

Internship report

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Introduction

Before the internship, I've made series of simulations of the flow of magnetically stirred liquid Ga-In alloy. My model was a 2D axisymmetric swirl model. Turbulence was solved by Realizable k-epsilon model with Enhanced Wall Treatment. A Volume Of Fluid multiphase model was used to model the free surface of the liquid metal to be able to compare with the measurements and equations of Arnold Rónaföldi [1]. My work in the lab of SIMAP EPM was a continuation of these simulations.

Investigation of the effect of slip on the tangential velocity

A previously used 2D axisymmetric swirl model was used to investigate the effect of the slip on the tangential velocity of magnetically stirred liquid aluminum alloy – Table 1.

Table 1. Material properties of the Al alloy

η	ρ	ω_0	σ
1,05E-06	2390	314	3,65E+06

The crucible was 130 mm high and had a diameter of 8 mm and was filled with the alloy. A realizable k- ϵ turbulence model was used (with Enhanced Wall Treatment). The values of the inductions and the Taylor numbers are in Table 2.

Table 2. The used inductions and the Taylor numbers

B_0	Ta_m
0,02051	2,32E+04
0,04581	1,16E+05
0,05025	1,40E+05
0,06487	2,33E+05

The Lorenz-force field was programmed as a tangential momentum source term. The equation without the slip was:

$$F_\theta = \frac{1}{2} \sigma B_0^2 r \omega_0 \quad (1)$$

And with the slip:

$$F_\theta = \frac{1}{2} \sigma B_0^2 r (\omega_0 - \omega) \quad (2)$$

The skin depth was:

$$\delta = \sqrt{\frac{2}{\mu \sigma (\omega_0 - \omega)}} \quad (3)$$

And the B_0 in equation (2) was replaced with B like:

$$B = B_0 e^{-d/\delta} \quad (4)$$

Where d is the distance from the wall.

The 3 models were made for the 4 different induction values. The result can be seen on Figure 1.

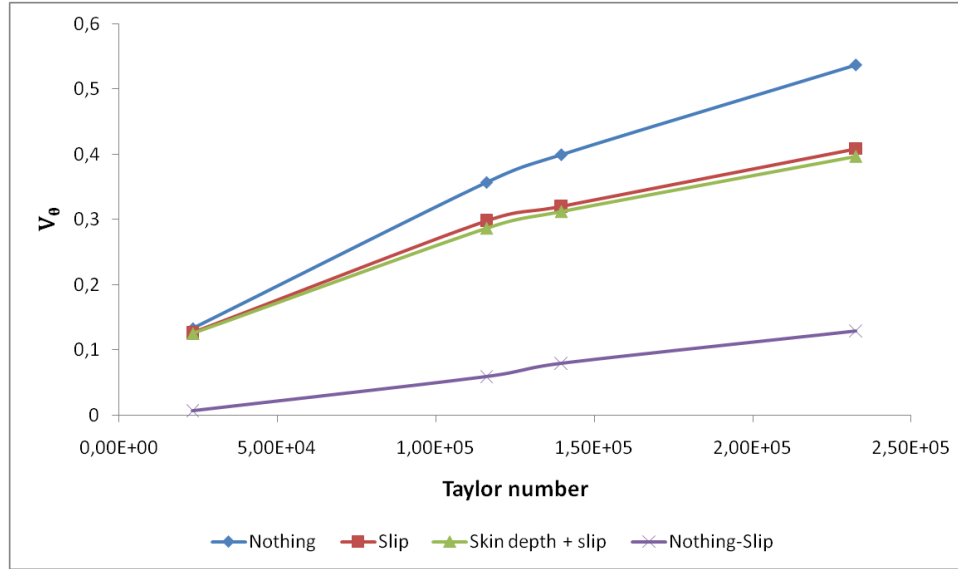


Figure 1. Effect of the slip and skin depth on the tangential velocity – m/s

The slowing effect of the slip can't be neglected, especially at high induction. The difference is linearly rises with the induction (or on the graph, with the Taylor number). The skin depth with this diameter is negligible.

Comparing Large Eddy Simulation and k-ε turbulence models

The aim of the work was to investigate the differences in the result of the 2 turbulence solvers and to compare LES models with different Smagorinsky constants and mesh density. The k-epsilon model solves everything with the averaging of the Reynolds number and computing turbulent viscosity, turbulent kinetic energy (k) and turbulent dissipation rate (ϵ). The LES is working with a kind of filtering method. The large scale of eddies is computed directly and the small scale is modeled with Smagorinsky subgrid scale model [2]. Two additional models were made also – one with higher induction and one multiphase with free surface – to see the differences in the flow.

The geometry

The measurements on the flow were made with a 60 mm high and 10 mm ID crucible. To be able to have a mesh with acceptable density, the height of the crucible were lowered to 30 mm for the models. A 5 mm x 30 mm rectangle was meshed with 0.1 mm size of hexa mesh for k-ε. The LES model needs to be 3 dimensional. In this case the full cylinder was made and meshed with 0.5 million and 2 million cells. The geometries are shown on Figure 2 and Figure 3.



Figure 2. 2D geometry and mesh for k-ε model

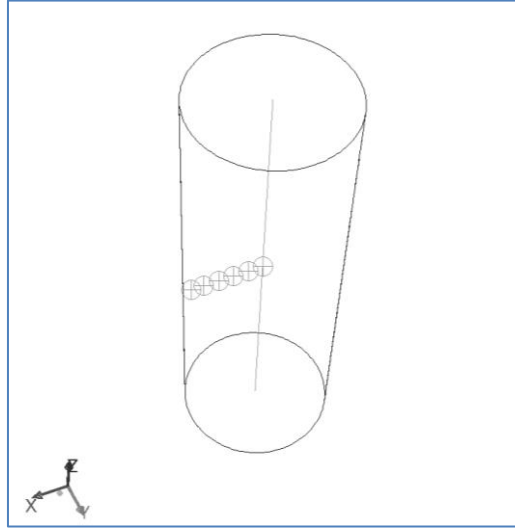


Figure 3. 3D mesh for LES

The force

The metal is stirred by an induced Lorenz force field. This field was applied on the media via user defined function as previously in the Slip-problem. In 2D, the force can be set as tangential directly, but in 3D the X and Y component of the force had to be set as momentum source. The equation of the force is the same as can be seen in the first chapter see equation (2). Slip is added, but skin depth is not. Additional data of the model:

- $B = 22.6 \text{ mT}$
- Density of Ga-In alloy = 6350 kg/m^3
- Viscosity = 0.00216535 Pa-s
- Electrical conductivity = $3.58 \cdot 10^6$

K-ε

Two models were made with k-ε, one standard with standard wall functions (hereinafter: STD) and another realizable with Enhanced Wall Treatment (hereinafter: EWT). The velocity components, the turbulent kinetic energy and the turbulent dissipation rate were monitored on 6 points. For the comparison with the experiments, the average angular velocity was plotted on the radius. The place of the points in the media can be seen on Figure 3. The names are explained on the next page.

- p0 → 0 mm from the axis – 15 mm height
- p1 → 1 mm from the axis – 15 mm height
- p2 → 2 mm from the axis – 15 mm height
- p3 → 3 mm from the axis – 15 mm height
- p4 → 4 mm from the axis – 15 mm height
- p48 → 4,8 mm from the axis – 15 mm height

Results of k-ε

The main difference in the two models can be seen on the plot of the angular velocity. The STD doesn't show any type of fluctuation in the velocity; however it is expected because of wall friction. It can be seen on the EWT's diagram – Figure 4.

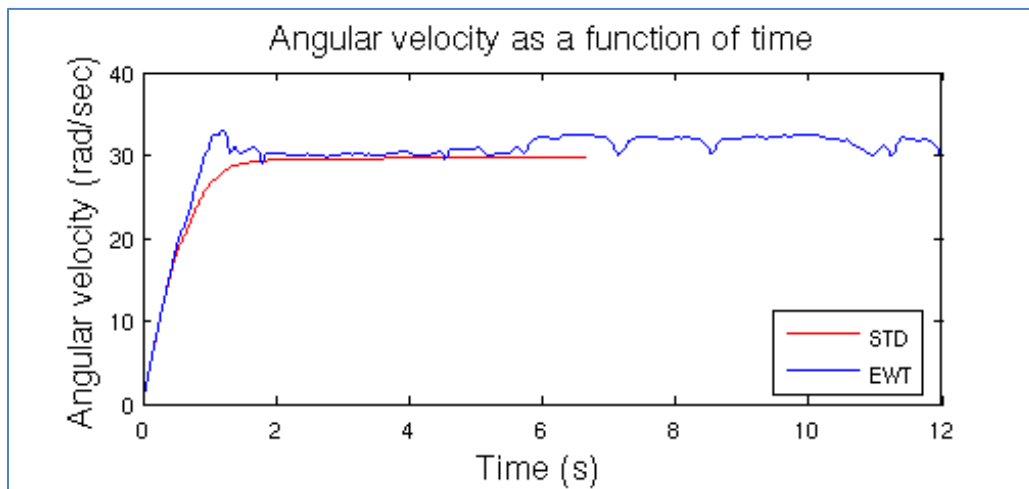


Figure 4. Average angular velocity of the melt on the radius - STD and EWT

The causes of the fluctuations are the small eddies nearby the wall. With standard wall functions, no eddy appears. Just the pump effect is visible, what is made by the pressure difference in the melt - Figure 5.

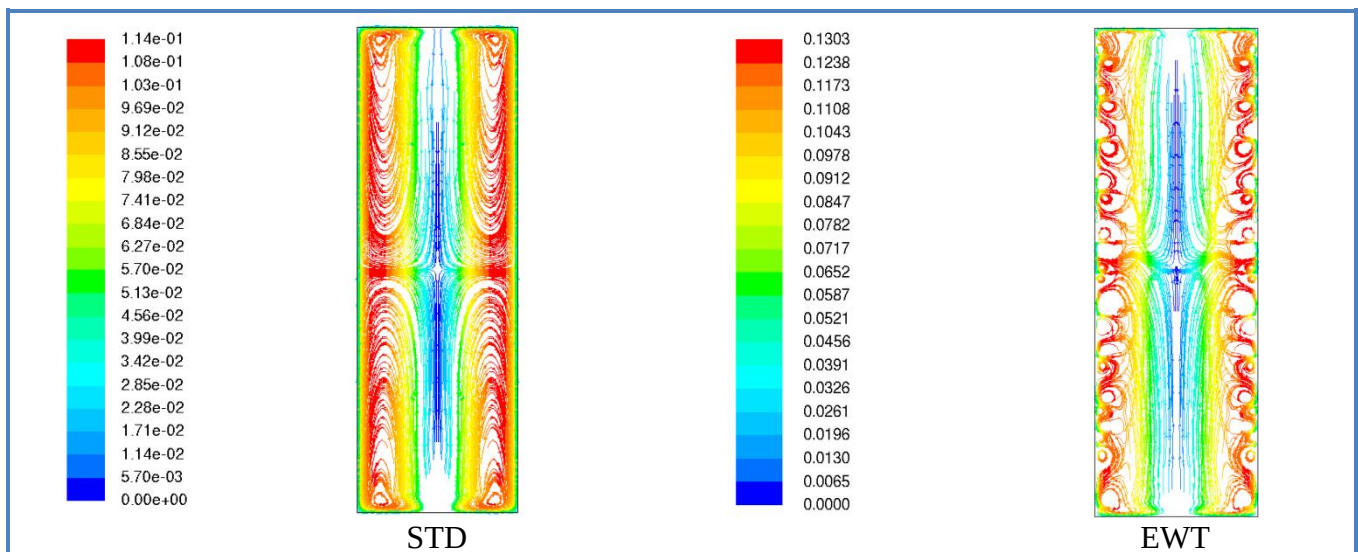


Figure 5. Path lines of secondary flows colored by velocity magnitude – colormap is in m/s

Figure 6 shows the contours of velocity magnitude inside the melt with settled flow. There's no major change in the flow with STD. However - with EWT - the eddies nearby the wall move in the same direction as the pump effect. The movements of the eddies are visible on Figure 7.

