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INFLUENCE OF TURBULENCE MODELS ON STEEL FLOW CHARACTER IN THE TUNDISH

WPŁYW MODELI TURBULENCJI NA CHARAKTER PRZEPŁYWU STALI W KADZI POŚREDNIEJ

The article presents the results of computer simulations of steel flow in the tundish. During numerical simulation six different turbulence model were applied. At work authors tested: k-ε, RNG k-ε, Realizable k-ε, k-ω, RSM and DES turbulence models. To research fragment of tundish with other form of tundish internal space equipment was chosen. Numerical computations were based on the control volumes method, using the computer program Fluent. As a result of computations, fields of steel flow, turbulence intensity, residence time were obtained. For all turbulence models mean residence time, variance of the time of residence and RTD curves (type E and F) were calculated.

W pracy rozważano zastosowanie różnych modeli turbulencji dla symulacji numerycznej procesu odlewania stali w kadzi pośredniej. Wzięto pod uwagę następujące modele turbulencji: "k-ε", "RNG k-ε", "Realizable k-ε", "k-ω", "RSM" i "DES". Dla badań wybrano fragment kadzi pośredniej charakteryzujący się różną konfiguracją wyposażenia. Symulacje numeryczne wykonane w programie Fluent oparto na metodzie objętości kontrolnych. Na podstawie obliczeń numerycznych wyznaczono: pola rozkładu prędkości, turbulencji oraz czasu przebywania stali w kadzi. Obliczono średni czas przebywania stali w kadzi oraz jego wariancję i charakterystyki RTD (typu E i F) według sześciu zastosowanych modeli turbulencji.

1. Introduction

The development of the continuous steel casting process is accompanied by research activities aimed at improving the operation of the tundish. Equipment of considerable sizes is being constructed and manufactured nowadays, with capacities reaching several dozens tons, which are furnished with additional features to improve the hydrodynamic and thermal conditions of operation of a particular facility. The optimisation of tundish operation conditions is only possible in the case of undertaking simulation studies using either physical or mathematical models, because studies on real facilities are too costly. The intensity of steel flow in the tundish depends on the size of the facility and on the cross-section and number of continuous castings being cast. Nevertheless, the motion of steel is some regions of a facility should be classified as flows of considerable turbulence; this is true in particular for the inlet region and the zone adjacent to the discharge nozzles.

It so happens that no single universal turbulence description has been found to date. Hence, results of steel flow modelling are presented in this work, which have been obtained by using different turbulence models that many CFD (Computational Fluid Dynamics) numerical packages are furnished with. The effect of selected models on results of some diagnostic characteristics of the tundish, which are essential for the assessment of their technical and technological quality, has been analysed, including: the residence time, the variance of residence time distribution, and the residence time distribution in the form of RTD curves.

2. Modelling of turbulent motion

For the description of the turbulent motion of incompressible and homogeneous fluid (ρ = const, μ = const), Reynolds equation, know also as the RANS (Reynolds Averaged Navier Stokes) equation, is used, which has the following form:

$$\rho\left(\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_j}\right)=F_i\frac{\partial}{\partial x_j}\left[-p\delta_{ij}+\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_j}\right)-\rho\overline{u_i' u_j'}\right], \quad (1)$$

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where: u, p, ρ, μ and F – velocity, pressure, density, viscosity and force, while the last term of the equation means the Reynolds stress tensor that represents the non-linear actions of the fluctuation components of velocity vectors $u_i^{'}$ and $u_j^{'}$. It introduces new unknown quantities, therefore the system of equations required for solving the fluid motion problem becomes unclosed. Hence, to solve this system of equations, additional equations defining the components of the stress tensor (R_{ij}) should be provided. The problem of closure of the system of equations is the subject of modelling turbulence. Presently, models that make use of so called turbulent or eddy viscosity (μ_T), according to the concept proposed by Boussinesq [1], make up the largest group. Equation 2 expresses the formal contents of Boussinesq's hypothesis:

$$R_{ij} = -\rho\overline{u_i^{'}u_j^{'}} = \mu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_J}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_T\frac{\partial u_i}{\partial x_i}\right)\delta_{ij}, \quad (2)$$

where: k – turbulent kinetic energy, while δ_{ij} is the Kronecker symbol, similarly as in Equation 1.

Because (μ_T) is a function which depends not only on fluid properties many phenomenological models were built. Among them, the following models are distinguished: zero-equation, single-equation, and two-equation models. From among those models, the standard k-ε is most often used for studies of the flow of steel in the tundish. Much more rarely, the two following newer variants of the standard model are used: the RNG k-ε, the Realizable k-ε and the k-ω model based on Wilcox's concept [2]. The turbulence viscosity in these models are calculated from one of the two following expressions:

$$\mu_T = C_\mu \rho \frac{k^2}{\varepsilon} \quad (3)$$

$$\mu_T = \alpha^* \rho \frac{k}{\omega}, \quad (4)$$

where: ε and ω – turbulent energy dissipation rate and specific velocity of turbulent energy dissipation, C_μ – constant (=0,09) or value computed analytically in the RNG k-ε and Realizable k-ε models, α^* – correction factor for low turbulence flows ($\alpha^* \to 1$, when $Re_T \to \infty$).

The quantities k, ε and ω occurring in Formulae 3 and 4 are determined by the solution of the system of two differential equations of transport k-ε and k-ω. Some drawbacks existing in the standard k-ε model have been corrected in the RNG and Realizable k-ε models. The RNG k-ε model has been derived based on the group renormalization theory, which is a complex mathematical procedure that makes the description of the system dependent on the scale of the phenomenon. In the Realizable k-ε model, expression 3 for the calculation of turbulent viscosity has been modified, and hence the C_μ is not a constant value, but a variable dependent on the average values of flow stresses and rotations. Moreover, a newer form of the transport equation for the dissipation of the turbulence energy ε was employed. The k-ω model is a model alternative to the k-ε, RNG k-ε and Realizable k-ε models, which is suitable for flows with a broader range of rotary structures, especially in wall boundary layers.

A detailed description of the above-mentioned models is provided in [3, 4]. All the presented turbulence models have a serious limitation, as they treat turbulence as being isotropic. A departure from the hypothesis of the isotropy of turbulence is made in a model relying on the direct determination of the components of the Reynolds stress tensor (R_{ij}), which is called RSM (Reynolds Stress Model). For this purpose, the solution of 7 additional Reynolds stress transport differential equations is required for 3-D problems [3]. As this model is much more complex compared to the former group of models, it requires greater computational outlays; hence, it not always can be employed in solving large engineering problems. In spite of these increased demands, it was occasionally used, also in steel flow simulation.

