

## Assessment of Different Turbulence Models for the Motion of Non-metallic Inclusion in Induction Crucible Furnace

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 IOP Conf. Ser.: Mater. Sci. Eng. 143 012026

(<http://iopscience.iop.org/1757-899X/143/1/012026>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 193.170.16.107

This content was downloaded on 22/09/2016 at 09:50

Please note that [terms and conditions apply](#).

You may also be interested in:

[Analysis and simulation of non-metallic inclusions in spheroidal graphite iron](#)

B Pustal, B Schelnberger and A Bührig-Polaczek

[In-situ observation of the behaviour of non-metallic inclusions at different interfaces in the system steel-slag-refractory](#)

S K Michelic, U Dieguez Salgado and C Bernhard

[Numerical simulation of tundish flow](#)

Rüdiger Schwarze, Frank Obermeier and Dieter

Janke

[Assessment of RANS to predict flows with large streamline curvature](#)

J L Yin, D Z Wang, H Cheng et al.

[Effective eddy viscosities in implicit modeling of decaying high Reynolds number turbulence with and without rotation](#)

J Andrzej Domaradzki and S Radhakrishnan

[Evaluation of turbulence models for the numerical prediction of transient cavitation around a hydrofoil](#)

W D Shi, G J Zhang and D S Zhang

# Assessment of Different Turbulence Models for the Motion of Non-metallic Inclusion in Induction Crucible Furnace

**H. Barati, M. Wu, A. Kharicha, A. Ludwig**

Chair for Modeling and Simulation of Metallurgical Processes, Department of Metallurgy, University of Leoben, Franz-Josef Street 18, 8700 Leoben, Austria

E-mail: menghuai.wu@unileoben.ac.at

**Abstract.** Turbulent fluid flow due to the electromagnetic forces in induction crucible furnace (ICF) is modeled using  $k$ - $\varepsilon$ ,  $k$ - $\omega$  SST and Large Eddy Simulation (LES) turbulence models. Fluid flow patterns calculated by different turbulence models and their effects on the motion of non-metallic inclusions (NMI) in the bulk melt have been investigated. Results show that the conventional  $k$ - $\varepsilon$  model cannot solve the transient flow in ICF properly. With  $k$ - $\omega$  model transient flow and oscillation behavior of the flow pattern can be solved, and the motion of NMI can be tracked fairly well. LES model delivers the best modeling result on both details of the transient flow pattern and motion trajectories of NMI without the limitation of NMI size. The drawback of LES model is the long calculation time. Therefore, for general purpose to estimate the dynamic behavior of NMI in ICF both  $k$ - $\omega$  SST and LES are recommended. For the precise calculation of the motion of NMI smaller than 10  $\mu\text{m}$  only LES model is appropriate.

## 1. Introduction

Understanding the turbulent flow and other transport phenomena, like dissolution of alloying elements and removal of non-metallic inclusions in induction crucible furnace (ICF) is one of the important subjects in steel metallurgy. The flow pattern in the melt is mainly governed Lorentz force. The interaction between the induced electrical current and magnetic field results in Lorentz force acting on the bulk melt in the direction towards the center of crucible. Typically two or more eddies with turbulent pulsations between them might form [1]. This phenomenon has been subject of various researches [2-5].

Jardy et al. [6] carried out experimental and theoretical study to characterize the hydrodynamic behavior and the transport of dissolved elements in the molten steel in vacuum induction furnace. 2D simulation using  $k$ - $\varepsilon$  turbulence model, with a standard set of constants, showed adequate results [7, 8]. Nevertheless, in spite of the  $k$ - $\varepsilon$  results demonstrating highest values of turbulent kinetic energy in the eddy centers and the lowest between the eddies, the experimental results showed that the maximum of the turbulent energy is between the vortices of the averaged flow and close to the wall of the crucible [5, 9]. Umbrashko et al. [5] simulated turbulent flow in an induction furnace for a low melting temperature metal and compared averaged with non-averaged Navier Stokes models. Their study revealed that the low-frequency velocity oscillations play the major role in the convective heat and mass transfer when flow structure contains two or more large vortexes of the mean flow. Therefore, they concluded that the Large Eddy Simulation (LES) model is more reliable in the melt agitation in the induction furnace.



LES model has also been applied for induction channel furnace [10]. Turbulent heat and mass transfer in the melt using a 3D transient LES model were simulated. On this base, distributions of alloying additions into the melt and disjointed impurities due to channel erosion were investigated.