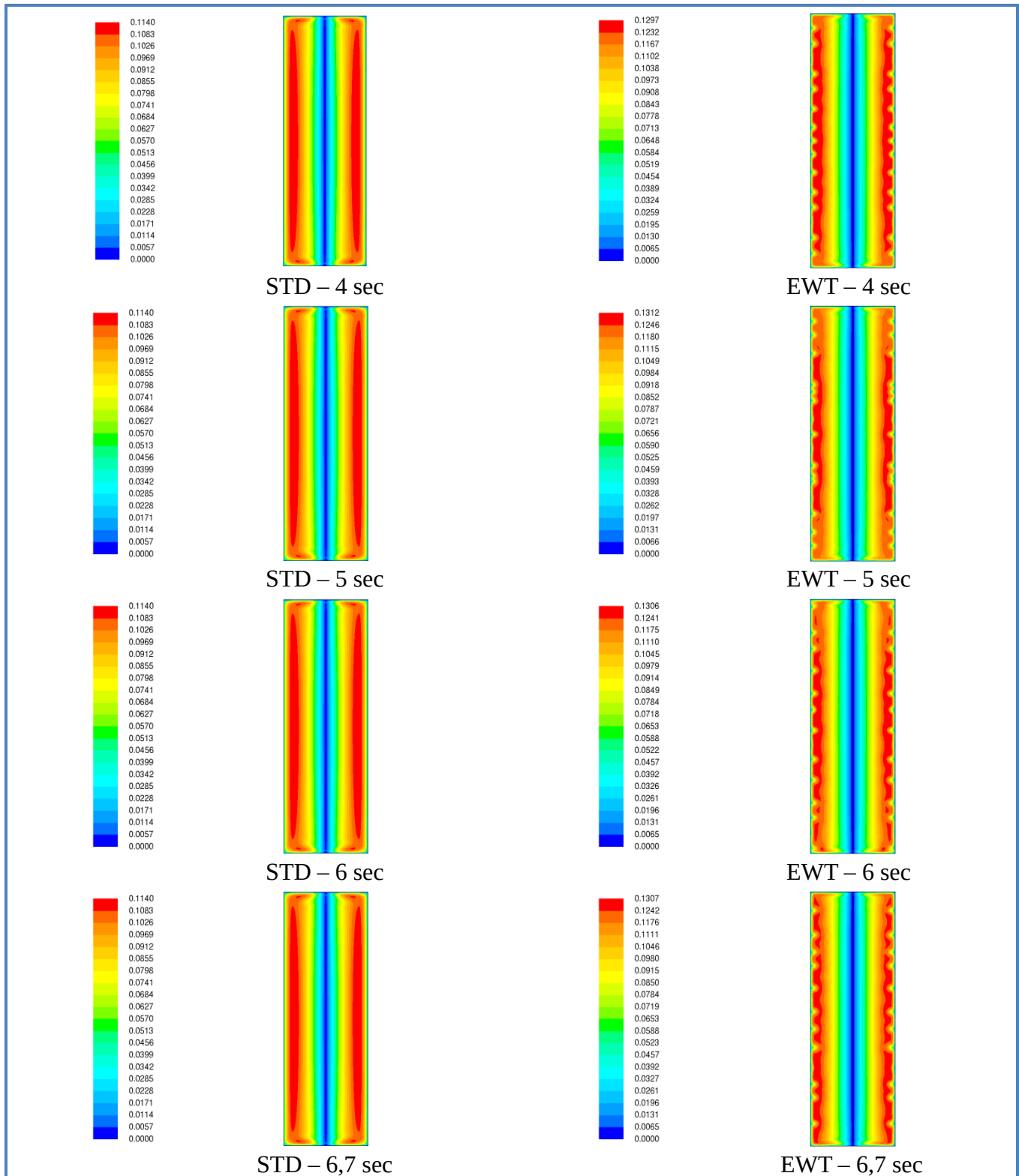


Figure 6. Contours of velocity magnitude at various time steps – colormap is in m/s

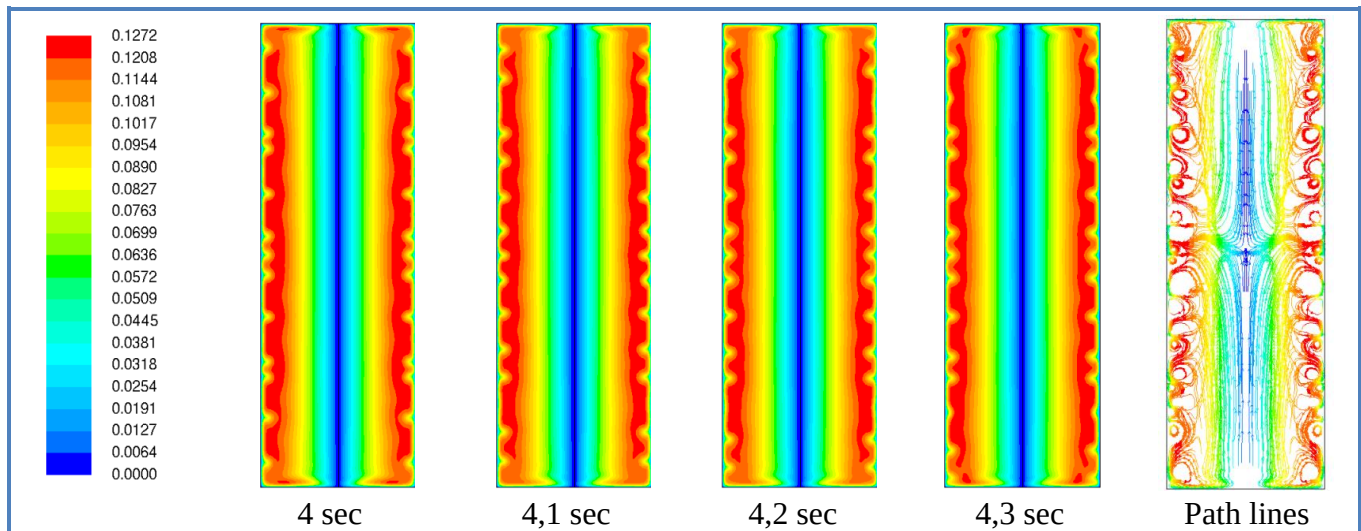


Figure 7. Movement of the eddies and path lines of the secondary flow (colored by velocity magnitude – m/s)

Regarding these results I stopped working with standard wall functions. The comparison between k- ϵ and LES will be done with the EWT version.

Results of LES turbulence models and comparison with the k- ϵ model

Three types of LES models were made. The first model was with 0.5 million cell number and the Smagorinsky constant was set to 0.5 (hereinafter: Cs05). The second had the same mesh, but the constant was set to 0.2 (hereinafter Cs02). The third model also had 0.2 constant, but it had a mesh with 4x higher density – 2 million cells (hereinafter: 2M). The aim of the LES models is to investigate:

- Differences from axisymmetrical k- ϵ model
 - LES is 3D → More info appears from the main flow
 - Turbulence details have to be computed during post processing → MatLab
- The effect of the Smagorinsky constant
 - Cut off frequency → border of the high scale and low scale turbulences
- The effect of the mesh density
 - Resolution of the flow → smaller eddies can be produced

Results of the LES models

Angular, tangential velocities

The LES simulations had much different results than the k- ϵ . The fluctuation of the average angular velocity can be seen on Figure 11 for each LES and the EWT model. The minimum and maximum values are much bigger. The data was gathered from the radius on the height of 15 mm – half of the crucible – and from the whole media. The means of the points and of the volume are quite different. It comes from the computation of the angular velocity.

$$\omega = \frac{v_t}{r} \quad (5)$$

The crucible is a cylinder, so if the data is gathered from the radius, the weight of the values will be different than in the volume. Figure 11 shows the distribution of ω in a horizontal plane with 2M model. The average on the radius and on the plane will be different – and inaccurate in the case of line method. The fluctuations can be investigated well on the radius, but for comparing with the measurements in [1], the data has to be checked as the average of the full media. The distribution of ω is also shown on Figure 9 and Figure 10. Enormous values appear nearby the axis. The zero coordinate of X and Y is at the bottom of the crucible at the axis, so the generated custom field function gets high – dividing with the coordinate in the middle generates high values for the angular velocity. It can also be seen on the figures, that most of the melt has angular velocity close to the measured value, what is 38.83 rad/sec. Some fluctuation appears in case of the volumetric measurement too, but it is just about 1.5% - Figure 12.

