be used for liquid steel refining. At the same time, the optimization of numerical models was continued by applying procedures enabling the description of the motion of particles being dispersed in continuous media. The developed models made it possible to track and describe the flow of, e.g., non-metallic inclusions in liquid steel [8-14]. For example, it was proved that the quantity of NMIs removed from the liquid steel depended on the casting speed [9], the non-metallic particle size [10], the type of the flow control device [11], natural convection forces [13], and the set of flow control devices [14]. NMIs behave in liquid steel in two ways: they can either flow out to the slag phase, or settle on the refractory lining of the tundish. The vast majority of applied mathematical models do not allow for the phenomenon of NMI settling on the tundish working lining. Works [8, 12] demonstrate that approx. 14-50% of NMIs may be removed from liquid steel this way.

The NMI behaviour in liquid steel is affected by gas bubbles. The authors of study [9] have demonstrated that the use of argon curtains improves the liquid metal purity by intensifying NMI flotation. It should be remembered, however, that the numerical models for the behaviour of particles dispersed in continuous media are largely only an attempt to approach the description of phenomena occurring in metallurgical processes. Some of the mathematical models employed in the commercial computer programme can generate too optimistic results for refining steel from NMIs [15]. This is also confirmed by the investigation carried out within this work [16]. Work [16] shows results of testing Discrete Phase Model which is used in the Ansys-Fluent program. When comparing results obtained using the above-mentioned mathematical model with the results of tests carried out on a physical model it was observed that, especially for an NMI size of up to 50 μm, the obtained computer simulation results were considerably more advantageous (as indicated by a greater amount of NMIs removed from the liquid steel). Of course, the water-oil-glass balls physical model does not render precisely the identical conditions prevailing during the CSC process in the liquid steel-slag-NMI system, either. Therefore, the Discrete Phase Model was chosen to be used in the present work for the assessment of tundish equipment with flow control devices. The obtained results unambiguously indicate which of the proposed tundish equipment configurations will be more advantageous for intensifying the process of liquid steel refining from NMIs. The present work is a continuation of studies on the optimization of the single-nozzle wedge-type tundish being used in one of steel mills in Poland [17-19].

2. Characterization of test facility

The facility under investigation is a tundish designed for slab casting. The wedge-shaped tundish has a characteristic depression of the bottom in the stopper rod system region (Fig.1). The stopper rod system regulates the velocity of steel flowing from the tundish to the CSC machine mould. To avoid clogging of the submerged entry nozzles (with an inner diameter of 70 mm) mounted underneath the tundish, inert gas argon is fed through the ceramic stopper rod at a flow rate of 0.004 m^3/min. Additionally, the steel stream feeding the tundish is also protected against the adverse influence of the atmosphere by a 70 mm-diameter ceramic ladle shroud. A nominal capacity of tundish is 30 tons. Currently, a 120 mm high dam equipped with two overflow windows is mounted in the tundish. A detailed description of this dam is provided in reference [17].