Scepanskis et al. [1] focused on particle-laden recirculated turbulent melt flow driven by electromagnetic forces, and compared numerical and experimental results for particle distribution on the melt surface. In another work [11] a methodology is presented that consists of the regression model for the identification of the time that is necessary to homogenize alloying inclusions in liquid metal inside an ICF. Such calculation can be carried out in the rational time and, therefore, it is possible to perform the industrial optimization of the mixing time as the function of size and density of the alloying inclusions.

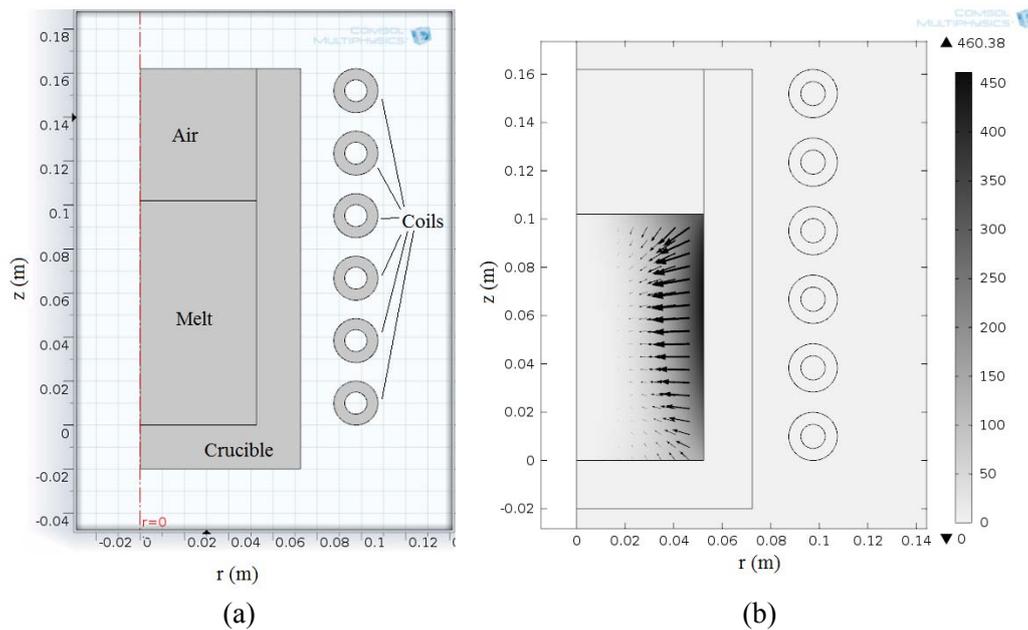
Single-phase flow in induction furnace is well researched. However, the particle motion is still not sufficiently investigated and knowledge about non-metallic inclusion inside the melt especially when it approaches crucible wall boundary is weak. Therefore, this paper presents a primary study of non-metallic inclusion behaviors in molten steel of laboratory ICF. We should firstly verify the melt flow and particle motion. So, velocity and turbulence inside melt are studied using different models in 2D and 3D. Single particle motion with different properties under the effects of different forces such as drag, lift, virtual mass and pressure gradient is investigated.

## 2. Model Description

A laboratory induction furnace is considered, as schematically shown in Figure 1(a). Six water cooled coils are located around an alumina-silica crucible. Dimensions, parameters, and physical properties used in simulations are listed in Table 1.

Numerical studies of the electromagnetically driven flow have shown that the influence of the pulsating magnetic field can be neglected if its frequency is higher than 5 Hz [12]. Thus in one way coupling manner, electromagnetic forces are calculated using COMSOL Multiphysics software and the time-averaged values are imported as momentum source terms in ANSYS FLUENT for the turbulent flow calculation. Figure 1(b) shows that most forces are toward centerline and localized in a 3 cm thick layer adjacent to the crucible wall. For the turbulent flow three models,  $k$ - $\epsilon$ ,  $k$ - $\omega$  SST and Large Eddy Simulation (LES) are used in 2D and 3D cases.