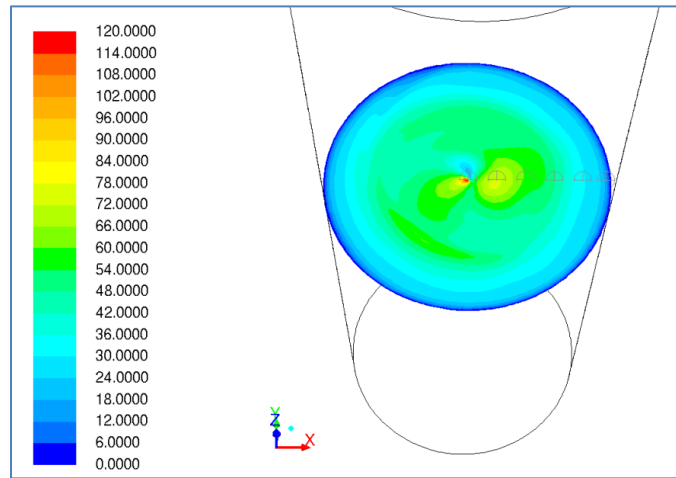


Figure 8. Contours of angular velocity on horizontal cut (h = 15) mm and the points of the measurement; fixed range – rad/s

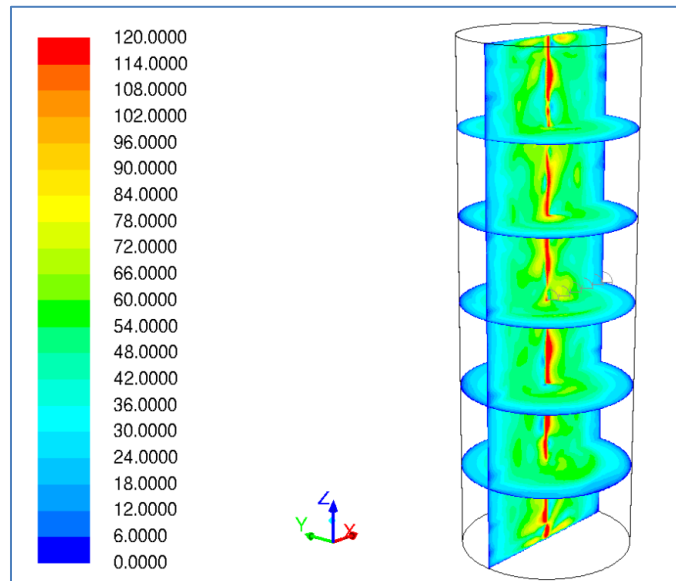


Figure 9. Contours of angular velocity on various planes in the media - fixed range – rad/s

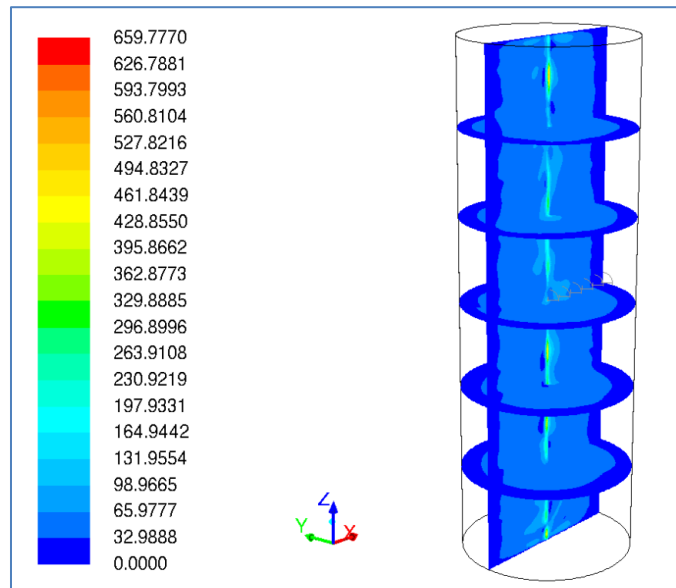


Figure 10. Contours of angular velocity on various planes in the media - auto range – rad/s

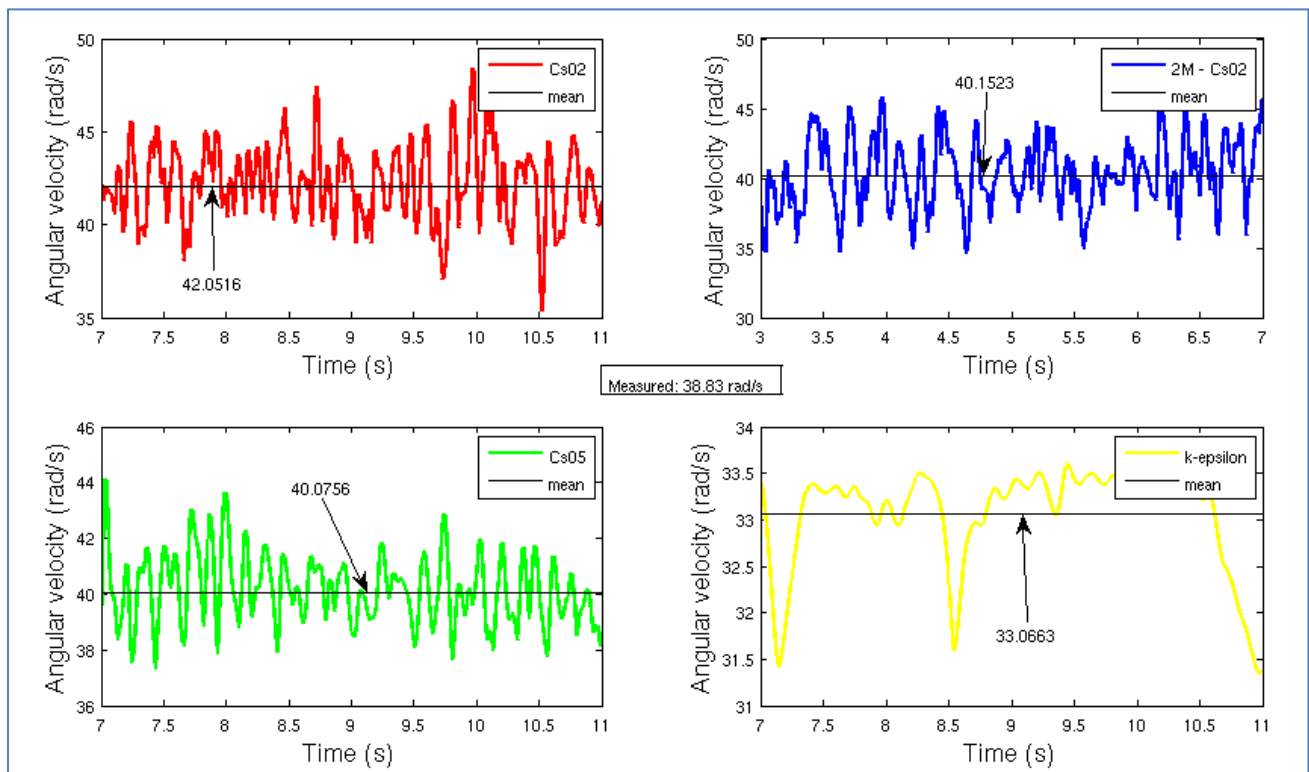


Figure 11. Angular velocity as a function of time for each LES and the EWT model – $h = 15$ mm – line method

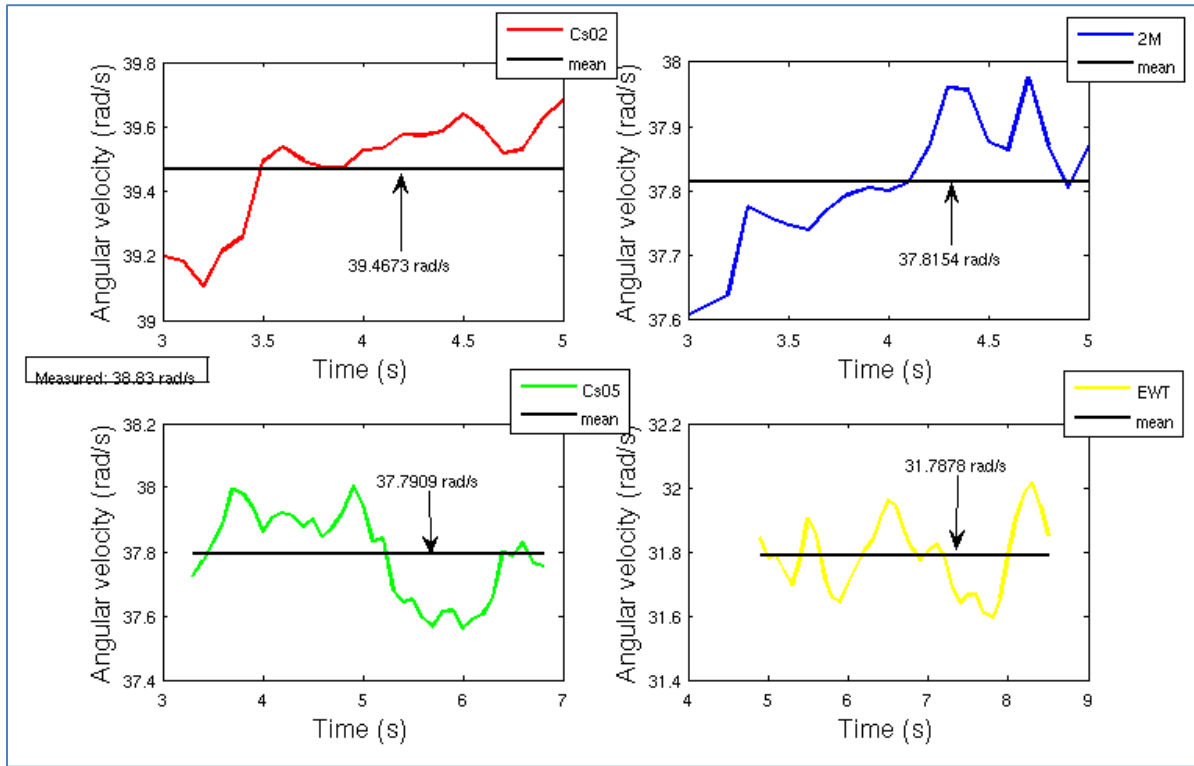


Figure 12. Angular velocity as a function of time - volumetric method

The relative errors of the models can be seen in Table 3. EWT shows bigger difference from the measurements, the LES models seem to be quite accurate.

Table 3. Relative error of the models - compared to measurements of [1]

	ω (rad/sec)	Relative error (%)
Measured	38,83	-
EWT	31,79	-18,14
Cs02	39,47	1,64
Cs05	37,79	-2,68
2M	37,82	-2,61

The contours of velocity magnitude can be seen on Figure 13 - Figure 16. for each model at the same time step, with fix range of the colormap. The flow patterns of the LES are more unequal, than the EWT's. The effects of the Reynolds averaging and the axisymmetrical case appear strongly. The velocity distribution is quite ordered with k- ϵ , while all of the LES results are less ordered. According to the patterns, more eddies appear in the volume of the melt – not just the near-wall region affected by turbulence. With LES, the contours change rapidly and the axis-close region is more and more disordered with lower Smagorinsky constant and finer mesh. The EWT has slower motion in the near wall region and straight contours in most of the volume. All the 4 cases have the value of average tangential velocity at about 0,085 m/s and ~80% of the volume has $v_t \sim 0,125$ m/s. The larger Smagorinsky constant don't give rise to the velocity of the small scale eddies. The Cs05 model has the maximum velocity of 0,1429, while in the Cs02 – with smaller Smagorinsky constant – 0,1656 m/s is

reached. This is the effect of the cut off frequency, what is smaller in Cs02 case, so lower scale eddies appear in the media. The mesh effect is similar to this. With finer mesh, finer resolution of the flow can be reached. The maximum of the velocity in 2M is 0.175 m/s – 5.68% higher than with same setup and coarse mesh. It is smaller difference than the 15.89% between the Cs02 and Cs05, but still not negligible. The data also can be seen in Table 4.