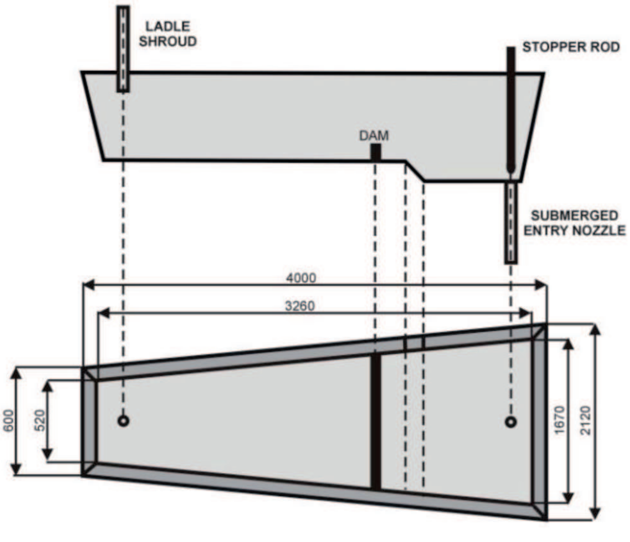

Fig. 1. Tundish with main dimensions

Figure 2 shows the view of proposal modification of tundish internal working space. For this purpose, two types of flow control device (FCD), namely a ceramic gas-permeable barrier and a subflux turbulence controller (STC), were proposed. Three locations of possible installation of gas-permeable barriers were selected, which was the area immediately behind the STC, at a distance of 1210 mm from the bottom tundish edge, and the location of the previously installed dam in the currently used tundish. It was assumed that argon would flow through the gas-permeable barrier at the following flow rates: 0.01, 0.02 and 0.03 m^3/min. The STC installation location is indicated with the broken line in Fig. 2. This location was directly connected with the tundish pouring region, as the STC is a device that is always mounted in the feeding stream axis.

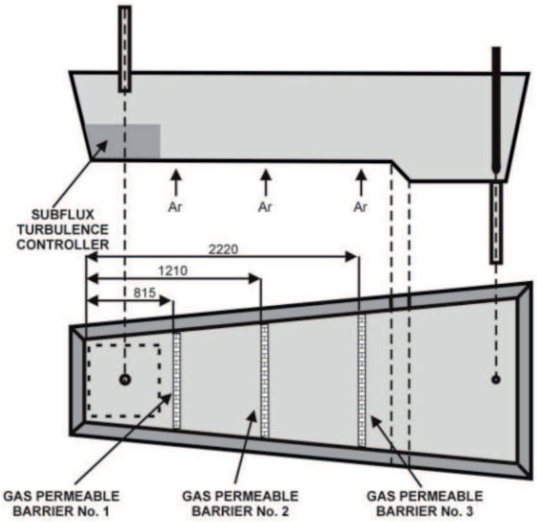

Fig. 2. View of argon injection system for all variants of modification tundish internal space

Figures 3 and 4 show the designed STC, together with the detailed dimensions of the external geometry and the internal space. The internal space of the controller, as shown in Figure 3, has the shape of a truncated cone. The other controller shown in Figure 4, on the other hand, has an internal working space in the form of a truncated pyramid with an inclined plane stimulating the steel flow in the direction of the free surface (slag phase) and the tundish outflow region. The external dimensions of the designed STCs are matched to the dimensions of the tundish working space. Table 1 gives all tundish internal space modification variants considered in the present paper. During the examinations, computer simulations were performed for tundish variants with an STC only and with a selected STC and a gas-permeable barrier, respectively. In subsequent computer simulations, the effect of variation in the position of the gas-permeable barriers and in the flow rate of inert gas introduced to the steel was examined.