Alumina particles have been considered as typical inclusions in steelmaking processes with different sizes and effect of diverse forces on their motion in the bulk melt are studied. Details of the model for the motion of non-metallic inclusions in the melt can be found in the previous works [13, 14]. Among all forces acting on a particle, buoyancy and drag are main factors of the particle motion and are not negligible. Due to the deformed electrical current path around the non-conductive particle in the conductive melt an electromagnetic force is also applied on the particle, and the maximum value of the electromagnetic force acting on an alumina particle near the crucible wall is about 1% of buoyancy force. Therefore it can be neglected in this case. Other forces are lift, virtual mass and pressure gradient. Since main agent of creation of both virtual mass and pressure gradient force is velocity acceleration ( $dU/dt$ ) [15], effects of these two forces are taken in account together. To consider dispersion of particles due to the turbulence a stochastic tracking model can be implemented in the momentum calculations, especially in Reynolds Average Navier Stokes (RANS) models like  $k$ - $\epsilon$  and  $k$ - $\omega$ . Fluctuating velocity components defined by Gaussian probability distribution include an artificial normally distributed random number. In order to compare particle trajectory caused by different forces, this stochastic tracking called random walk is here disabled. Moreover, random walk model might lead to unrealistic result when particles enter laminar sublayers close to the crucible wall.



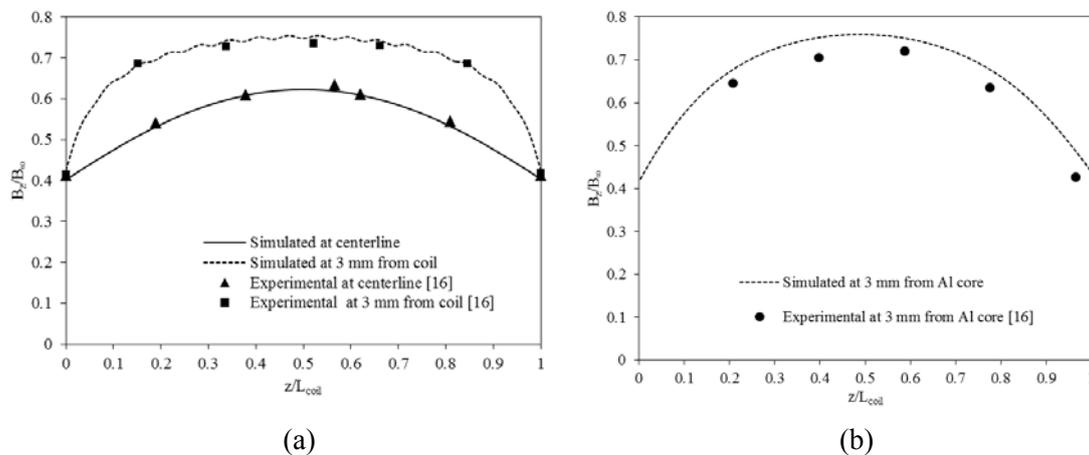
**Figure 1.** (left) Geometry, (right) Direction and magnitude of Lorentz force ( $N/m^3$ ).

**Table 1.** Dimensions, parameters, and physical properties.

| Property   | Unit       | Value              |
|--|------------|--------------------|
| Inner radius of crucible ( $R_{crucible}$ )      | mm         | 52.5               |
| Radius of coil ( $R_{coil}$ )                    | mm         | 97.5               |
| Height of melt ( $H_{melt}$ )                    | mm         | 102                |
| Length of coil ( $L_{coil}$ )                    | mm         | 162                |
| Inner radius of coil cross section ( $r_{in}$ )  | mm         | 5                  |
| Outer radius of coil cross section ( $r_{out}$ ) | mm         | 10                 |
| Thickness of crucible ( $Th_{crucible}$ )        | mm         | 20                 |
| Electrical conductivity of melt ( $\sigma$ )     | S/m        | $2.86 \times 10^5$ |
| Imposed electrical current ( $J_e$ )             | A          | 4000               |
| Frequency ( $f$ )                                | Hz         | 50                 |
| Density of melt ( $\rho$ )                       | $kg/m^3$   | 7020               |
| Viscosity of melt ( $\mu$ )                      | $kg/(m.s)$ | 0.006              |
| Density of alumina ( $\rho_p$ )                  | $kg/m^3$   | 3700               |

### 3. Results and discussion

To validate the calculated Lorentz forces a comparison has been done with experimental results [16]. Figure 2 indicates that the simulation results match those gained using Gauss meter in both cases with and without an aluminum core inside the coil.  $B_\infty$  is theoretical value of magnetic flux density at the axis of the coil.



