Advanced CFD investigations of electromagnetic stirring of molten steel in continuous caster tundish

ZIELIŃSKA Monika[1,2,a *], YANG Hongliang[3,b], MADEJ Łukasz[2,c] and MALINOWSKI Łukasz[1,d]

[1]Corporate Technology Center CTC, ABB Sp. z o. o., Zeganska 1 st., 04-713 Warsaw, Poland

[2]Department of Applied Computer Science and Modelling, AGH University of Science and Technology, Mickiewicza 30 av., 30-059 Krakow, Poland

[3]ABB AB/Metallurgy, Terminalvagen 24, Bldg 340, Vasteras 72159, Sweden

[a]monika.zielinska@pl.abb.com, [b]hongliang.yang@se.abb.com, [c]lmadej@agh.edu.pl, [d]lukasz.malinowski@pl.abb.com

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Abstract. The continuous casting process is one of the initial operations in the entire metal forming chain used in the metallurgical industry. The phenomena of solidification and unification of properties that occur during slab casting are highly dependent on the steel composition and the purity of the metal. The high cleanliness of steel is the determinant of the good quality of the final products, without internal cracks or inhomogeneities in mechanical, thermal or electrical properties. Therefore, one of the production goals is to avoid the non-metallic inclusions in the molten steel by intensifying their removal processes. One of the most important metallurgy equipment responsible for cleaning the steel is the ladle furnace, where special mixing processes are executed to increase the removal process of unfavourable elements. Another critical piece of equipment is the tundish, located just before the slab casting, which can additionally improve the microstructure final composition and homogeneity. Therefore, the investigations presented in the paper are centred on the development of an advanced Computational Fluid Dynamic (CFD) model of the flow behaviour of the molten steel inside the tundish. The key element of the model is to include the effect of an additional electromagnetic stirring device which can improve the cleanliness and the composition of the steel and hence its final properties. The role of this device is often omitted during practical research, but its direct influence on the properties of the steel has a clear impact on the characteristics of the formed metallic parts under further processing operations. Therefore, optimization of the process inside the tundish is essential from an industrial point of view. The paper includes a detailed analysis of the flow and stirring energy distributions to predict and understand the active and dead zones inside the tundish to avoid the regions with stagnant velocity distribution. As an outcome of such a developed coupled electromagnetic/fluid dynamic model, optimizing the mixing processes to control the product's properties is possible.

Introduction

In the metallurgical industry, intensive investigations are conducted to obtain the best properties of the products and, at the same time, reduce production costs and environmental pollution. The steel composition and microstructure significantly influence material behaviour during further metal forming processes and need to be optimized early in the production stages. Thus, researchers have been working to improve the steel's cleanliness by, e.g., minimizing the amount of non-metallic inclusions leading further to, e.g., crack initiation. In reality, the proper classification and detection of inclusions is a crucial aspect of developing the production process. Zhang and Thomas in [1] reviewed the different sources of inclusions which occur during the whole continuous casting process. The phenomena leading to the generation of inclusions in molten steel are complex. Many

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aspects influence their formation, e.g., the high oxidizing atmosphere in the electrical arc furnace (EAF), which is the first stage of the process, reoxidation or slag entrainment in the next steps of the production etc. Researchers also focus on the improvement of steel cleanliness, mainly in the ladle, tundish and directly, in the slab casting operation. The common practice is the absorption of inclusions to the slag layer [2], intensification of the removal process by the additional inert gas injection [3-5], introduction of special channels with induction heating [6] or finally, dedicated control devices can be added to improve the stirring of the melt like baffle walls or electromagnetic stirrers (EMS) [7,8]. Currently, the research in this area mainly focuses on mathematical or numerical modelling due to the difficulties with the measurements under real production conditions. The numerical approach of Computational Fluid Dynamics (CFD) enables the wide investigation of the flow and inclusions behaviour for each metallurgical equipment starting from the electrical arc furnace, ladle furnace, and tundish. It also enables the solidification phenomena predictions occurring during the casting.