Besides the already mentioned models, another turbulence model was used in the author's studies, which is classified into hybrid models and is called DES (Detached Eddy Simulation) [4]. It is a combination of a RANS-type model and a LES (Large Eddy Simulation) model. Large vortex simulation models, LES, consist in splitting the vortex size scales into large scales that are solved using the Navier-Stokes equation, and into fine (sub-grid) scales, for which different phenomenological turbulence models are employed. LES models have the advantage of being able to describe the turbulence process itself in a manner very close to the nature of the phenomenon, as they model fine scales, which reveal the isotropy of the vortex structure, while numerically solving large vortex fields. In the DES model taken for computation, the non-stationary RANS model is used in the wall boundary region, whereas the LES model is employed for the remaining region of flow in the facility under study. When selecting turbulence models, one should be aware of the fact that a more complex model will not always provide better results compared to the simpler model, and that computation results depend also to a large extent on the employed computational algorithms and the density of the grids used. It is certain, however, that by using more complex models the computation time will be increased considerably.

3. Residence time distribution characteristics

The technical and technological quality of a tundish is determined by many factors. The most important of them include the ability to refine steel from NMI (non-metallic inclusions) and the homogenisation of chemical composition of the casting in the transition zone during sequential steel casting. The above-mentioned properties can be evaluated based on the analysis of RTD (Residence Time Distributions) characteristics. The form of the RTD depends on the configuration of tundish internal geometry and on the hydrodynamic conditions prevailing during the flow of steel. Making use of the fact that the mathematical description of turbulent flow in the investigation undertaken was based on many models, it was decided to verify their influence on the view of formation of the steel mixing process, the distribution of the concentration of steel constituents, and the spatial residence time of steel. To this end, the steel casting process was simulated, with a virtual marker in the form of a pulse signal (Dirac function δ) and a unit step (Heaviside) function being fed at the gate, while recording the response signal in the form of the so called E (exit-age distribution function) and F (cumulative distribution function) curves at the outlet. A detailed description of the RTD characteristics for the tundish can be found in work [5]. On the basis of these relationships, two important quantities were obtained, namely the average residence time and the variance of the time of steel residence in the tundish:

$$\bar{t} = \sum_i c_i t_i \Delta t \Big/ \sum_i c_i \Delta t \qquad (5)$$

$$\sigma_t^2 = \sum_i (t_i - \bar{t})^2 c_i \Delta t \Big/ \sum_i c_i \Delta t, \qquad (6)$$

where: c_i and t_i, – denote the marker concentration for respective measurement times, Δt – measurement time interval.

For the determination of the marker concentration in the steel, the solution of the transport equation for the scalar function in the form of the following expression was used:

$$\frac{\partial}{\partial t}(\rho X_i) + \nabla(\rho u X_i) = 0, \qquad (7)$$

where: X_i – marker concentration, as expressed in mass fraction.

4. Numerical simulation conditions

The considerable size of the tundish causes the computer simulation of steel casting to be a long-lasting process, taking several dozens or hundreds hours on good computer hardware; hence, the possibility of using the facility's symmetry conditions or choosing a characteristic fragment of the facility is taken advantage of, if allowable. To verify the effect of different turbulence models, a (1.0m×0.4m×0.25m) cuboid section of the facility was chosen for analysis, which encompassed the steel pouring gate and the neighbourhood of one of the discharge nozzles, and so formed object was named variant A. In variant B, the weir is situated closer to the pouring zone than the dam is, whereas in variant C this situation is the opposite, with the same dimensions of the barriers and distances between them being preserved. It was assumed that the flow rate of steel flowing through the nozzle during casting would amount to 25 kg/s, which corresponds to the average flow rate in industrial facilities. Numerical computations were based on the control volumes method, using the computer program Fluent. For the discretization of the facility examined, a hybrid grid composed of 152300 computational cells was used, which was subjected to localized concentration. The process of adaptive grid concentration at the walls was based on the criterion y^+, because of using the "wall function" for the analytical solution in the wall boundary layer. The controlled value of y^+ was approx. 100. The steel flow computations were conducted under isothermal conditions where properties of liquid steel are:
7010 kg/m^3 i μ= 0,005 Pa·s.

The following boundary conditions were assumed for the facility filled with steel: the velocity of steel at the tundish gate was 3 m/s with the intensity of turbulence equal to 5%; the free steel surface was defined as a flat wall with zero tangential stresses; the remaining walls were assigned the "no slip" condition; while the "outflow" condition was set at the nozzle.

With the aim of acquiring the RTD characteristics, a marker with physicochemical properties identical to those of the liquid steel was taken in the amount of 0.05 kg. To determine the spatial distribution of the time of residence, an expression (in the form of a UDF code) for the source of the transport equation scalar was used. The boundary condition (at the tundish inlet) for so defined scalar is zero. For the discretization of equations being solved, 2nd-order approximation of the *upwind* type was employed; only for the DES model, a procedure of the *bounded central differencing* type was used for the momentum function. The SIMPLEC algorithm was used as the pressure correction method. In non-stationary computations, a 2nd-order procedure of the implicit type was employed for the time.

5. Computation results

A basic characteristic of steel flow in the tundish, which was obtained as a result of numerical simulation, were vector velocity distributions. For the illustration of the steel motion pattern, a distribution of vectors of a uniform size in the plane crossing the tundish in the inlet and nozzle axis is presented. Figures 1a, 1b and 1c show results obtained from computation according to the RSM model, while Figure 1d illustrates results obtained from the Realizable k-ε model. When comparing Figure 1c and Figure 1d, no significant difference in the formation of steel streams in the facility can be noticed. To illustrate the turbulent character of steel flow in the tundish fragment analysed, the intensity of turbulence, Fig. 2, and the value of the turbulent Reynolds number, Fig. 3, were presented, as calculated from the following relationships:

$$I = \frac{(\overline{u_i' u_j})^{1/2}}{u} \tag{8}$$

$$Re_t = \frac{\rho d \sqrt{\frac{1}{2}\overline{u_i' u_j^i}}}{\mu}, \tag{9}$$

where d – denotes the distance of fluid particles from the nearest wall.