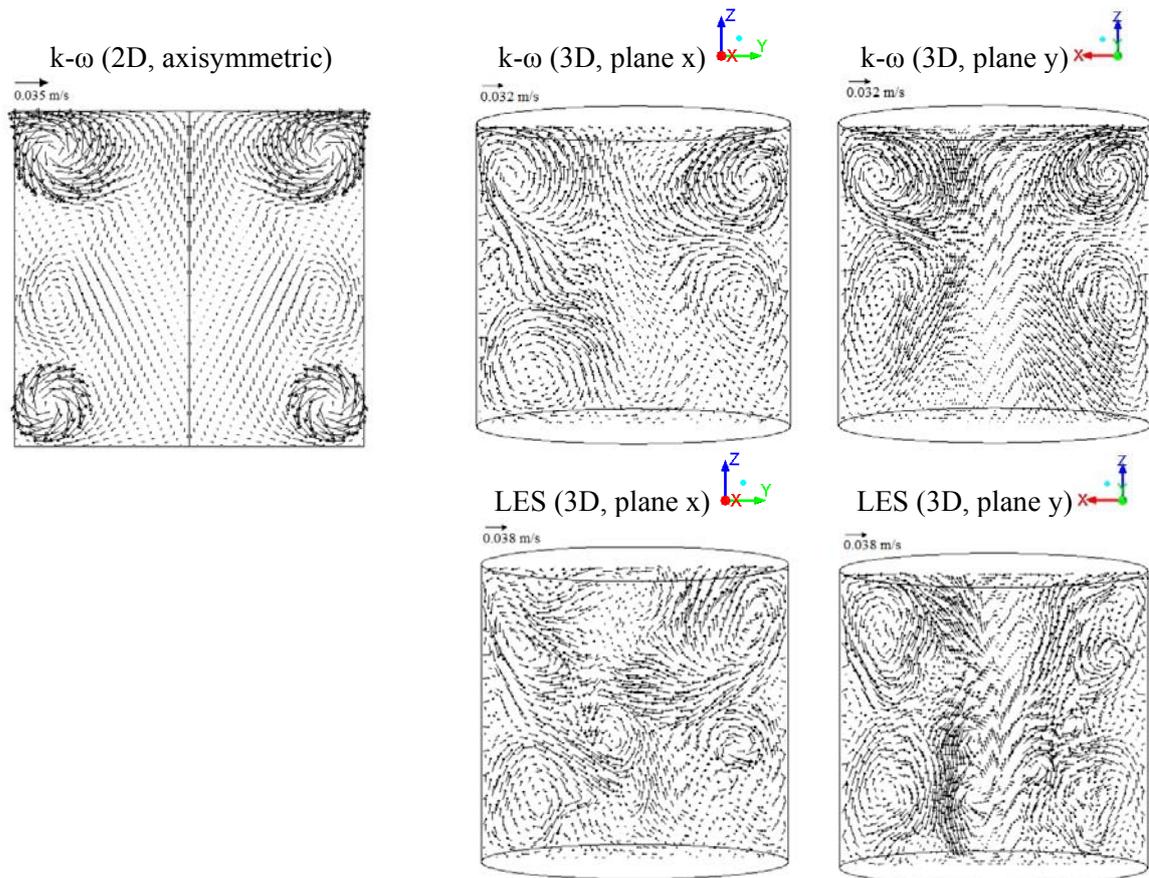
**Figure 2.** Dimensionless magnetic flux density in  $z$  direction inside a coil for the simulation and experiments [16]: (a) coreless coil, (b) coil with an aluminum core.

Velocity distributions for two turbulence models,  $k-\omega$  SST and LES, are shown in Figure 3 that 2D-axisymmetric and 3D simulations are compared. For better presentation of 3D flow pattern velocity vectors are displayed on two main coordinate planes. Despite of the  $k-\epsilon$  model which is claimed to be proper for completely turbulent flow and gives a steady flow pattern for the melt [5], the  $k-\omega$  model delivered a transient result of the flow pattern in both 2D-axisymmetric and 3D calculations. Like typical time averaged simulation results [5, 11] two main eddies form in upper and lower zones. Size, strength, and location of main eddies change frequently. Moreover some local weak vortices are created and vanished between main eddies.