Therefore, the main goal of this research is the development of a complex coupled electromagnetic/fluid dynamic model of the steel behaviour in the tundish equipped with electromagnetic stirrers. Material flow in the tundish is critical as it is the last production stage with fully liquid metal. The overall goal is to simulate the molten steel flow, the velocity and stirring energy distributions to understand the development of so-called active and dead zones inside the tundish. As a result, the mixing process could be appropriately designed to increase the homogeneity of the steel and avoid areas with the stagnant flow or inhomogeneous temperature distribution. Both phenomena lead to catastrophic problems related to the quality and clogging of outlets. These issues are dangerous from a safety point of view and can lead to production faults, exposing the company to unexpected costs.

Methodology

The numerical investigations of the flow behaviour inside the tundish were conducted in the commercial CFD software Ansys Fluent. The geometry of the tundish was prepared according to the industrial specification of the real device. Simulations focused on the different computational scenarios within the tundish with additional control devices namely baffle walls, electromagnetic stirrers and stoppers, to control the mass flow rate through outlets. The tundish geometry used during the research is presented in Fig. 1a, as a case with additional stoppers and in Fig. 1b, as a case with a baffle wall to control the flow distribution. In both cases, additional electromagnetic stirring is also considered.

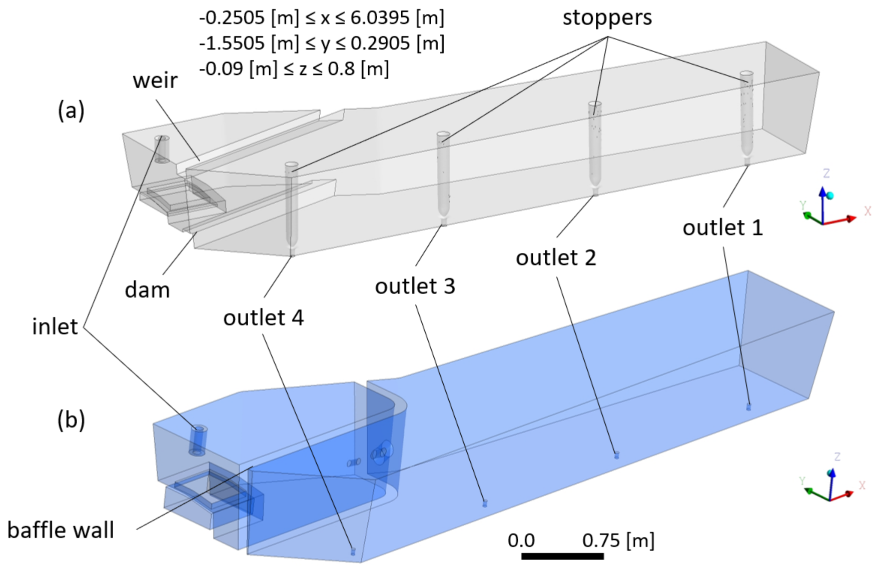

Fig. 1. The geometry of the tundish used in the numerical simulations (a) with stoppers and (b) with baffle wall.

The parametric study included comparing the different scenarios of the current applied during EMS operation to understand the influence of such additional stirring mechanism on the mixing process and optimize the power input to avoid energy losses. The list of cases which were conducted to compare the velocity and stirring energy distributions is presented in Table 1.

Table 1. List of cases to compare the flow behaviour.