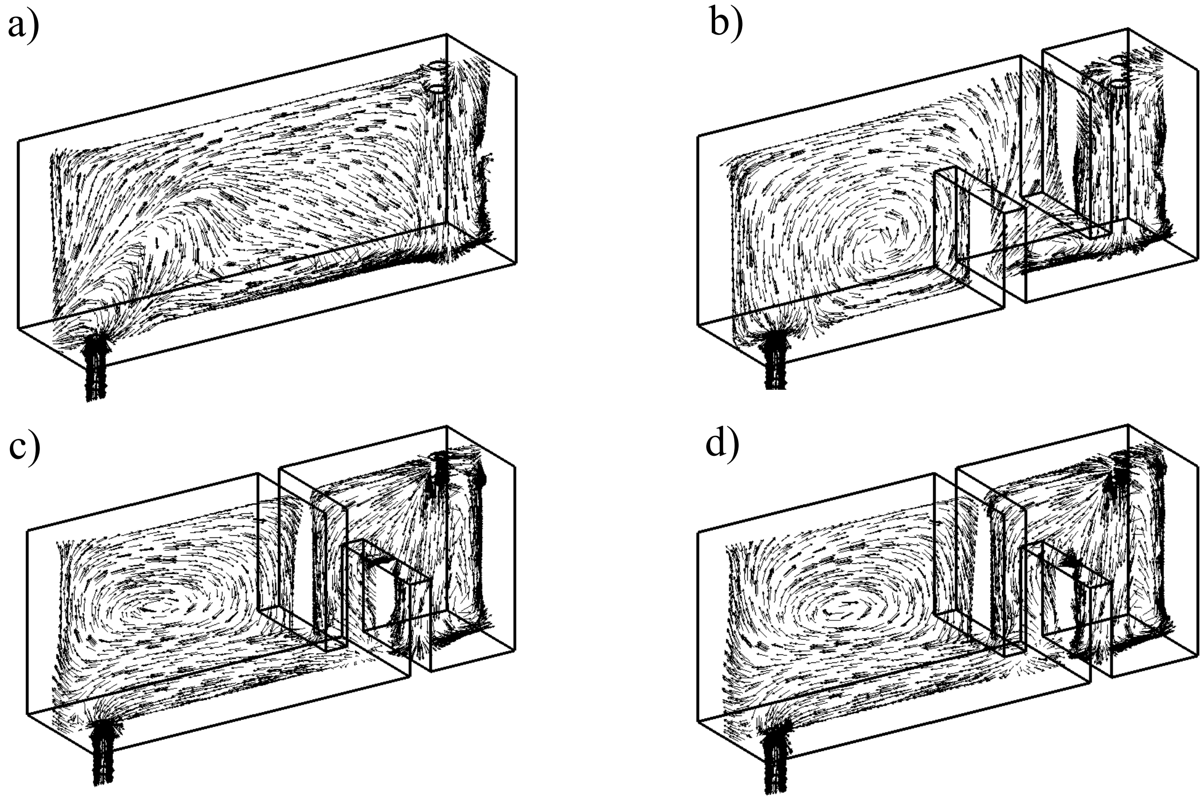

Fig. 1. Steel flow field in the tundish: a) tundish variant A, RSM turbulence model, b) tundish variant B, RSM turbulence model, c) tundish variant C, RSM turbulence model, d) tundish variant C, Realizable k-ε turbulence model

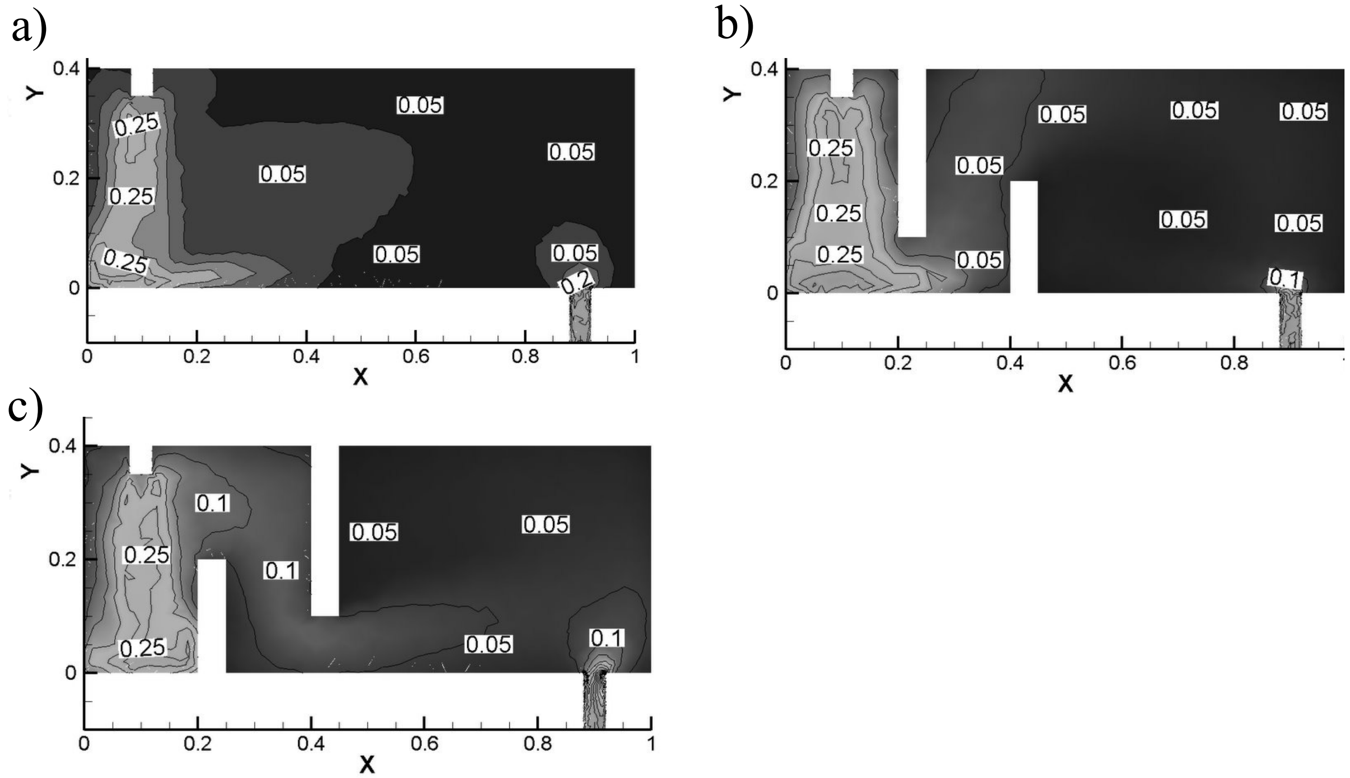

Fig. 2. Turbulence intensity field in the tundish, Realizable k-ε turbulence model : a) tundish variant A, b) tundish variant B, c) tundish variant C