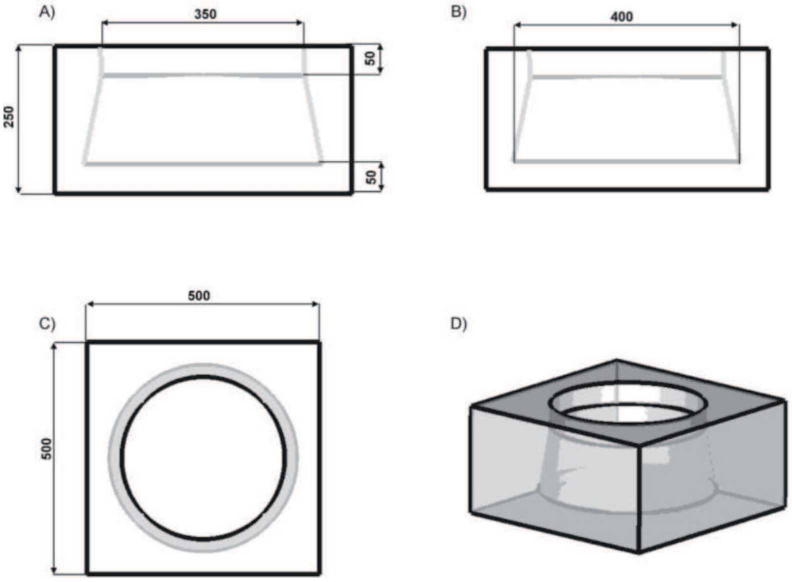

Fig. 3. Subflux turbulence controller no. 1

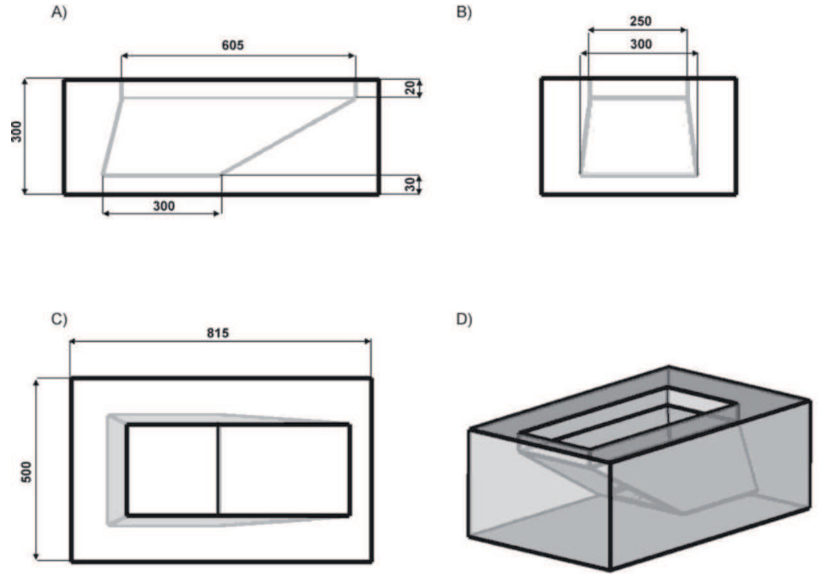

Fig. 4. Subflux turbulence controller no. 2

TABLE 1

Considered variants of tundish modification

Variants of tundish modification	Type of flow control devices			Intensity of gas blowing, Nl/min		
	Dam	Subflux turbulence controller	Gas permeable barrier	10	20	30
1	x	–	–	–	–	–
2	–	No. 1	–	–	–	–
3	–	No. 2	–	–	–	–
4	–	No. 1	No. 1	x	–	–
5	–	No. 1	No. 1	–	x	–
6	–	No. 1	No. 1	–	–	x
7	–	No. 1	No. 2	x	–	–
8	–	No. 1	No. 2	–	x	–
9	–	No. 1	No. 2	–	–	x
10	–	No. 1	No. 3	x	–	–
11	–	No. 1	No. 3	–	x	–
12	–	No. 1	No. 3	–	–	x
13	–	No. 2	No. 1	x	–	–
14	–	No. 2	No. 1	–	x	–
15	–	No. 2	No. 1	–	–	x
16	–	No. 2	No. 2	x	–	–
17	–	No. 2	No. 2	–	x	–
18	–	No. 2	No. 2	–	–	x
19	–	No. 2	No. 3	x	–	–
20	–	No. 2	No. 3	–	x	–
21	-	No. 2	No. 3	–	–	x

3. Numerical modelling

The computer simulations under discussion were carried out for stationary non-isothermal conditions. The mathematical equations of mass conservation, momentum and energy were described in the work [20]. For simulation of movement of gas phase and non-metallic inclusions, a discrete phase model was used. This model is described as follows:

$$\frac{du_{dp}}{dt} = F_D(u_{-}u_{dp}) + \frac{g(\rho_{dp} - \rho_S)}{\rho_{dp}} \tag{1}$$

$$F_D = \frac{18\mu}{\rho_{dp} d_{dp}^2} + \frac{C_D Re}{24} \tag{2}$$

$$Re = \frac{\rho d_{dp} \left| u_{dp} - u \right|}{\mu} \tag{3}$$

$$C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} \tag{4}$$

where: $a_1 \div a_3$ – are constants that apply to smooth spherical particles given by Morsi and Alexander [21],d_{dp} – diameter of discrete particle [m], C_D - drag coefficient, F_D – drag force of bubble [N], u – velocity of the steel flow [m/s], g – gravitational acceleration [m/s], Re – Reynolds number, t – time [s], u_{dp} – velocity of discrete particle (gas bubble or non-metallic inclusions) [m/s], ρ_{dp} – density of discrete particle (gas bubble or non-metallic inclusions) [kg/m^3], ρ_S – density of steel [kg/m^3], μ – viscosity [kg/m·s].