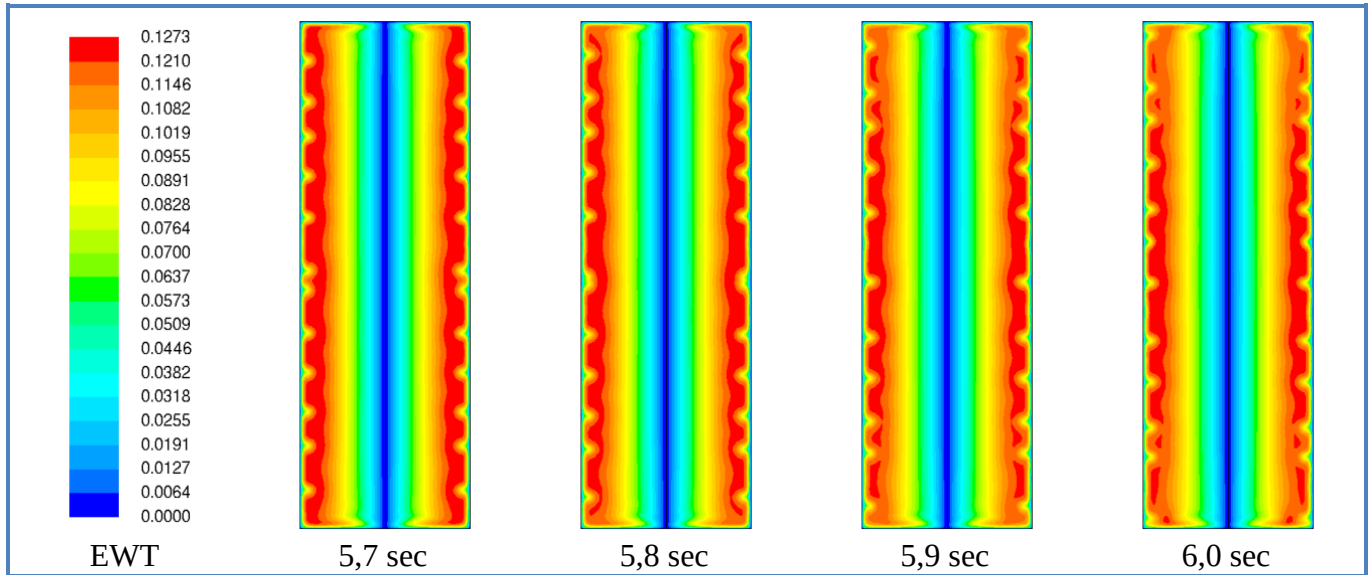


Figure 13. Contours of tangential velocity - 5.7-6.0 sec flow time – EWT – colormap is in m/s

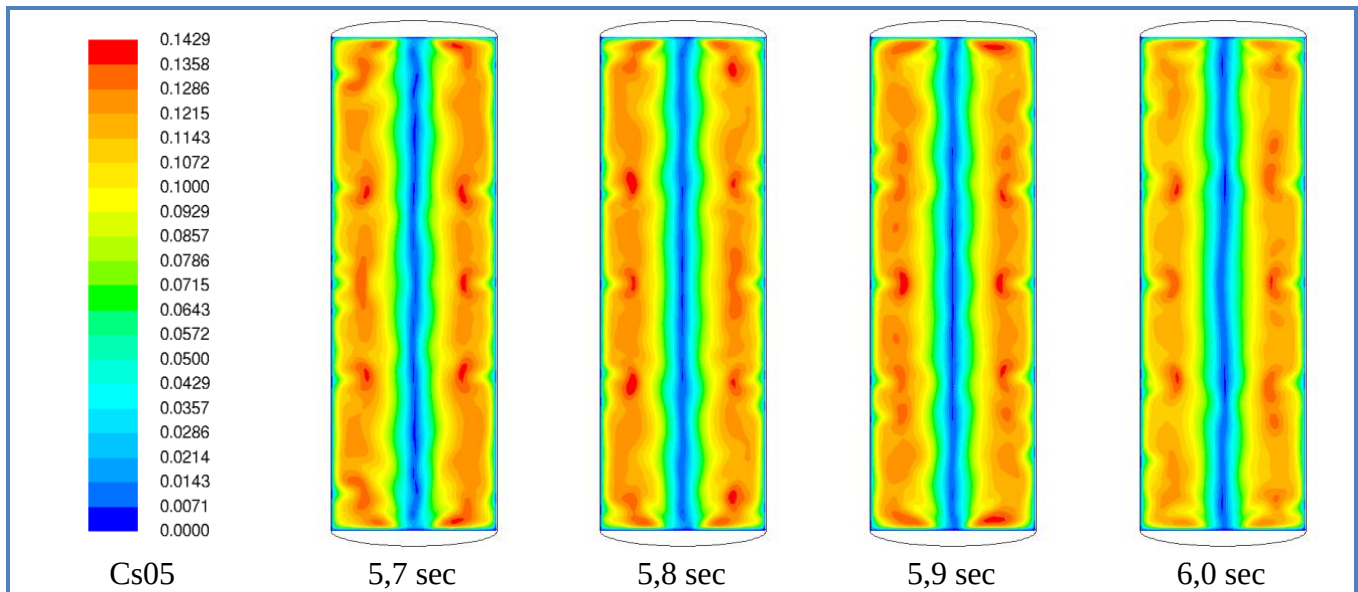


Figure 14. Contours of tangential velocity - 5.7-6.0 sec flow time – Cs05 – colormap is in m/s

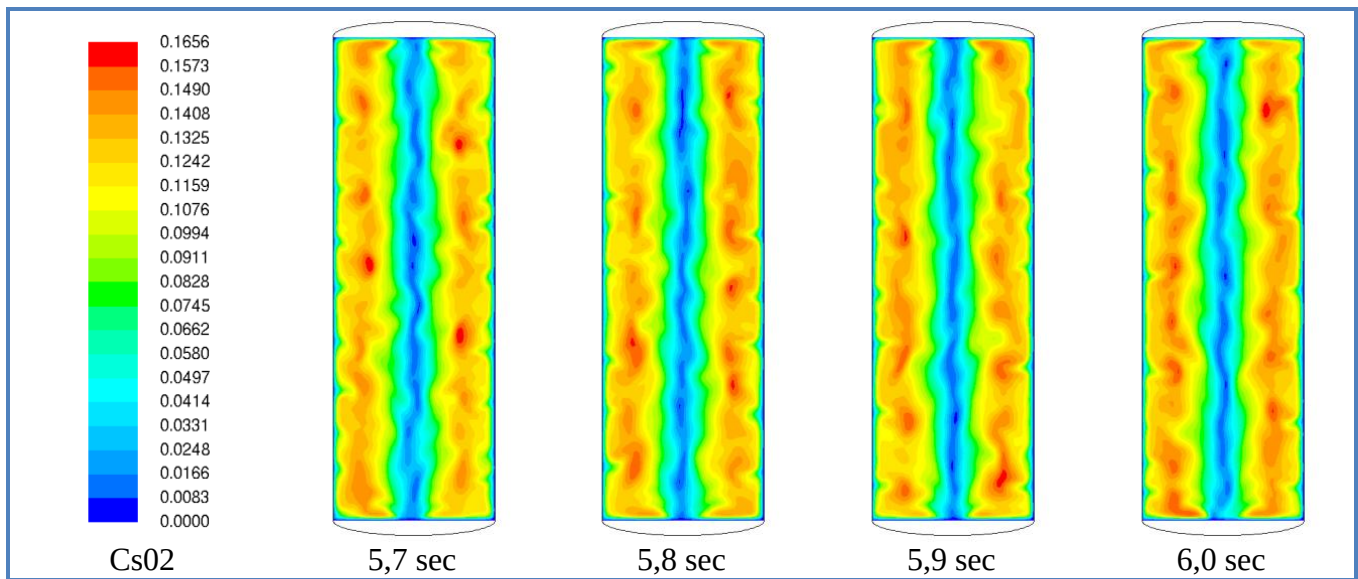


Figure 15. Contours of tangential velocity - 5.7-6.0 sec flow time – Cs02 – colormap is in m/s

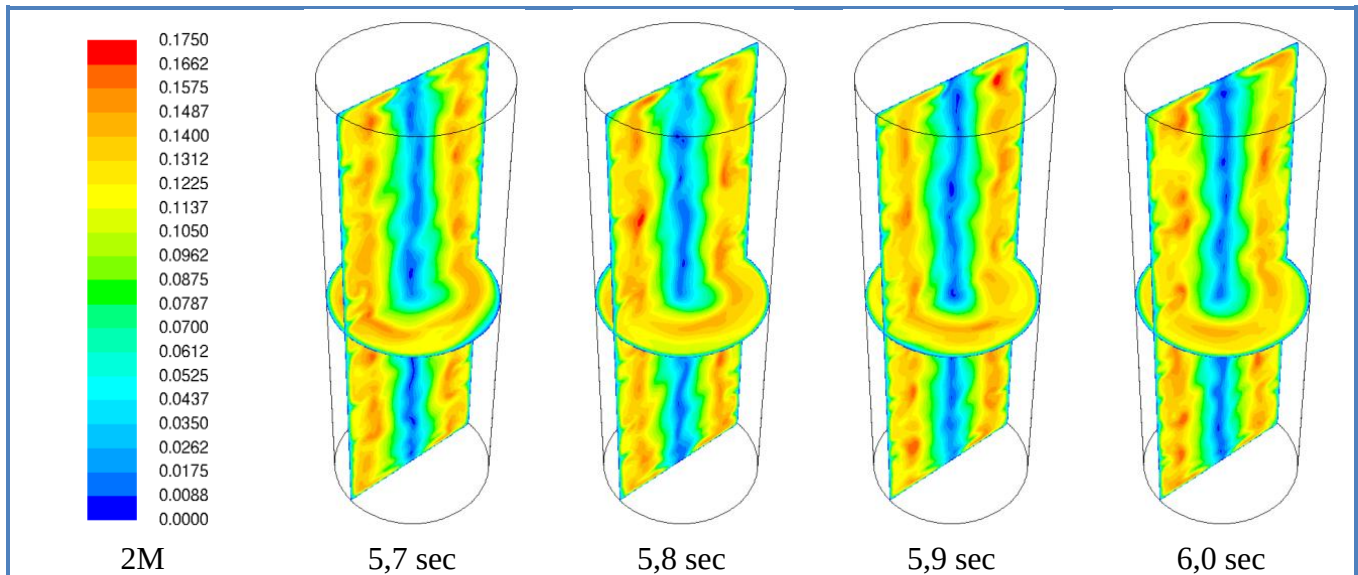


Figure 16. Contours of tangential velocity - 5.7-6.0 sec flow time – 2M – colormap is in m/s

Table 4. Maximum velocities in the media and differences between the models

Moedel	Max velocity (m/s)	Diff. from Cs05 (%)	Diff from Cs02 (%)
Cs05	0.1429	-	-
Cs02	0.1656	15.89	-
2M	0.1750	22.46	5.68

The ordered flow pattern of k- ϵ appears on the radial velocity distribution too; but there's no major difference between each LES model – see Figure 17 (the thick black line shows the average distribution and the red shows the mean value).