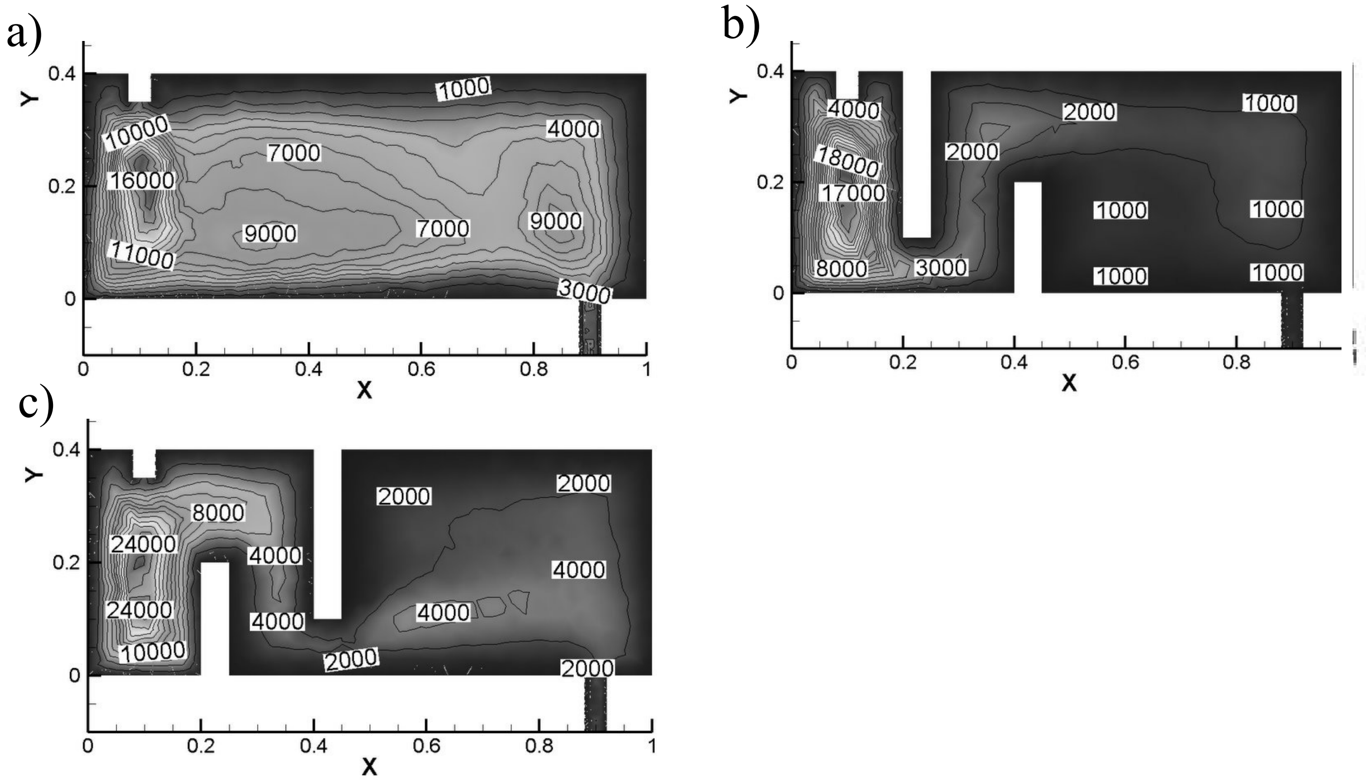

Fig. 3. Reynolds number field in the tundish, RSM turbulence model : a) tundish variant A, b) tundish variant B, c) tundish variant C

Due to the fact that the aim of the study was not to make a detailed analysis of different variants of tundish geometry, but only to assess the effect of the turbulence models on the behaviour of steel in the continuous casting process, hence no complete characteristics in the form of RTD E and F curves are given for particular variants. The obtained RTD characteristics type E, as recorded in the necessary time interval (approx. 150 s), served for the determination of the mean and variance of the distribution of the time of steel residence in the tundish. The numerical values of the computed parameters for three tundish variants, with the application of different turbulence models to the numerical simulation of steel casting, are given in Table 1.

TABLE 1

Results of calculation residence time parameters

Turbulence model	Mean residence time, (t), s	Variance of the time of residence (σ_t^2), s^2	Dimensionless variance of the time of residence(σ^2),-
Tundish variant A			
k-ε	27,9	472	0,61
Realizable k-ε	27,6	486	0,64
RNG k-ε	27,4	550	0,73
k-ω	27,5	648	0,86
RSM	27,3	617	0,83
DES	27,4	466	0,62
Tundish variant B			
k-ε	22,5	286	0,56
Realizable k-ε	22,7	293	0,57
RNG k-ε	25,5	259	0,40
k-ω	24,3	325	0,55
RSM	22,6	282	0,55
DES	26,0	294	0,43
Tundish variant C			
k-ε	21,2	481	1,07
Realizable k-ε	21,8	600	1,26
RNG k-ε	24,6	493	0,82
k-ω	24,5	483	0,80
RSM	21,9	495	1,03
DES	26,0	472	0,70

The dimensionless variance of the time of residence was determined from the formula:

$$\sigma^2 = \frac{\sigma_t^2}{\bar{t}^2}. \tag{10}$$

In Figure 4, the distributions of the time of steel residence in response to pulse marker addition are plotted, as computed for particular turbulence models. For a greater transparency, the diagram was cropped at the point of elapsing 80 seconds of the casting process. At the further stage of the process until the point of 150 seconds, the curves almost coincide and come down asymptotically to the marker concentration value X_i, being close to zero. Figure 4 indicate that the E curves for the k-ω and RSM models have a shape slightly different than that of the remaining curves. They suggest that at the initial stage of steel casting more marker reached the nozzle than in the other cases. Figures 5 and 6 show F type curves recorded during the simulation of steel casting in the tundishes according to tundish variants B and C.