The discrete Phase Model was used in two steps. At first DPM describes behaviour of gas bubble in the liquid steel. After this simulation into gas bubble-liquid steel system author introduce NMI particle. Then DPM model describes behaviour of NMI.

The effects of the chaotic behaviour of bubble and non-metallic inclusions in the volume of steel movement are described by the discrete random walk model (DRW), also called the stochastic model, in which the local components of bubble velocity or non-metallic inclusions is proportional to the local effective energy of turbulence:

$$u'_{dp} = \zeta \sqrt{\frac{2k}{3}} \tag{5}$$

where: u'_{dp} – random velocity fluctuation [m/s], ζ – random number [-], k – kinetic energy of turbulence [m^2/s^2].

For the simulation of NMI behaviour in the tundish working space, the following boundary conditions were adopted:

- On the tundish walls and bottom, and on the STC surfaces – the NMI rebounding condition
- On the tundish outflow, the boundary condition of NMI free outflow together with liquid steel was implemented.
- On the free surface, on the other hand, the NMI absorption condition was applied.

Non-metallic inclusions were introduced to the liquid steel via the pouring gate. The behaviour of NMIs of sizes in the range from 10 to 100 μm with 10 μm size step was simulated, with an NMI group of 5000 particles for each size. Spherical Al_2O_3 NMIs were introduced into liquid steel. The boundary conditions applied are a considerable simplification, because NMIs may equally well be absorbed by the tundish working lining, and the NMI absorption by the slag phase is dependent both on the chemical composition of the refining powder, as well as on the chemical composition of non-metallic inclusions itself. The performed computer simulations concerned CSC sequences, during which 220×1500 mm concast slabs were cast at a casting speed of 0.9 m/min.

4. Computation results

From the computer simulations, a distribution of the quantities of NMIs passing to the slag phase and to the CSC machine mould was obtained. The quantity of NMIs absorbed by the slag phase determines the purity of the metal being cast. Due to the fact that the NMI random walk model applied had a turbulent character, in order to obtain a reliable result, the computer simulations were repeated three times. The obtained values for the quantities of NMIs absorbed by the slag phase were then converted into percentage fractions, according to relationship 6.

$$NMI_{\underset{flux}{tundish}} = \frac{NMI_{\underset{inlet}{tundish}} - NMI_{\underset{outlet}{tundis}}}{NMI_{\underset{inlet}{tundish}}} \cdot 100\% \tag{6}$$

where: $NMI_{tundishflux}$ – quantity of NMIs absorbed by the tundish flux, $NMI_{tundishinlet}$ – quantity of NMIs flowed with liquid steel from ladle into the tundish, $NMI_{tundishoutlet}$ – quantity of NMIs flowed by tundish outlet.

Figure 5 shows results for the potential of liquid steel refining from NMI in the tundish currently in use in one of steel mills in Poland, and in the tundish with subflux turbulence controller. The presented diagram indicates that for the tundish currently used in the steel mill, as much as 75% of NMIs of a size of 10 μm and 90% of NMIs of a size of 100 μm may successfully flow out to the free surface of the liquid steel, before they enter the CSC mould together with the steel. In the case of the tundish with the controller no. 1, a 5-9% drop in NMI flotation capability is observed in particular NMI size groups. Whereas, the controller no. 2 installed in the tundish has definitely intensified the NMI refining process by 6-10% for NMIs of a size of 50 μm.