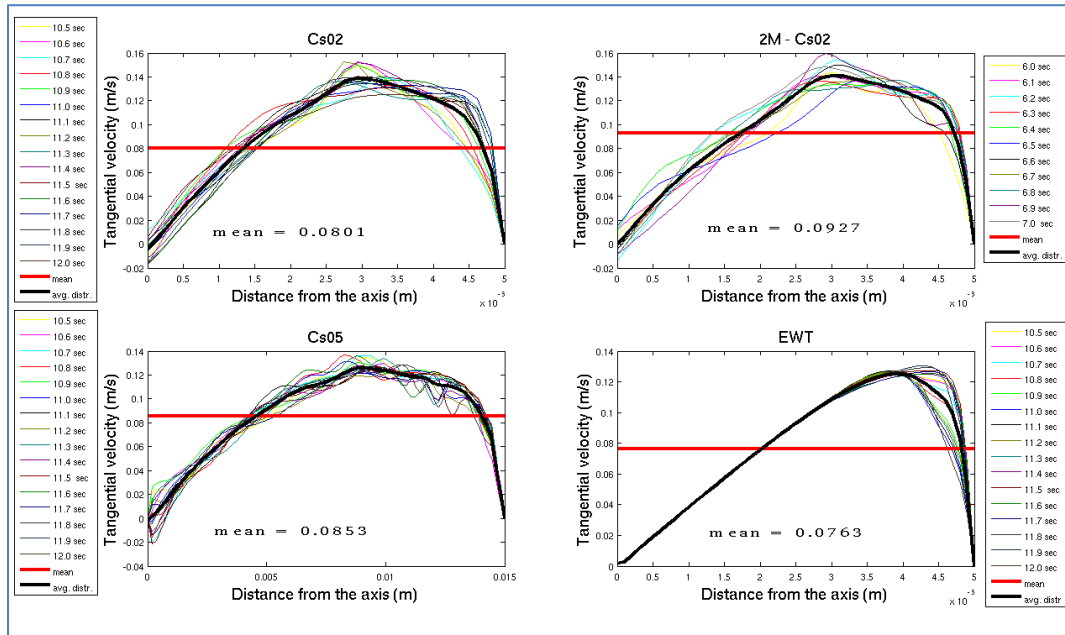


Figure 17. Distribution of tangential velocity along the radius at various time steps – $h = 15 \text{ mm}$

Axial velocities

Two pairs of cases can be separated by axial velocity – Cs05+EWT and Cs02+2M (the two models with the value of 0.2 of Smagorinsky constant). It can be done by looking at the velocity values on Figure 18. The order of magnitude is the same in EWT&Cs05 and also the same in the case of the Cs02 and 2M models. The 2M version has more and bigger fluctuations, but the mean flow is similar. The $k-\epsilon$ model has much less fluctuation – like in the tangential component.

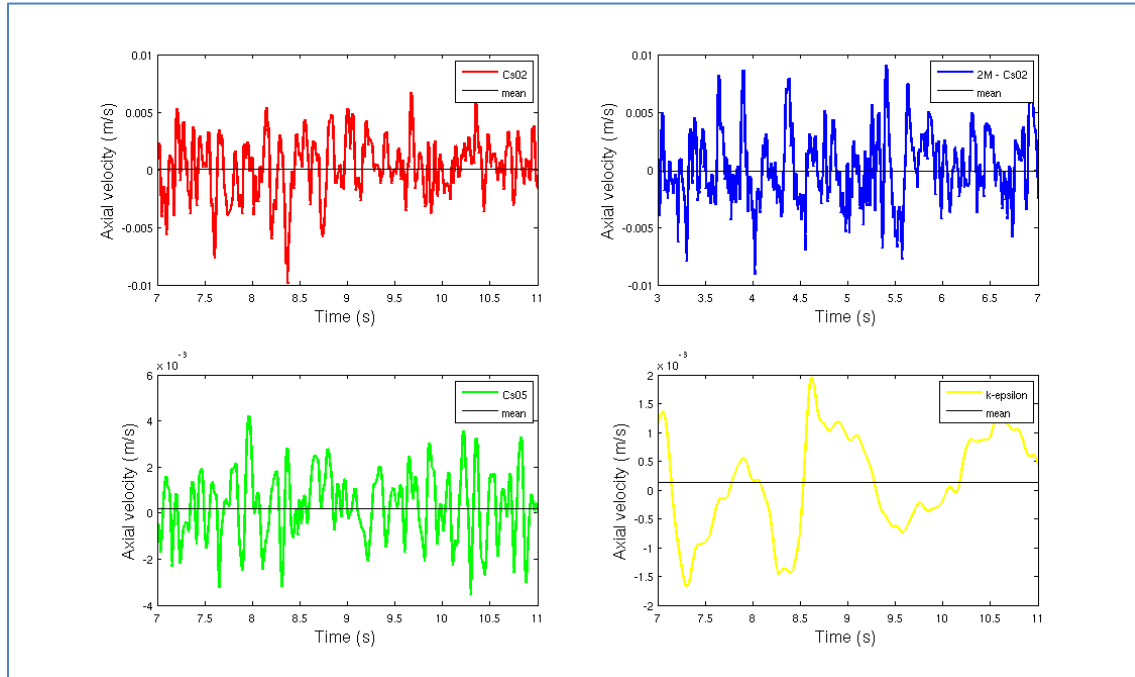


Figure 18. Average axial velocity on the radius as a function of time for each LES and the EWT model – $h = 15 \text{ mm}$

The contours of axial velocity prove, what is expected from Figure 18. The k- ϵ model (Figure 19.) is quite ordered. The Cs05 (Figure 20.) has a contour like it is a transition between k- ϵ and more accurate LES models. Cs05 still has 4 different levels of secondary pump effect – like EWT, what has 2 – but it is a less ordered flow. The four-level-effect should be also a numerical error of the model, because the models were made with parallel FLUENT with 4 processes. The contour of Cs02 and 2M are similar – see Figure 21 and Figure 22.