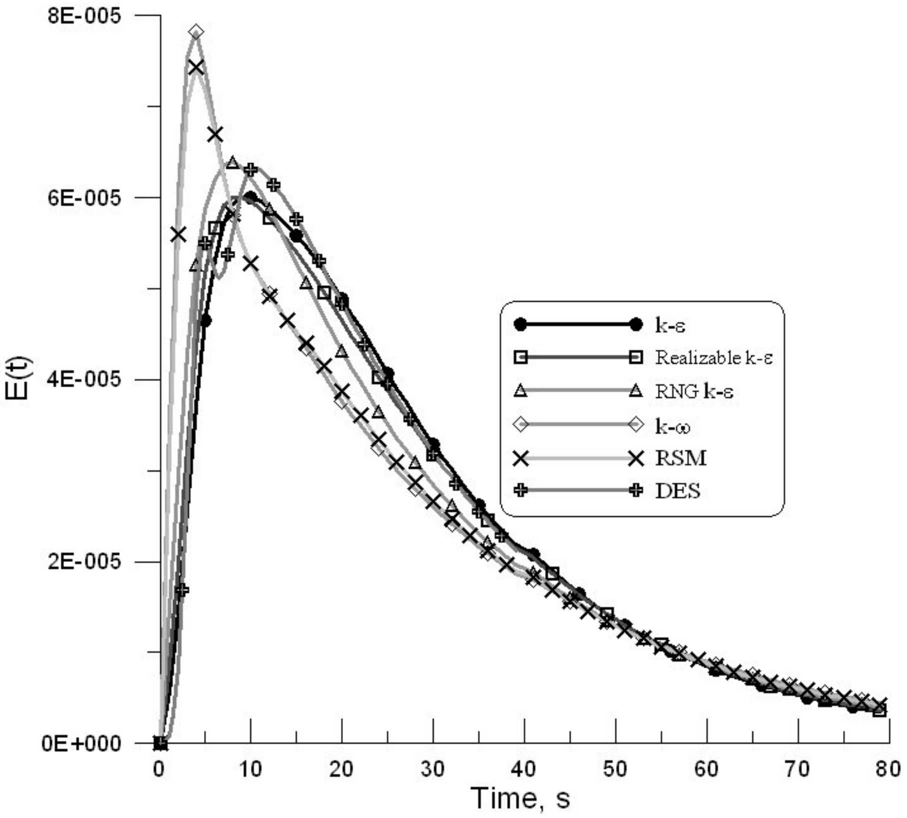

Fig. 4. Residence time distribution curve (E) of steel flow for the tundish (variant A) during continuous casting with application different turbulence models

In Figures 5 and 6, lines are marked, which correspond to the upper (80%) and lower (20%) limits of the chemical composition of the casting being cast, which does not meet the chemical composition standards for steel being cast in a sequence, where change to the steel grade takes place after the next consecutive melt. The quantity of steel that does not fall into the permissible range, as measured with the casting time (s), is represented as the length of the respective interval, Δ_t. The lengths of the time intervals, denoted as δ_t, correspond to the magnitude of the error that can be made when determining the transition zone of a continuous casting, depending on the selected turbulence model. For a greater transparency of the figures, the curves F in Figs. 5 and 6 were cropped at the point of 80 and 100 seconds, respectively; beyond these time limits, the curves lies close to each other and converge asymptotically to the value of F equal to one at the time equal to approx. 200 seconds. It can be seen from the figures that the F curves for the upper limit of the chemical composition specification differ from each other more than for the lower specification limit. The spatial distributions of the residence time and flow direction of steel are shown in a plane passing through the inlet and the nozzle of the facility (Figs. 7-9).

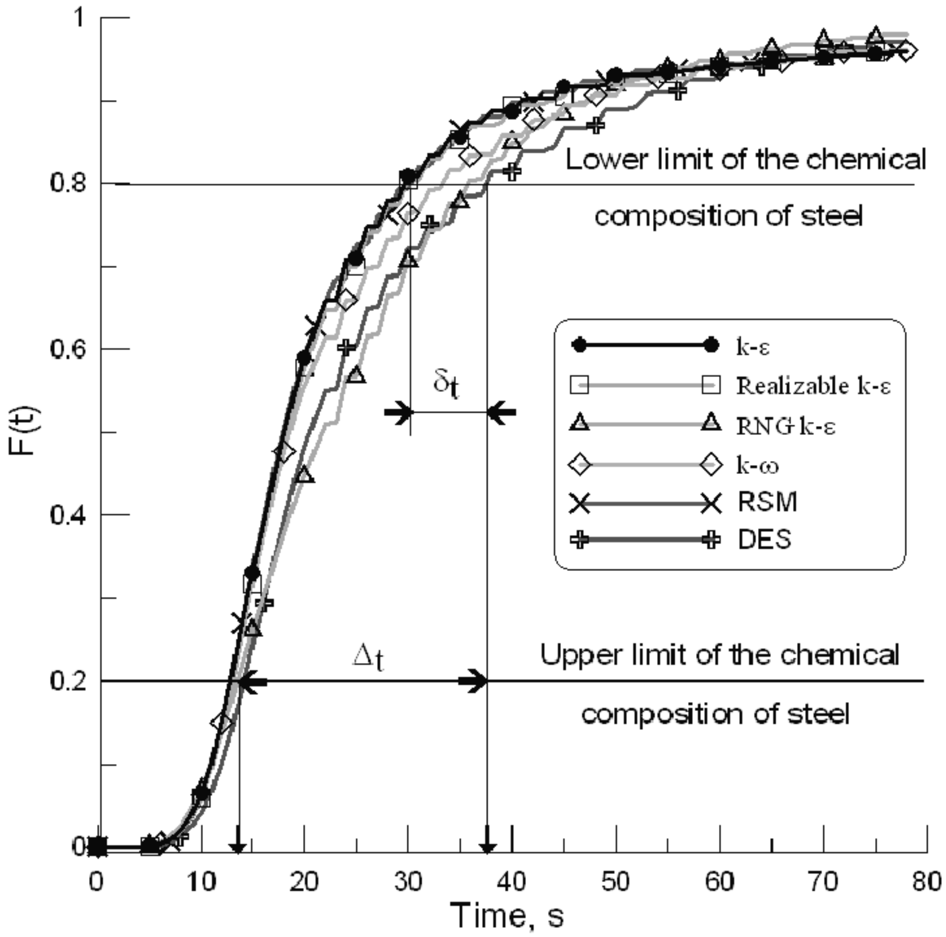

Fig. 5. Residence time distribution curve (F) of steel flow for the tundish (variant B) during continuous casting with application different turbulence models