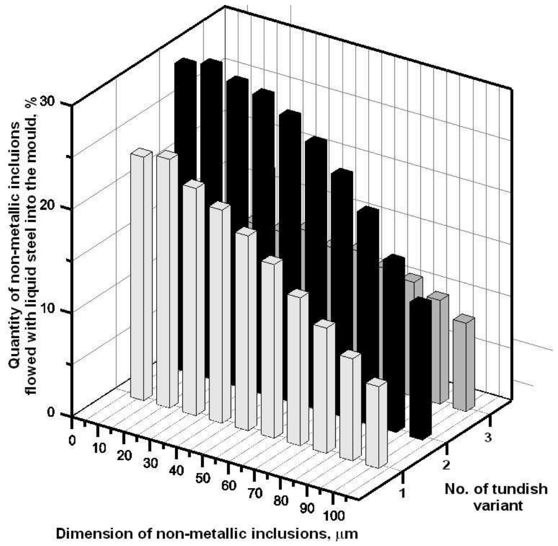

Fig. 5. Fraction of non-metallic inclusions flowed with liquid steel into the mould for variants nos. 1-3 of tundish modification

Figure 6 shows computation results for the tundish equipped with the STC no. 1 and with gas-permeable barriers. It can be seen from the obtained results that the FCD set consisting of the STC no. 1 and the gas-permeable barrier mounted immediately behind the controller has intensified the process of liquid steel refining from NMIs (10-50 μm) by 9-12% compared to the tundish being currently operated in industrial conditions. The obtained NMI refining results for the STC no. 1 and for particular variants including gas-permeable barriers indicate a lesser effect of both the change of barrier mounting location and inert gas flow rate. The difference in the quantity of NMIs absorbed by the slag phase for all computation variants (4-12) for NMI sizes from 10 to 100 μm ranges from 89 to 95%.