Case no.	Description
1	without EMS, without baffle wall
2	with 100% of EMS, normal direction of stirring
3	with 100% of EMS, reversed direction of stirring
4	without EMS, with baffle wall
5	with 100% of EMS, without baffle wall, with stoppers
6	with 84% of EMS, without baffle wall, with stoppers
7	with 69% of EMS, without baffle wall, with stoppers
8	with 60% of EMS, without baffle wall, with stoppers
9	with 31% of EMS, without baffle wall, with stoppers

Electromagnetic stirring used to induce the steel flow is realized by the additional momentum source terms introduced into the momentum equation. Forces from the electromagnetic stirring are mapped into the fluid computational domain and depend on the velocity. The following equation describes this dependence:

$$\vec{F} = \overrightarrow{F_0}\left(1 - \frac{\overrightarrow{F_0} \bullet \vec{V}}{2\tau f \bullet |\overrightarrow{F_0}|}\right), \quad (1)$$

where $\overrightarrow{F_0}$ - stirring force calculated for stationary melt [N/m3], $\vec{F}$ - stirring force after compensation with moving melt [N/m3], τ - pole pitch [m], f - frequency [Hz], $\vec{V}$ - velocity of melt [m/s].

The exemplary force field mapping operation to include the effect of electromagnetic stirring in the tundish is presented as a force density in Fig. 2.

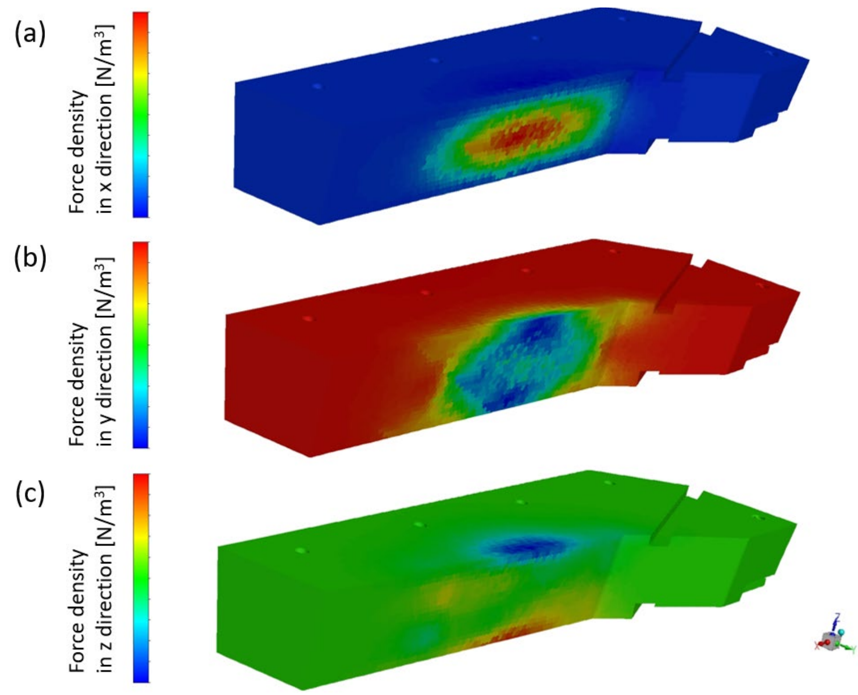

Fig. 2. Force densities in (a) x-direction, (b) y-direction and (c) z-direction, respectively.

During the investigations, the mixing process was also taken into consideration. Visualization of the mixing operation in the molten steel is realized by additional discrete phase particles available in the Discrete Phase Model (DPM), which interact with the continuous phase. To understand the flow behaviour, the massless particles were injected into the domain in accordance with the boundary conditions of the stream. The particles, as a tracers, travel with the continuous phase and enable observation of the liquid steel's movement.