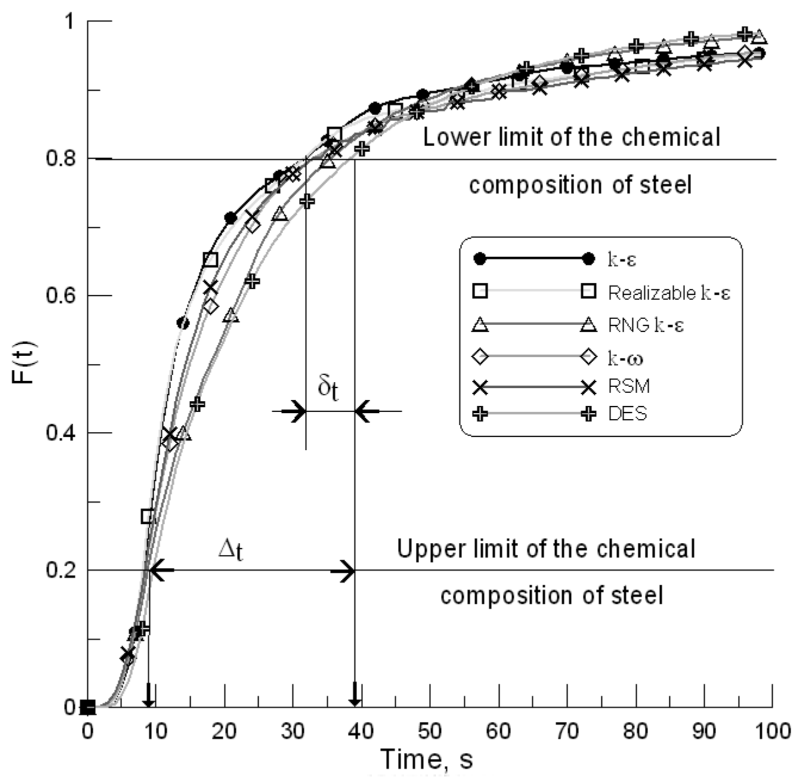

Fig. 6. Residence time distribution curve (F) of steel flow for the tundish (variant C) during continuous casting with application different turbulence models

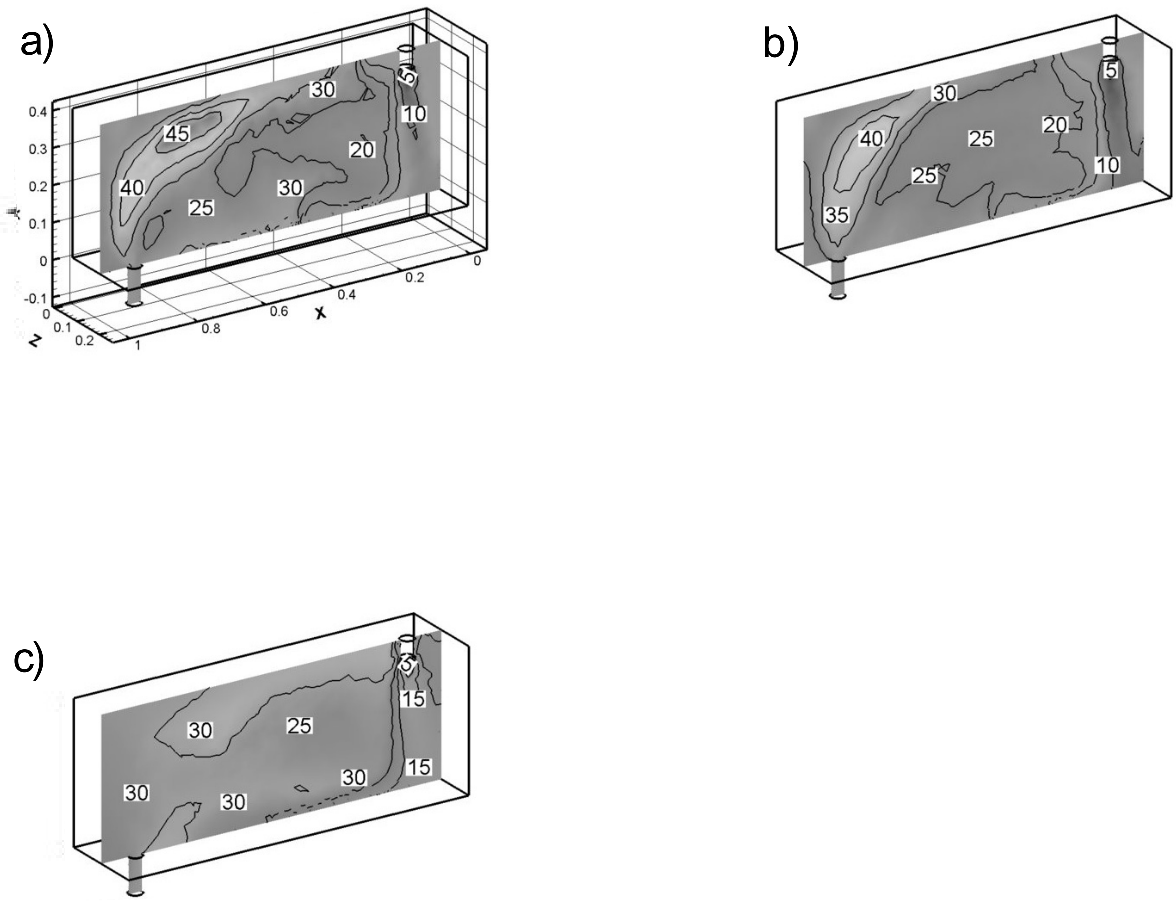

Fig. 7. Residence time (s) field in the tundish variant A: a) k-ε turbulence model, b) Realizable k-ε turbulence model, c) RSM turbulence model