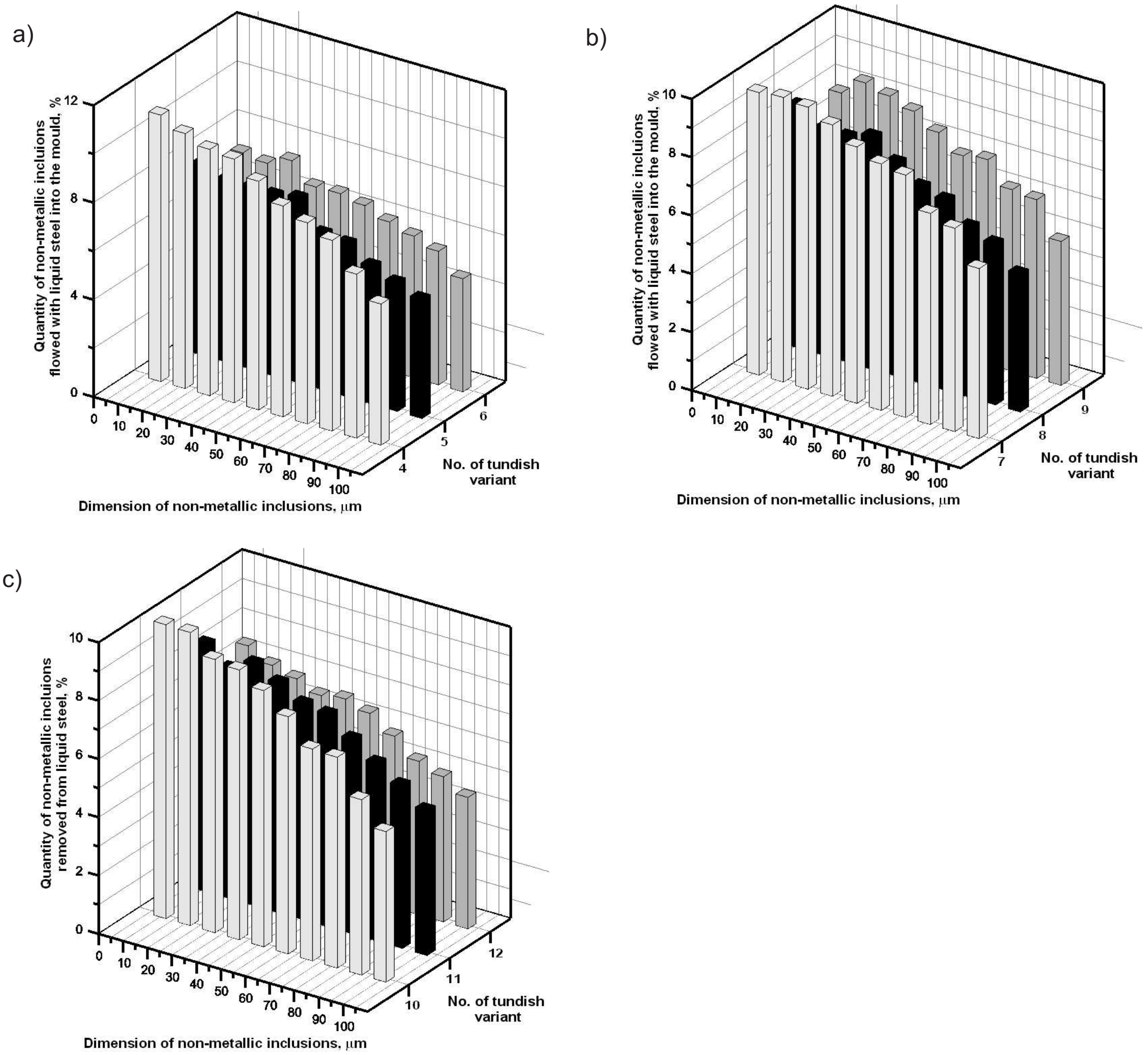

Fig. 6. Fraction of non-metallic inclusions flowed with liquid steel into the mould: a) variants nos. 4-6 of tundish modification, b) variants nos. 7-9 of tundish modification, c) variants nos. 10-12 of tundish modification