Results and Discussion

CFD simulations help to understand the flow inside the tundish under the additional electromagnetic forces. Based on the evaluated turbulent dissipation rate that occurs in the molten steel, the stirring energy can be calculated. The simulations were performed for different cases to evaluate the influence of the applied current scenarios, which directly correspond to the force factor of the EMS, on the velocity distribution and stirring effectiveness. The first comparison between the velocity and stirring energy distribution for 100% , 84%, 69%, 60% and 31% of EMS stirring force and for the case with stoppers is presented in Fig. 3. It should also be pointed out that inside the tundish, the clogging of outlets is a rather common phenomenon and depends on the solidification of the molten steel, mainly in the areas of the dead zones and sedimentation process, where different remains detach from walls are clogged up the outlets. This issue is very often inside the tundish because of the relatively low stirring energy inside compared with the ladle furnace, where the mixing process is the most intensive. Based on that, the analysis of the stirring energy close to the outlets can improve the design process and optimization of the work of the device. The comparison between the stirring energy distribution in the area of each outlet for cases with stoppers for 100% and 31% of EMS is presented in Fig. 4.

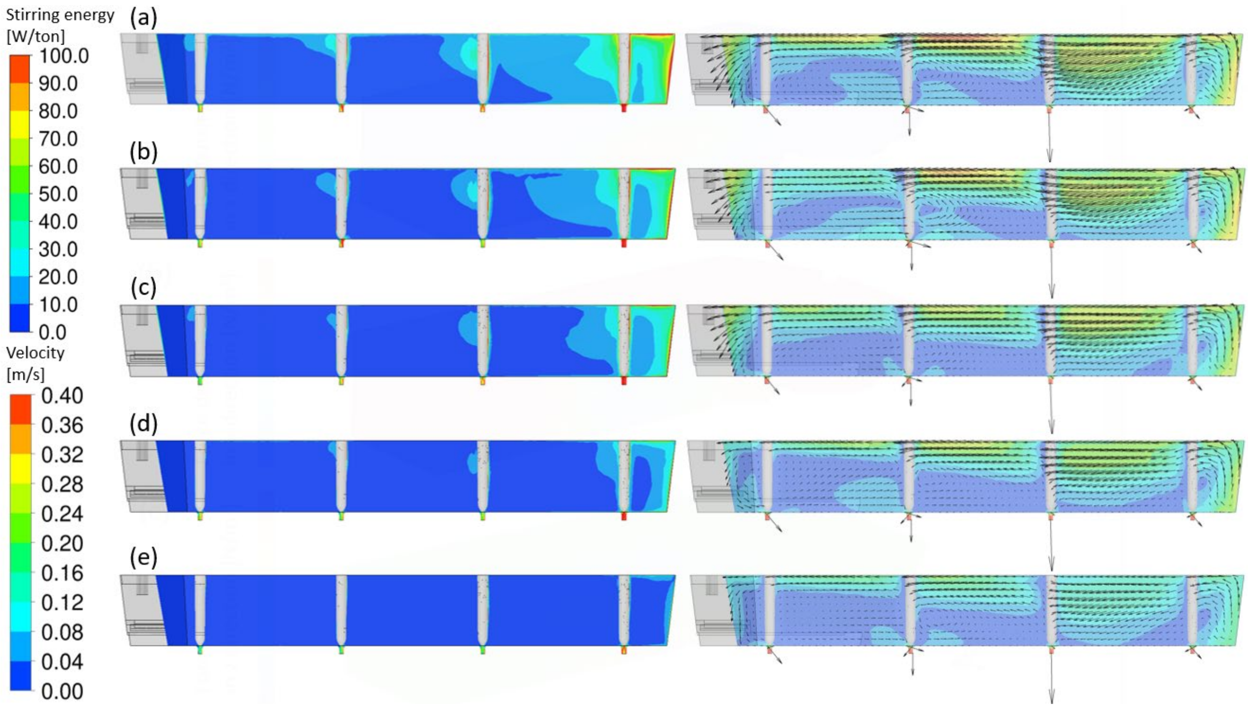

Fig. 3. Stirring energy (left) and velocity (right) distribution for different EMS force factors (a) 100% - case no. 5, (b) 84% - case no. 6, (c) 69% - case no. 7, (d) 60% - case no. 8, (f) 31% - case no. 9.