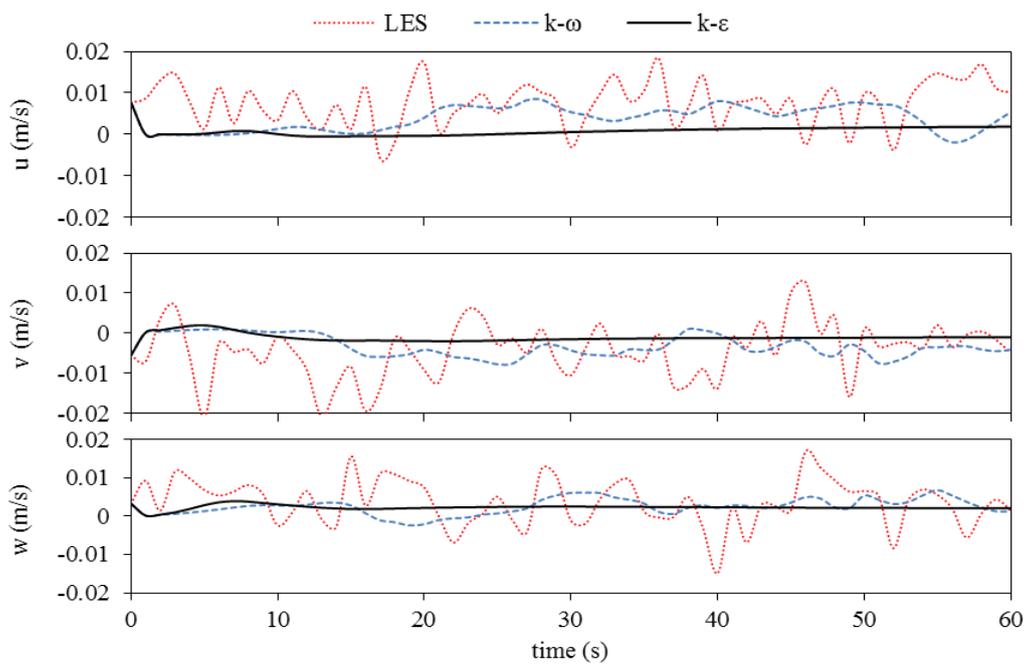
Because of mathematical filtering in the calculation of variables in LES, instantaneous velocity results are more time dependent. Therefore, there is no stabilized flow pattern. Several erratic vortices form whose locations and sizes vary frequently. It causes oscillation of velocity at different points. The same phenomena were observed by experimental investigations [5, 9].

Instantaneous variation of velocity components at the center of crucible for  $k-\epsilon$ ,  $k-\omega$  and LES are plotted in Figure 4. It can be observed that  $k-\omega$  model can solve the oscillation of velocity like LES while  $k-\epsilon$  results are generally constant for all components. Hence, in the cases where accurate local and instantaneous velocity is not of interest,  $k-\omega$  SST is a reasonable model for the transient simulation of transport phenomena in induction furnace.

After study of fluid flow in the ICF, particle motions under diverse circumstances are calculated. Figure 5 shows trajectories of a particle with  $5\ \mu\text{m}$  diameter started from the center of the crucible. In Figure 5(a)  $k-\omega$  results depict that consideration of lift force results in no change in particle path comparing with drag only condition. However, applying virtual mass and pressure gradient forces makes little distinction. Hence, it can be concluded that the velocity gradient across the particle, i. e. lift force, is almost zero, but the velocity acceleration, i. e. virtual mass and pressure gradient force, is effective to some extent. Nevertheless, all three calculations by  $k-\omega$  model indicate that the drag force is dominant.