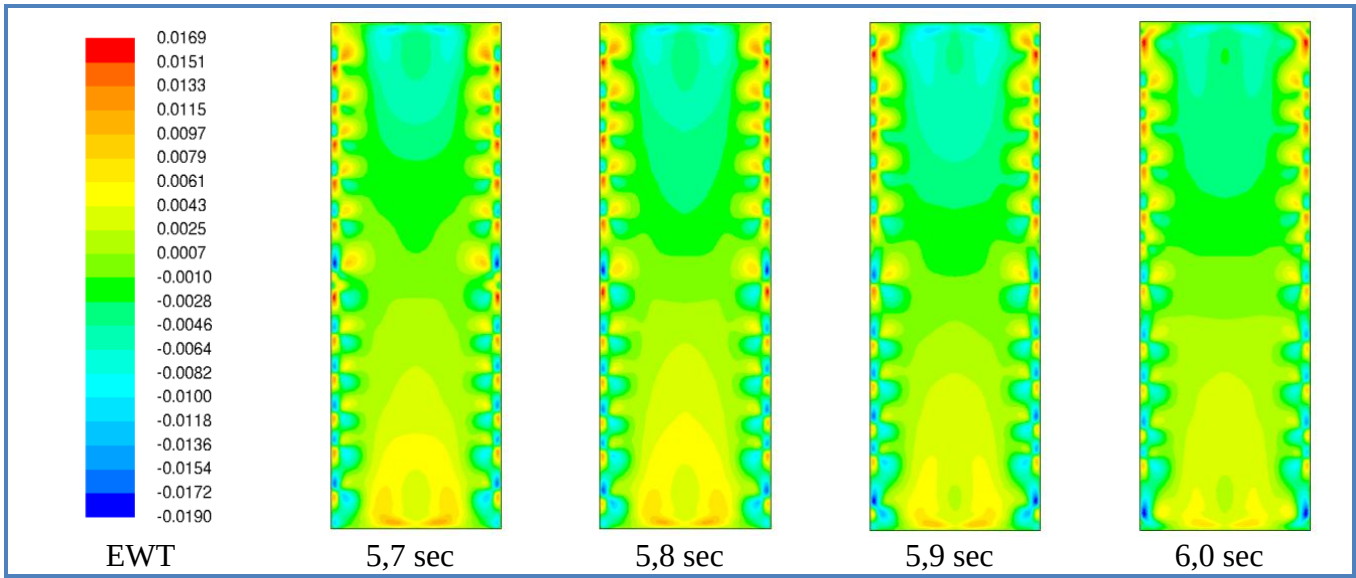


Figure 19. Axial velocity pattern - EWT - 5.7-6.0 sec – colormap is in m/s

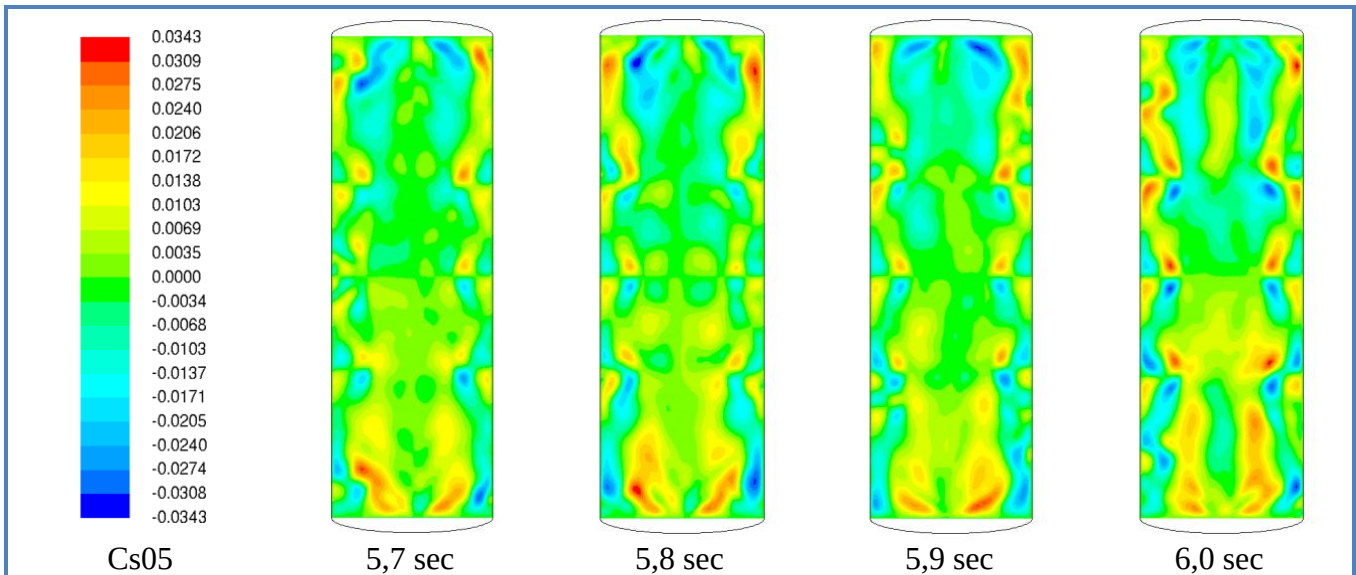


Figure 20. Axial velocity pattern - Cs05 - 5.7-6.0 sec – colormap is in m/s

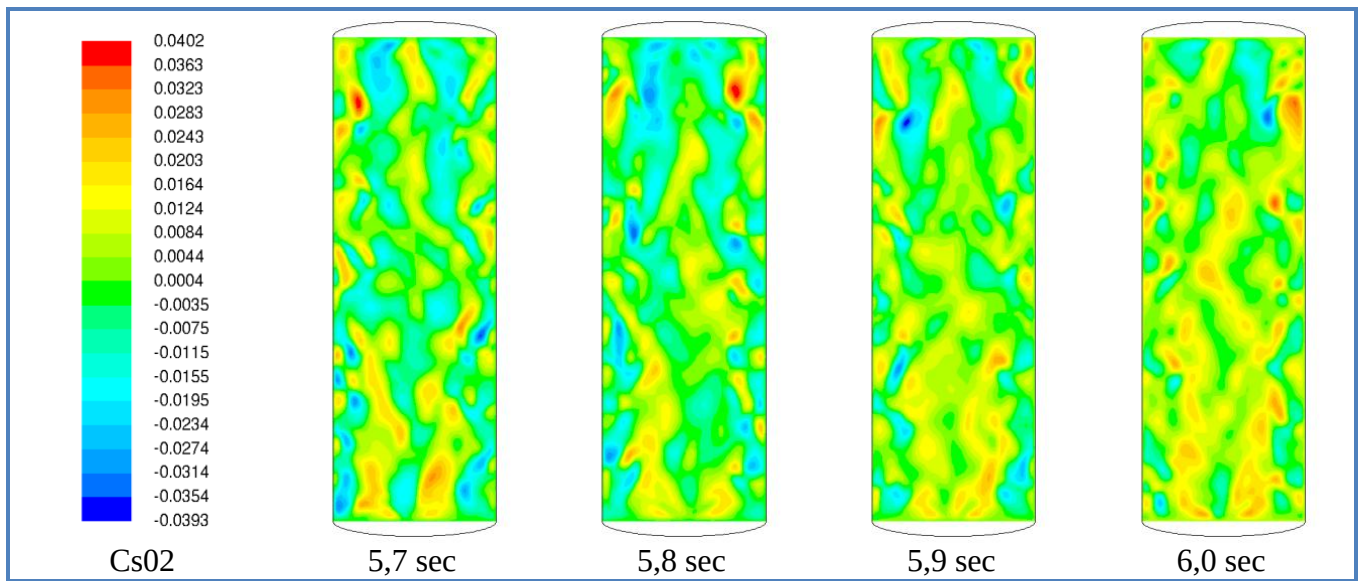


Figure 21. Axial velocity pattern - CsO₂ - 5.7-6.0 sec – colormap is in m/s

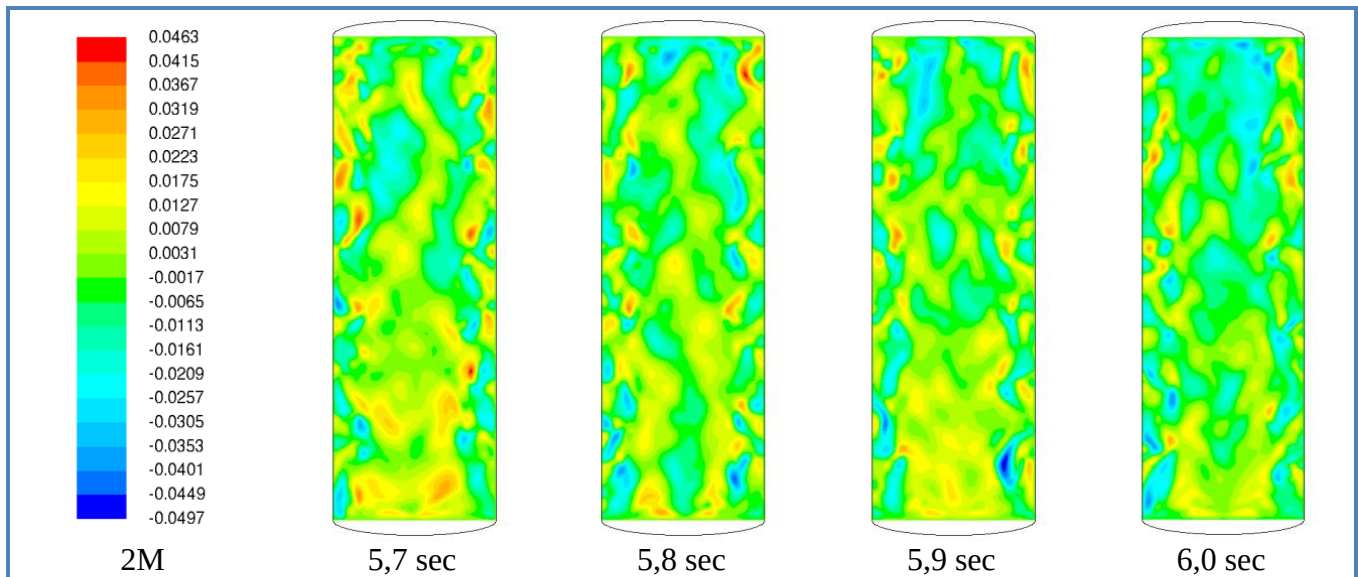


Figure 22. Axial velocity pattern - 2M - 5.7-6.0 sec – colormap is in m/s

The radial distributions are similar with LES models, but k- ϵ seems to be ordered again – Figure 23 (the thick black line shows the average distribution and the red shows the mean value). Mostly the near wall region is fluctuating. Remember, that the main flow also showed the same effect. No major rules can be found in the fluctuation of the velocities with LES.

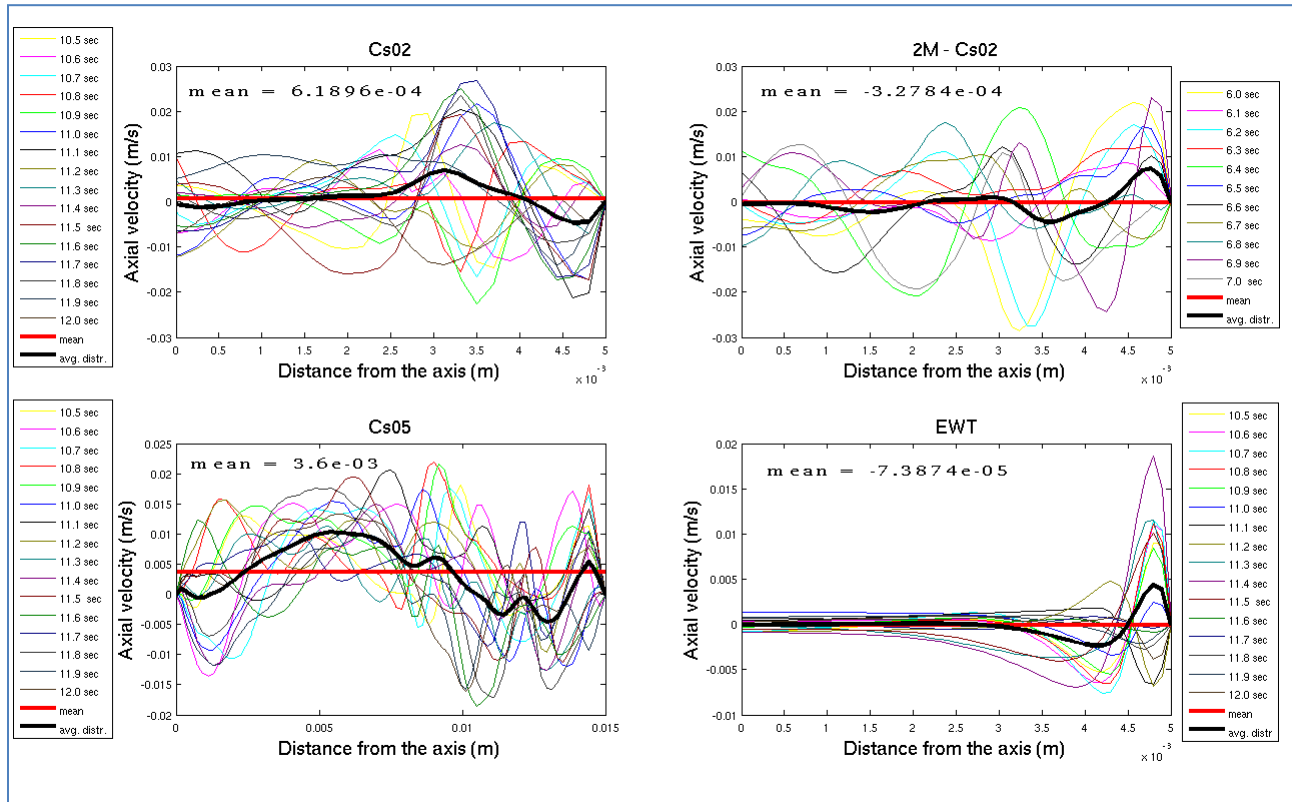


Figure 23. Axial velocity along the radius at various time steps – $h = 15$ mm

Basically the pump effect of Zimmermann [3] appears with all of the models, but the turbulence in LES affects it very much. The levels of the pump effects with different directions also visible in the patterns but this phenomenon should be investigated with a higher crucible in the FLUENT, just like the parallel processing's effect – Figure 20.

Radial velocities

The fluctuations are similar in all the LES cases and ordered with $k-\epsilon$ – Figure 24. I have made pairs of models in the last chapter. The case is the same if we look at the flow patterns and the radial distribution of the velocities – Figure 25 to Figure 29. Cs05 is the “transition-model” again. The flow pattern and the radial distribution is close to all of the models – see Figure 29 (the thick black line shows the average distribution and the red shows the mean value). The near-wall effect appears in all models – as expected. The distribution in Cs02 and 2M is absolutely random. 2M model has slightly better resolution, but no major mesh effect is visible in case of radial velocity.