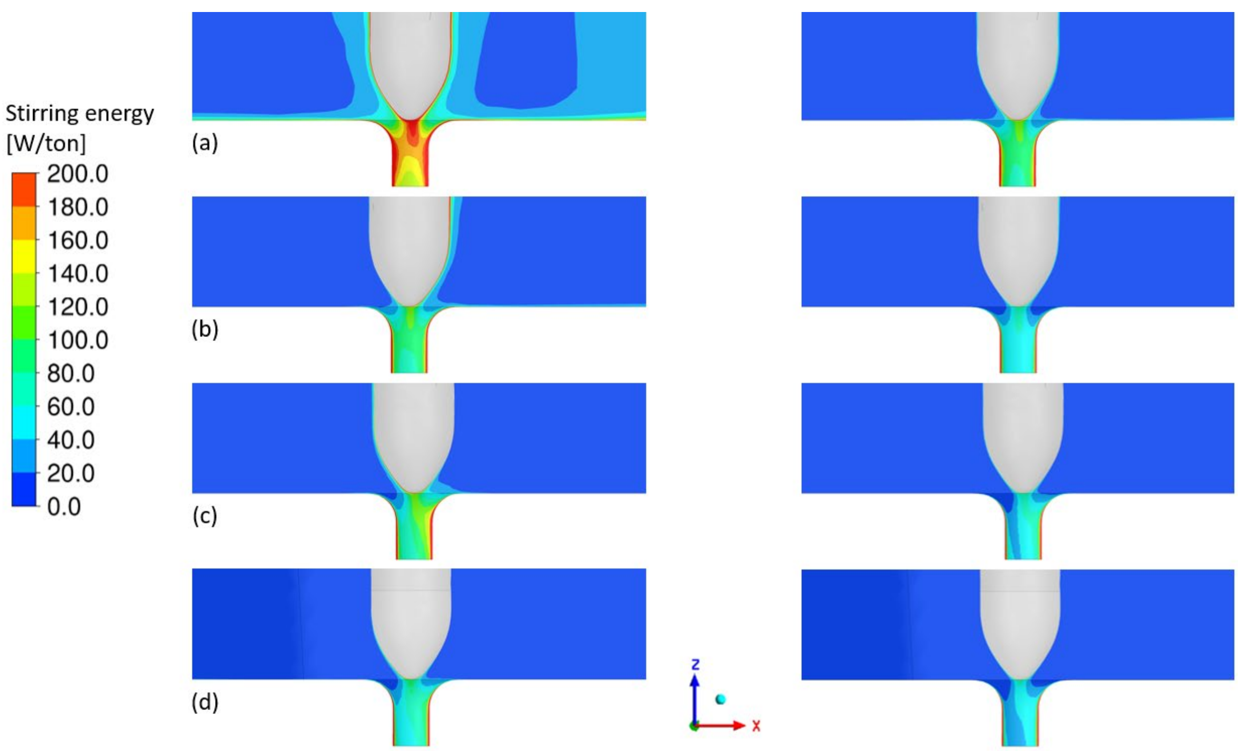

Fig. 4. Stirring energy distribution for case no. 5, 100% of EMS (left) and case no. 9, 31% of EMS (right) for different outlets: (a) outlet 1, (b) outlet 2, (c) outlet 3, (d) outlet 4.

Based on Fig. 4, stirring energy distribution close to outlet 3 has the most asymmetric character, and the gradients of the values are the highest.

Another important investigation is the evaluation of the molten steel mixing inside the tundish. This mixing can be easily visualized by the mentioned massless particles whose behaviour is dependent on the steel flow in the tundish. The observation of the tracers in the numerical model can be compared to the analysis of the dye injected into the water during the water model tests. The particles flow inside the device is presented in Fig. 5 and Fig. 6, where different types of cases were compared to each other. The simulation model without any additional control devices is presented as a reference case. Then, the results for the case with 100% of EMS are shown. The investigation also included the reversed direction of the stirring to compare the behaviour of particles and the results with a common control device like a baffle wall with openings used to improve the liquid steel mixing process. The comparison confirms that the best mixing is presented for the case with 100% EMS stirring. The results are much better than the baffle wall and indicate the high efficiency of homogenising velocities and temperatures. Obtained results also indicate an increase in the inclusions removal process, which is important to the steel's quality.