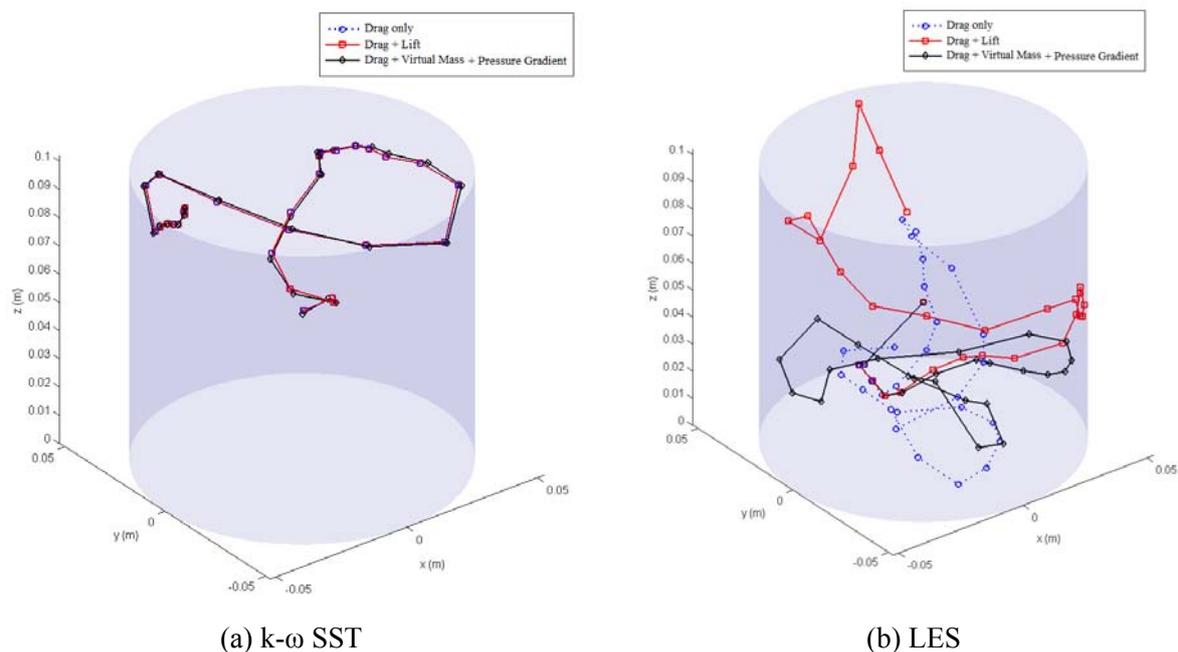


**Figure 3.** Snapshots of velocity field calculated by  $k-\omega$  and LES models.



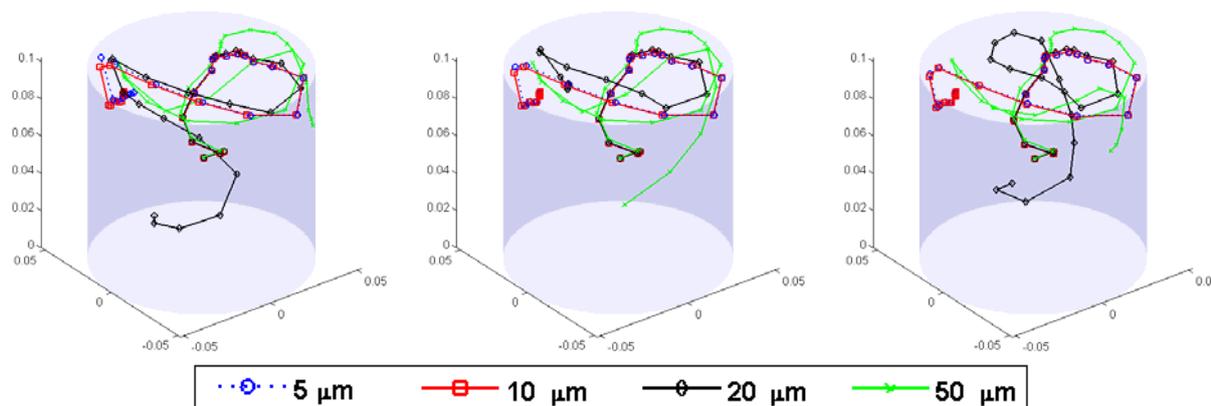
**Figure 4.** Transient velocity components of  $k-\epsilon$ ,  $k-\omega$  and LES at center point of crucible.

LES result, Figure 5(b), indicate that in first few seconds particle under different forces moves in the same paths and then chooses completely different paths. These results are observed repeatedly. Regarding disabled random walk model the only reason resulting in particle movement through diverse paths is due to the different forces. Intense oscillations of velocity in LES (Figure 4) make more locally shear flow regions so lift force can effectively change particle path and moves it into one of numerous local eddies. Also it is obvious from Figure 4 that  $dU/dt$  in LES model, i. e. virtual mass and pressure gradient forces, is higher with respect to  $k-\omega$ . Therefore, these forces in LES model are more effective. On the other hand, local eddies in LES are many and variable, so a short deviation in the particle motion may cause a totally different path. Hence, effective particle motion is fulfilled precisely using LES model.