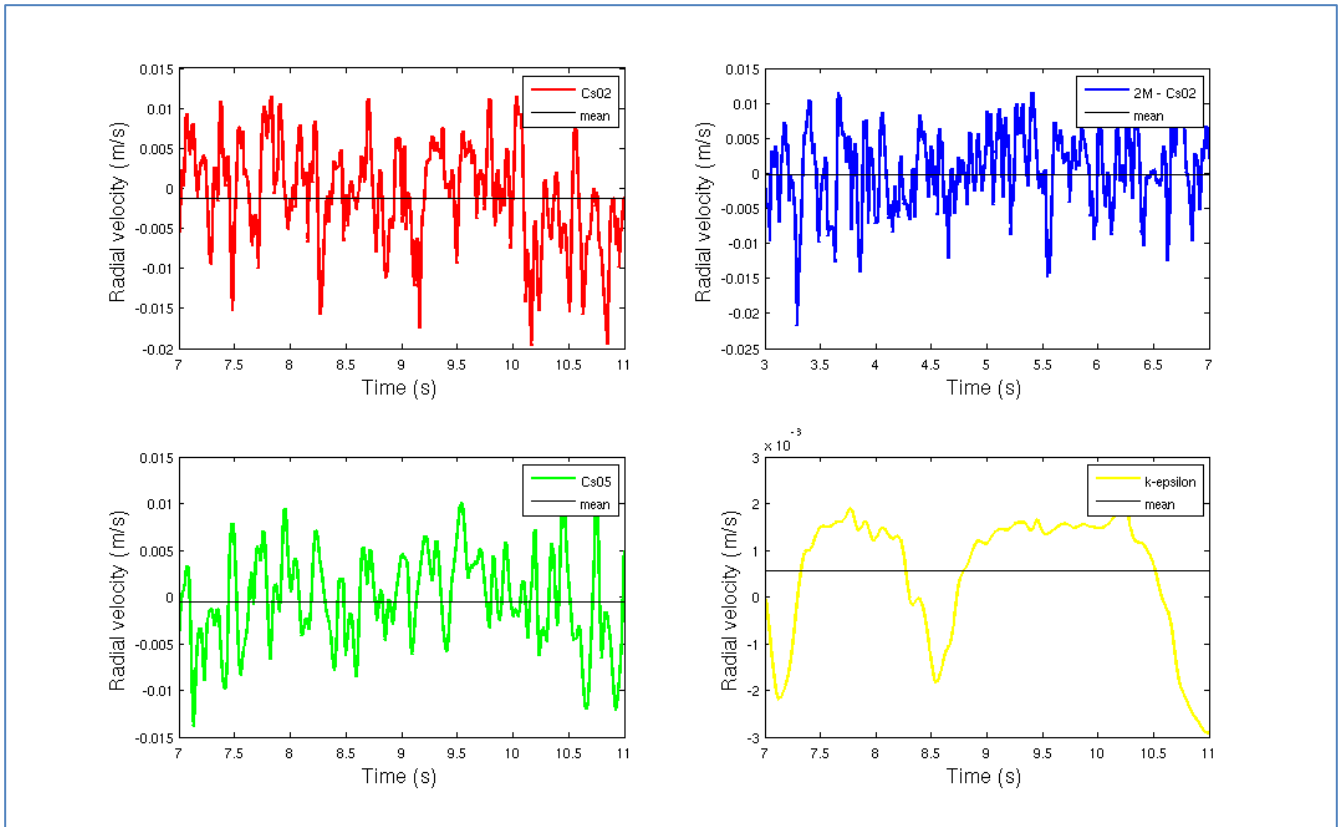


Figure 24. Average radial velocities on the radius as a function of time for each LES and the EWT model - $h = 15$ mm