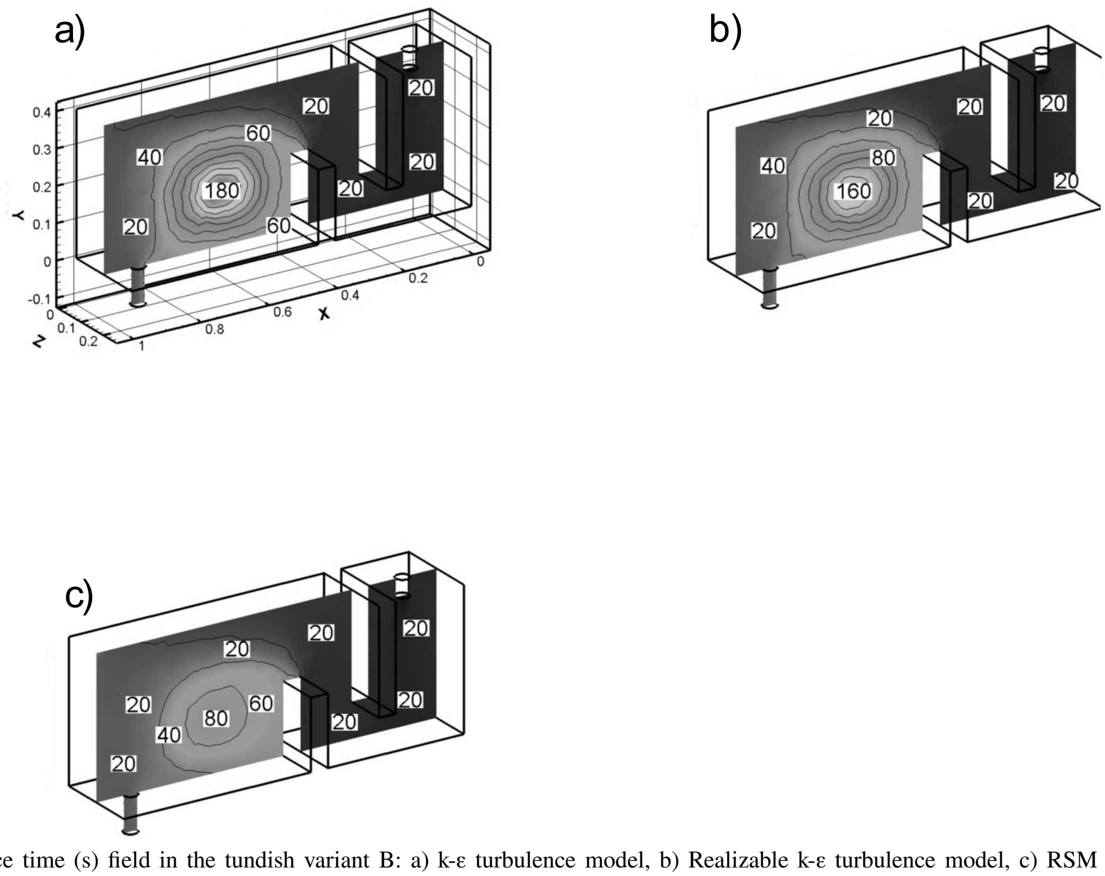

Fig. 8. Residence time (s) field in the tundish variant B: a) k-ε turbulence model, b) Realizable k-ε turbulence model, c) RSM turbulence model

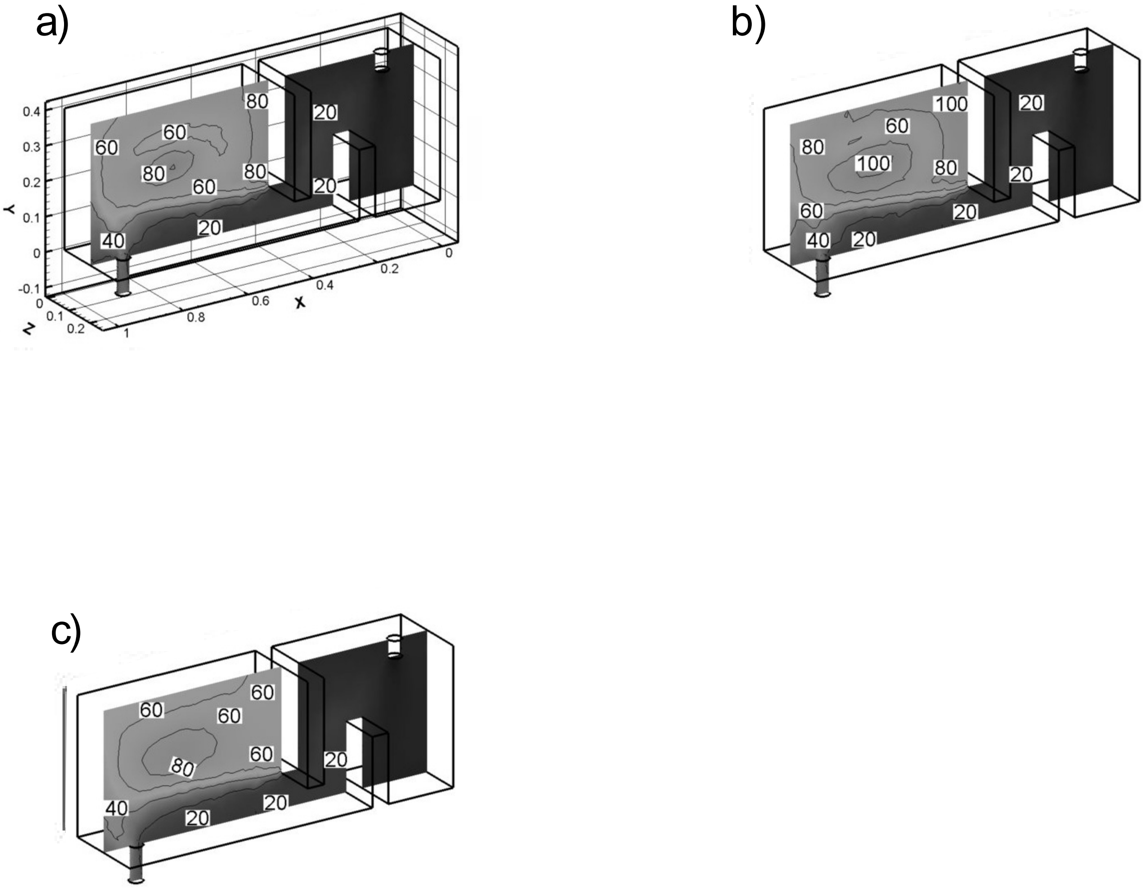

Fig. 9. Residence time (s) field in the tundish variant C: a) k-ε turbulence model, b) Realizable k-ε turbulence model, c) RSM turbulence model

The isolines of the time of steel residence in the tundish represent the situation for three different turbulence models, namely: the k-ε, Realizable k-ε and RSM. It can be noticed from them that the turbulence model type has a perceivable effect on the distribution of the time of residence within the facility.