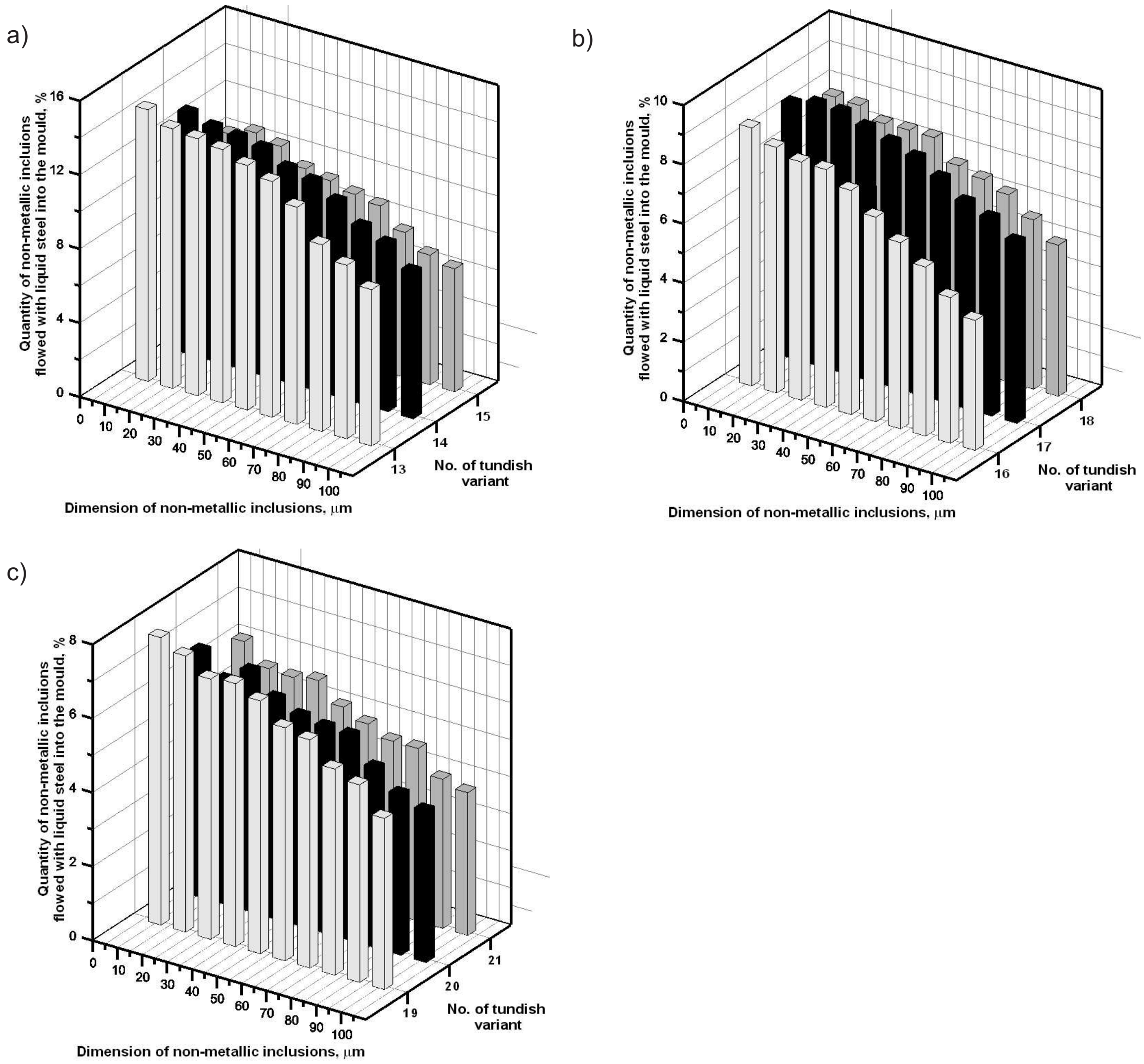

Fig. 7. Fraction of non-metallic inclusions flowed with liquid steel into the mould: a) variants nos. 13-15 of tundish modification, b) variants nos. 16-18 of tundish modification, c) variants nos. 19-21 of tundish modification

Figure 7 represents computation results for the tundish equipped with the STC no. 2 and with gas-permeable barriers. Respective computation variants concern the tundish with STC and gas-permeable barriers mounted in successive locations, and with successive flow rates of argon passing through the membrane. Introducing inert gas argon at a flow rate of 0.01 m^3/min clearly intensifies the process of liquid steel NMI refining by 5-9% for NMI sizes from 10 to 50 μm. For NMIs of a size up to 50 μm, the increase in flow rate up to 0.03 m^3/min additionally intensifies the steel refining process by 4%. A definitely lesser effect of introduced gas and the argon flow rate itself on the intensity of NMI flotation is observed for NMI sizes from 60 to 100 μm. The NMI flotation over the entire range of sizes, i.e. from 10 to 100 μm, is strongly affected by the location of installation of the gas-permeable barrier. Mounting a gas-permeable barrier in the immediate vicinity of the stopper rod system zone intensifies the NMI flotation process by 4-18%. It was also observed that in the FCD set under examination, i.e. the STC no. 2 plus a gas-permeable barrier, starting the inert gas injection through the gas-permeable barrier intensifies the steel refining process only by 5-7% for an NMI size of 100 and 10 μm, compared to the tundish variant with the sole STC.

5. Summary

From the performed computer simulations it has been found that:

- The NMI refining process as conducted in the tundish is influenced by the shape of the internal space of the subflux turbulence controller.
- Forming the STC working space to stimulate the liquid steel flow towards the free surface of the liquid

steel table intensifies the NMI flotation process, especially in the range of sizes from 10 to 50 μm.

- Employing gas-permeable barriers in the tundish favours the liquid steel NMI refining process.
- Increasing the intensity of argon flow from 0.01 m^3/min to 0.03 m^3/min results in a small increase in the quantity of refined NMIs, namely by 2-3%.
- The course of the liquid steel NMI refining process is influenced by the selection of the location of gas-permeable barrier installation.

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