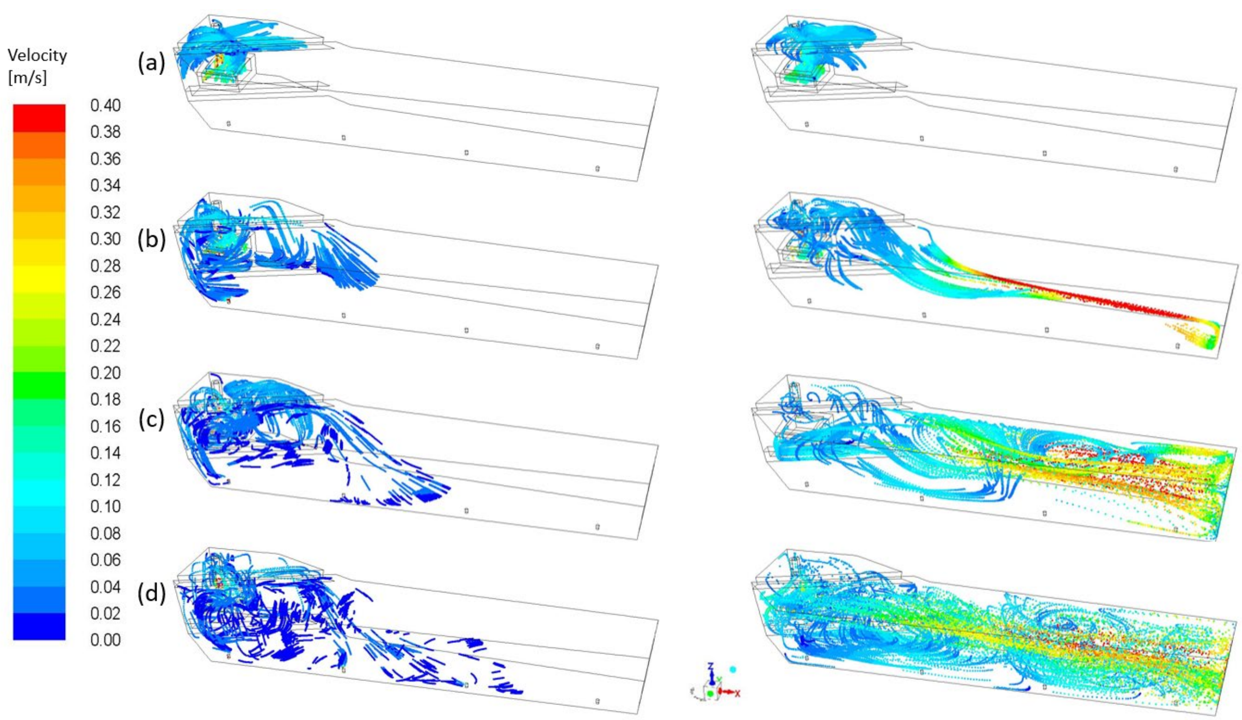

Fig. 5. Massless DPM tracers to visualize the mixing process for case no. 1 without EMS, without baffle wall (left) and for case no. 2 with 100% of EMS, the normal direction of stirring at (a) 20 [s], (b) 50 [s], (c) 100 [s], (d) 200 [s].