6. Analysis of results

The k-ε model is the most frequently used description of turbulent incompressible flows at small velocities, thus playing a predominant role in simulations of steel flows in tundishes. There are few studies, where other turbulence models are used for the simulation of steel flow in tundishes, and their results have been verified against the results of studies on water models. Morales *et al* used the k-ε, k-ω and RSM models [6, 7]. By assessing the velocity fields against the results of PIV measurements on a water model they point out that the RSM model is the most appropriate for the description of turbulence. When examining RTD characteristics they noticed that differences existed between the k-ε and RSM models, and the authors took the view that the latter model seemed to be closer to the experimental test results; however, they recommended further studies in this respect [8]. When examining a prototype tundish with a rotational flow it was found that the RNG k-ε model was more appropriate than the k-ε [9]. Schwarze and the co-authors of works [10] and [11] report that they used the RNG k-ε model for the simulation of steel flow in the tundish. The only known case of examining steel flow in the tundish, where the LES turbulence model was used, is work [12]. However, that case differed significantly from all the others, as a strong electromagnetic field was used there for inducing a centrifugal motion in the pouring zone and a more intensive steel circulation.

When observing steel flows in tundishes, one can expect an occurrence of the anisotropy of vortices and recirculation streams, which is also indirectly confirmed by the investigation results quoted. This depends also on the complexity of the facility's geometry. Therefore, it seems justifiable that the present study employed the wide range of models to enable a reliable and comparable assessment of their influence on the RTD characteristics.

With the development of the tundish interior, the steel motion pattern changes, which is clearly indicated by Fig. 1a, 1b and 1c. Placing dams produces a large distinct vortex between the nozzle and the dam wall. From the patterns of the velocity vector fields it is difficult to assess the significance of the effect of the turbulence model on simulation result of steel behaviour in the continuous steel casting process, which is documented by comparison of Figures 1c and 1d. An additional obstacle is the considerable variation of steel velocities – there is a high velocity in the pouring zone and in the tundish nozzles, and a low velocity in the other facility's regions. Hence, the velocity vectors have intentionally not been differentiated, as it would be difficult to illustrate the flow directions within the entire tundish.

The considerable variation of steel velocity is associated with a specific formation of turbulence. The fact that the tundish is a facility with considerably diversified flow turbulence is confirmed by Figures 2 and 3. The intensity of turbulence in the steel pouring zone is 0.25, whereas in the predominant region of the facility it is less than 0.05, regardless the tundish variant. The Reynolds number in the pouring zone, as calculated from Formula 9, reaches the value of 24000, whereas outside this region it is lower. High values of turbulence in the pouring zone indicated that the flow control device such as "turbostop" in the tundish should be used.

When taking a closer look at the simulation results for tundish variant A, as given in Table 1 and represented in Figure 4, it can be seen that the models can be categorized into three groups: the first group including the k-ε, Realizable k-ε and DES models, and the second group with the k-ω and RSM models, and the RNG k-ε model being an intermediate link between the former two groups. This is clearly indicated by the variances and the shapes of the E curves, while the average residence times differ only slightly and, in addition, they do not deviate from the average theoretical residence time. Assuming, as the reference state for steel flow in the tundish, two flow types: plug flow ($\sigma^2 = 0$) and ideal-mixing flow ($\sigma^2 \to \infty$), it can be found that the actual flow in the facility under study has a large prevalence of mixing, irrespective of the adopted turbulence model. The situation of the marker concentration peaks illustrates that the k-ω, RSM models indicate also a lower share of plug flow compared to the other models (Fig.4). Thus, the above results mean that the latter models determine a higher level of steel mixing, and if this is true, it will be of importance to the practical assessment of an industrial facility. By analysing the examination results for tundish variants B and C it can be found that:

- there is a greater variation in the average mixing times compared to variant A;
- the shortest mixing times occur for the k-ε and Realizable k-ε models;
- the longest mixing time is determined for the model DES;
- the applied turbulence model k-ω defines the intermediate mixing time for all the model categories used;
- the dimensionless distribution variations for tundish B are smaller than for tundish A, while for tundish C they are the greatest of all the three variants used.

The latter finding means that tundish variant B is distinguished by the highest share of plug flow, which creates a favourable situation for NMI refining during the flow of steel through the tundish, and reduces the length of the transition zone in sequential casting.

When analysing the shape of the F curves it can be found that there is a noticeable span of dimensionless concentration values, and the limits of the largest span are defined by the curves for the k-ε and DES models, while the RSM model takes on intermediate values; in variant B, however, they are closer to the k-ε model (Fig.5 and 6). Using the magnitudes of the intervals Δ_t and δ_t, the relative error of estimation of the transition zone can also be determined, which results from the type of turbulence model applied; in an extreme case, it is equal to 25%. Additional information about the influence of the turbulence description on the residence time is provided by Figures 7-9. They enable one to get an insight into the facility and to judge what the distribution of residence time isolines is. To characterize the residence time span, diagrams for three characteristic models, namely the k-ε, Realizable k-ε and RSM, have been selected. They show that the pattern of lines for the models k-ε and Realizable k-ε is similar, whereas the isolines for the RSM model have a slightly different character; in particular, they encompass a smaller range of the time of steel residence in the tundish, which indicates greater homogeneity of residence times. Such characteristics are very useful for the practical determination of stagnation regions in a tundish, that is the regions, where the residence time is two times as long as the average residence time.

7. Summary

Because of the lack of a universal model of fluid flow turbulence, in order to describe the flow of steel in a tundish it is necessity to choose one from among many alternative solutions to the problem of Reynolds equation closure. From the application of six different turbulence models it can be found that they have a different effect on the results of basic quantities taken into account in the assessment of the technical and technological efficiency of industrial facilities considered:

1. No significant effect on the determined average time of steel residence in the tundish was noticed for tundish variant A.
2. An influence of the turbulence model on the average residence time can be observed in the tundishes (variants B and C) – the greatest residence time is determined by the DES model.
3. Distinct differences in the residence time distribution occur, as evidenced by the variances determined independently of the investigated tundish variant.
4. The selection of the turbulence model will have a practical effect on the estimation of the transition zone length during sequential steel casting – the maximum estimation error is 25%.
5. The simulation computations have not established which of the models applied is closer to reality.
6. The simulation computations performed according to all of the models (on the three tundish variants used) have confirmed that there is the need for developing the inner geometry of the tundish to improve the hydrodynamic and refining conditions of this type of industrial facilities.

Also, the issue of computational outlays required for solving industrial problems is not without significance for the application of turbulence models, as seen from the practical point of view. From this viewpoint, the DES and RSM models are much less attractive compared to the remaining models, as their computation time is longer by several times.

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