**Figure 5.** Particle trajectories calculated by considering different forces in  $k-\omega$  and LES turbulence models. (Time interval between sequential points is 1 s.)

Most of non-metallic inclusions in primary steelmaking process such as  $Al_2O_3$ ,  $SiO_2$  and  $MgO$  are lighter than molten steel and their density vary in a small range, 3970, 2320 and 3650  $kg/m^3$  respectively. So, for comparison of different inclusions, density is not an impressive factor. To perform a parameter study of particle properties trajectories of the particle with different size from the same beginning point and at different injection times are studied with  $k-\omega$  model, Figure 6. Difference between injection times is 0.05 s and all forces mentioned before have been applied. It can be observed in Figure 6 that particles with small diameter (5 and 10  $\mu m$ ) have almost the same trajectories. However, particles with diameter of 20  $\mu m$  go through paths like small ones in almost 10 s then select different paths and the largest particles (50  $\mu m$ ) are separated in few beginning seconds. Results of different particle sizes for LES model are too chaotic, as shown in Figure 5, therefore the trajectories are not comparable with each other.



**Figure 6.** Particle trajectories with different particle diameters in  $k-\omega$  turbulence model. (Time interval between sequential points is 1 s.)

#### 4. Conclusions

Numerical simulations have been done to model the turbulent flow and the motion of non-metallic inclusion (NMI) in induction crucible furnace (ICF). Studies focused on  $k-\omega$  SST and LES turbulence models. Results showed that transient flow pattern and velocity oscillations in the ICF can be modeled using  $k-\omega$ , while the conventional  $k-\epsilon$  is unable to model this phenomenon. The motion of NMI can also be tracked by the  $k-\omega$  model fairly well. When precise trajectory of NMI in the melt is of interest, LES model is the most suitable option. Of course, LES model requires fine mesh and small time step size which increase calculation costs. Therefore, for general purpose to estimate the dynamic behavior of NMI in ICF both  $k-\omega$  SST and LES are recommended. For the precise calculation of the motion of NMI, especially for those NMIs with diameter smaller than  $10\ \mu\text{m}$ , only LES model is appropriate. However, to confirm above statements further modeling and experimental evaluation efforts are desired.

#### 5. References

- [1] Scepanskis M, Jakovics A, Baake E and Nacke B 2014 *Int. J. Multiphase Flow* **64** 19–27
- [2] Bojarevics V, Djambazov G, Harding R A, Pericleous K and Wickins M 2003 *Magneto hydrodynamics* **4** 395–402
- [3] Schwarze R and Obermeier F 2004 *Modell. Simul. Mater. Sci. Eng.* **12** 985–93
- [4] Baake E, Nacke B, Jakovics A and Umbrashko A 2001 *Magneto hydrodynamics* **37** 13–22
- [5] Umbrashko A, Baake E, Nacke B and Jakovics A 2006 *Met. Mater. Trans. B* **37** 831–838
- [6] Jardy A, Gosset D, Ablitzer D and Witzke S 1993 *J. Phys. IV France* **3** C7–1151–C7–1156
- [7] El-Kaddah N and Szekely J 1983 *J. Fluid. Mech.* **133** 37–46
- [8] Baake E, Muhlbauer A, Jakowitsch A and Andree W 1995 *Met. Mater. Trans. B* **26B** 529–536
- [9] Kirpo M, Jakovics A, Baake E and Nacke B 2007 *Magneto hydrodynamics* **43** 161–172
- [10] Pavlovs S, Jakovics A, Baake E, Nacke B and Kirpo M 2011 *Magneto hydrodynamics* **47** 399–412
- [11] Scepanskis M, Jakovics A, Baake E and Nacke B 2015 *Steel Research Int.* **86** 169–174
- [12] Felten F, Fautrelle Y, Du Terrail Y and Metais O 2004 *Appl. Math. Model.* **28** 15–27
- [13] Pfeiler C, Wu M and Ludwig A 2005 *Mater. Sci. Eng., A* **413–414** 115–120
- [14] Pfeiler C, Thomas B G, Wu M, Ludwig A and Kharicha A 2008 *Steel Research Int.* 599–607
- [15] Crowe C, Sommerfeld M and Tsuji Y 1998 *Multiphase Flows with Droplets and Particles* (Boca Raton: CRC Press LLC)
- [16] Kennedy M W, Akhtar S, Bakken J A and Aune R E 2011 *COMSOL Users Conference* (Stuttgart)