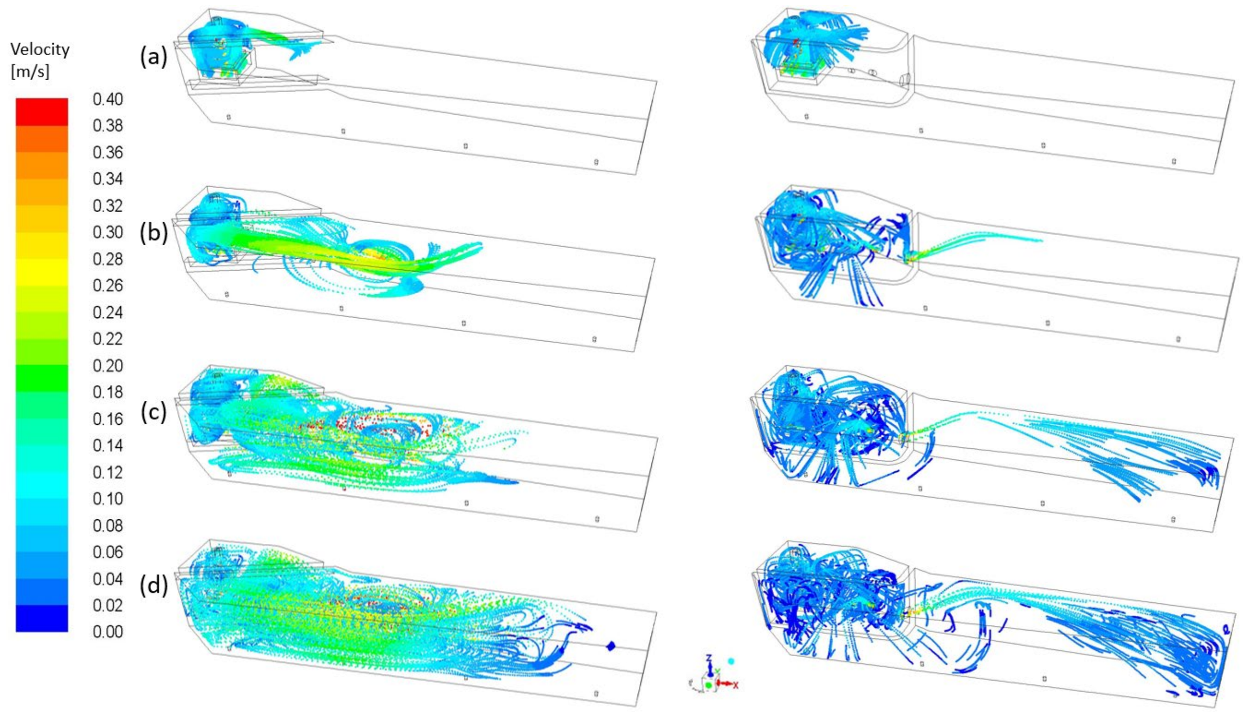

Fig. 6. Massless DPM tracers to visualize the mixing process for case no. 3 with 100% of EMS, reversed direction of stirring (left), and for case no. 4 without EMS, with baffle wall at (a) 20 [s], (b) 50 [s], (c) 100 [s], (d) 200 [s].

Summary

Based on the presented research, the following conclusions can be formulated:

- CFD simulations enable to understand the issues in the steelmaking industry and optimize the continuous casting process to improve the effectiveness of the work of metallurgical devices.
- The molten steel flow inside the tundish can be highly improved by the electromagnetic stirrers. In this case relatively low power input significantly improves the effectiveness of the mixing. As a result the homogenization of the structure and purity of the steel is improved. At the same time, agglomeration of inclusions into the slag occurs due to the prevention of the dead zones. So areas with stagnant flow influencing the velocity, temperature and inclusions distribution are minimized. All those aspects directly influence the final products' quality,
- The EMS stirring also prevents uncontrolled solidification and sedimentation, which is dangerous from a safety point of view due to the risk of clogging and faults of the production line.
- The above-mentioned advantages confirm that the structure of the molten steel can be controlled by the usage of electromagnetic stirrers, which also influence further metal forming operations .

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