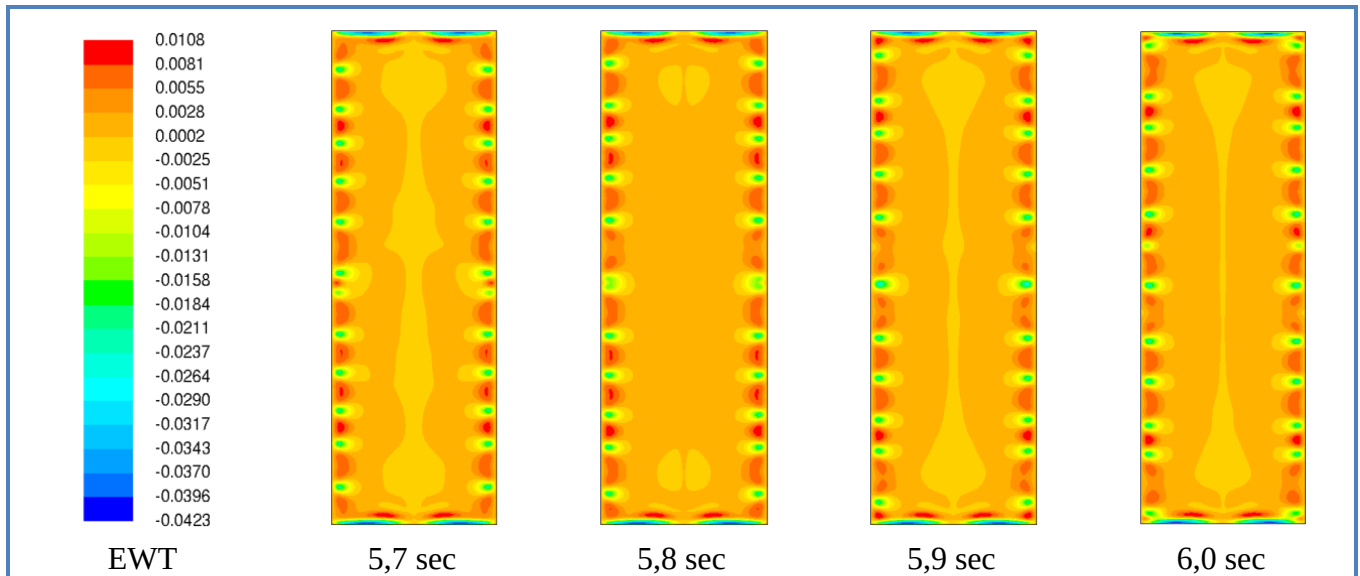


Figure 25. Radial velocity pattern - EWT - 5.7-6.0 sec – colormap is in m/s

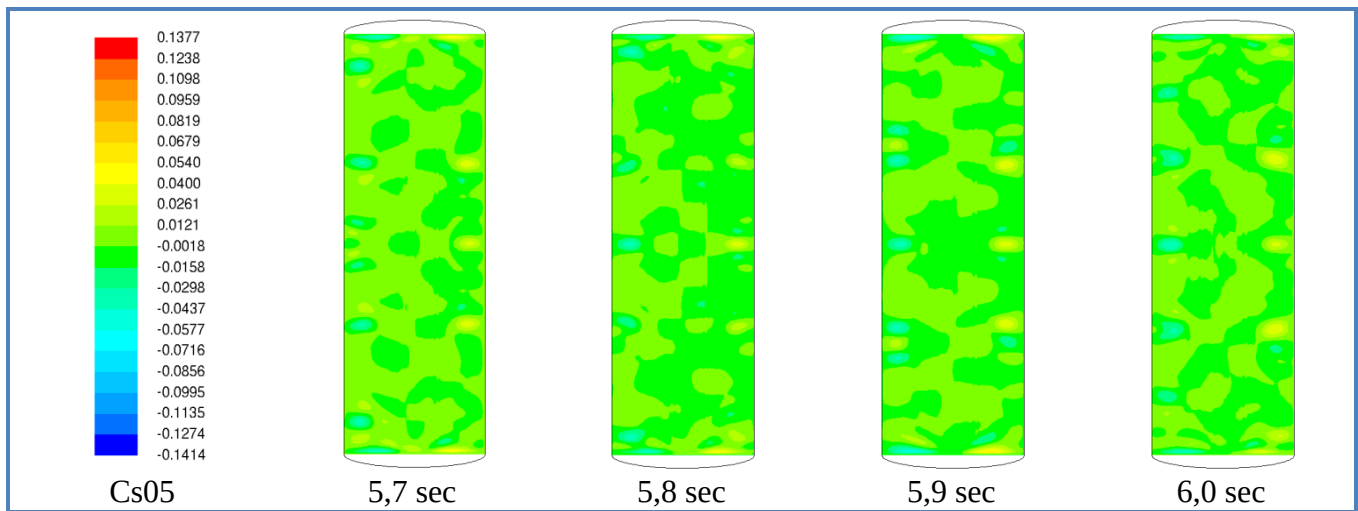


Figure 26. Radial velocity pattern - Cs05 - 5.7-6.0 sec – colormap is in m/s

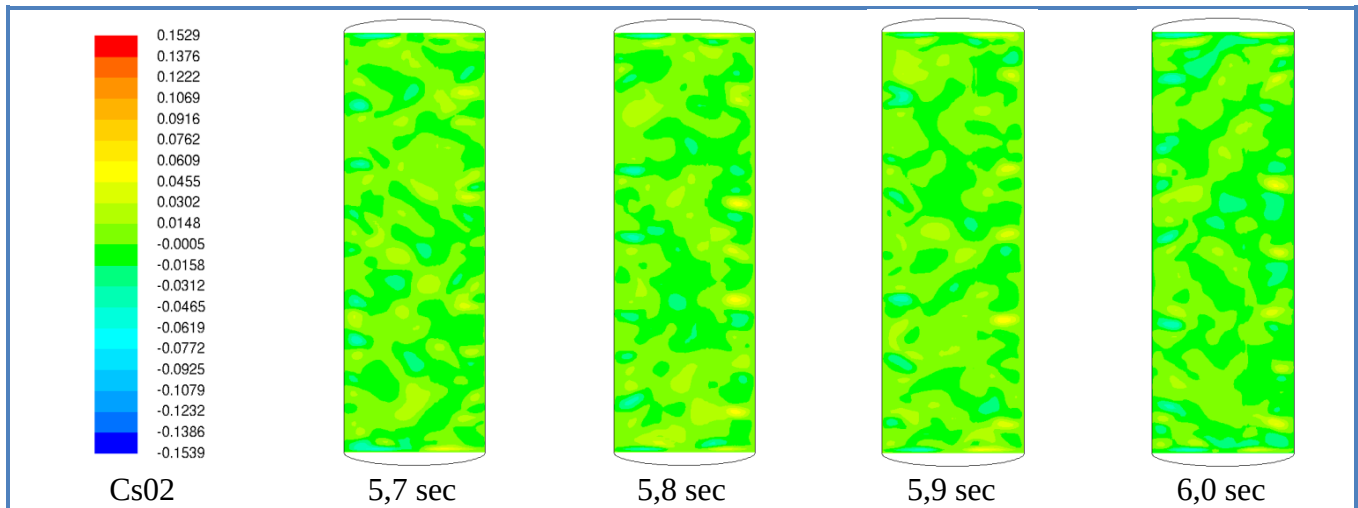


Figure 27. Radial velocity pattern - Cs02 - 5.7-6.0 sec3 – colormap is in m/s

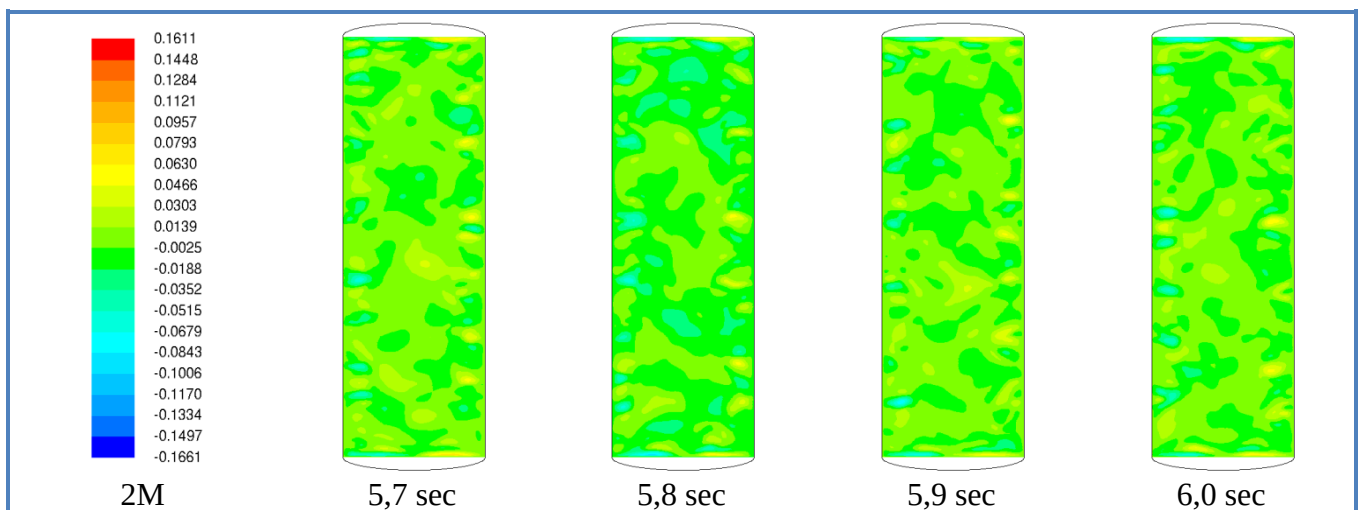


Figure 28. Radial velocity pattern - 2M - 5.7-6.0 sec – colormap is in m/s

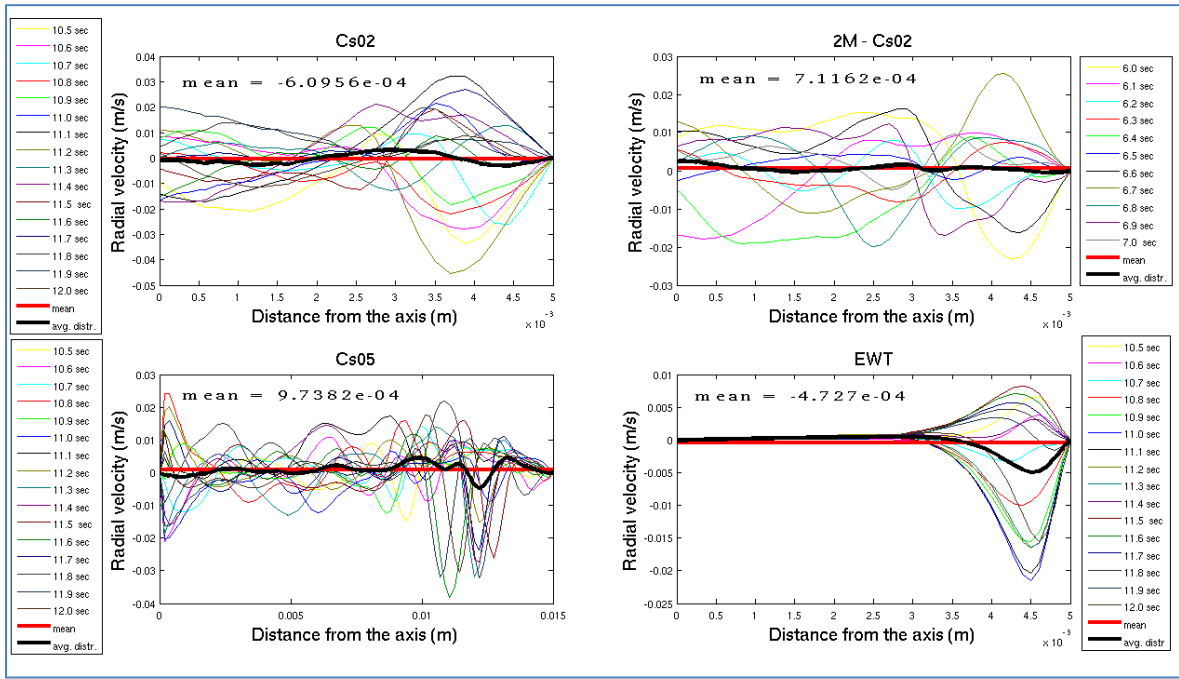


Figure 29. Radial velocity along the radius at various time steps for all models - $h = 15$ mm

Turbulent kinetic energy

The fluctuation of turbulent kinetic energy is visible on Figure 30. The range is ~ 3.5 times smaller with $k-\varepsilon$. Cs05 show smaller mean energy, than Cs02 and 2M – see thick black lines. This is also the effect of the higher Smagorinsky constant – the more small scale eddies provide more turbulent kinetic energy. No major difference appears between Cs02 and 2M.

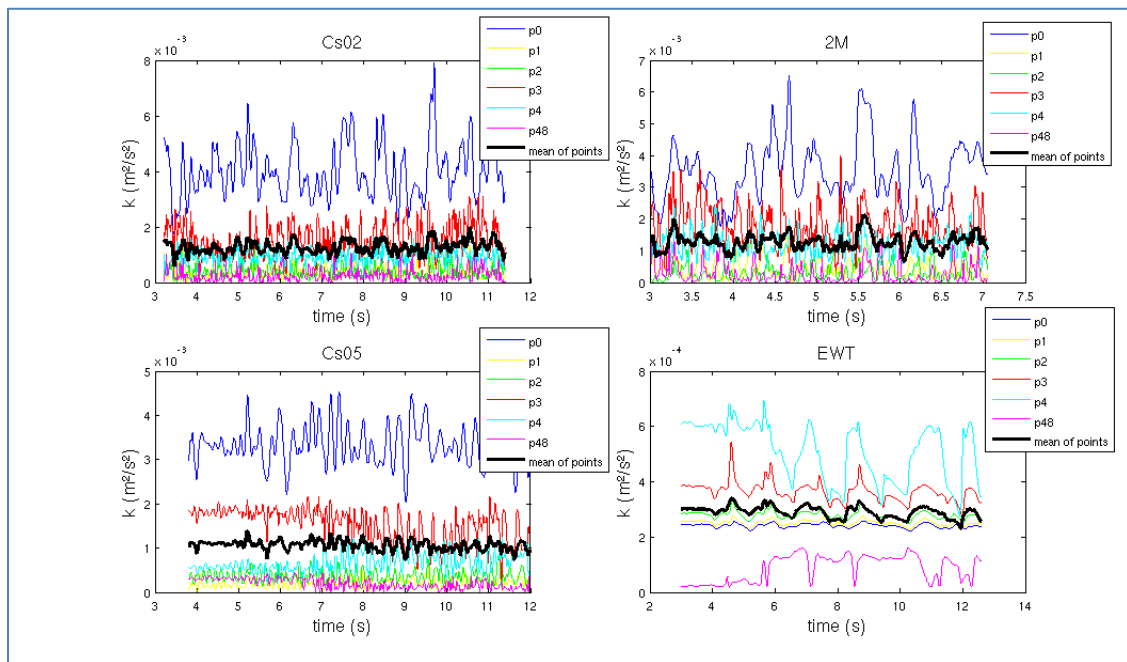


Figure 30. Turbulent kinetic energy as a function of time for all models (data gathered from 6 points across the radius on $h = 15$ mm)

The models seem to be similar; however the distribution of k is different with EWT and LES. It is noticeable on Figure 30, but for better comparison the distribution of the **mean k** – mean by time – on the radius is shown on Figure 31. The maximum appears at 4 mm with EWT. With all LES models, higher values appear at 3 mm and the maximum is at the axis.

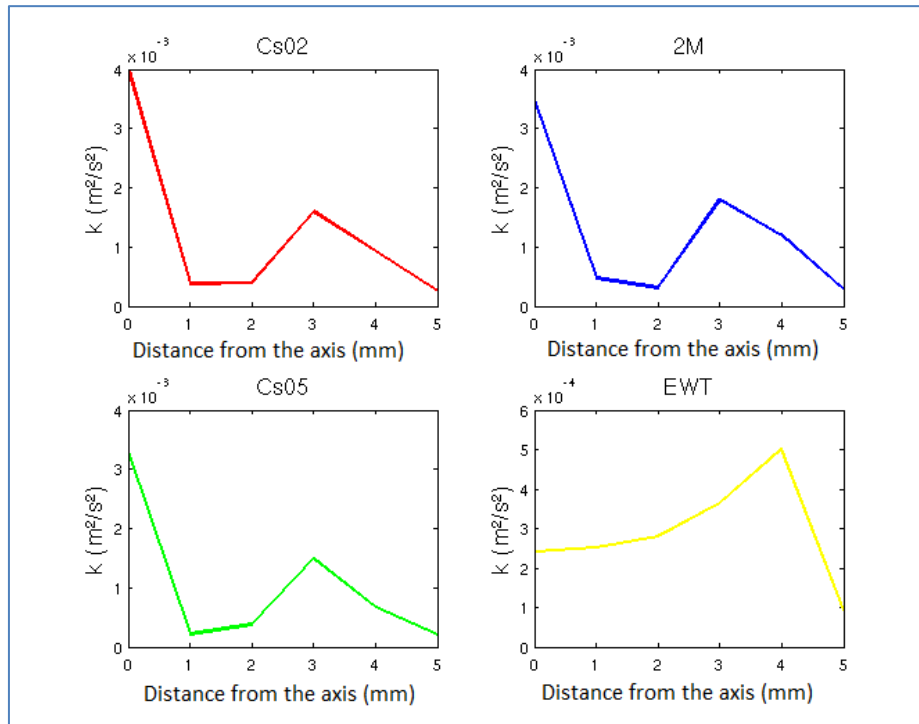


Figure 31. Distribution of the mean turbulent kinetic energy along the radius – m^2/s^2

Remember the tangential velocity distribution in EWT. Until about $r = 3$ mm, the flow is mostly laminar. With LES, no purely laminar zone can be found and both near-wall and near-axis regions are affected by turbulence. The secondary flow of the EWT and the 2M is shown on Figure 32. Major differences appear. 2M has eddies at various part of the media, but EWT has just some near the wall.

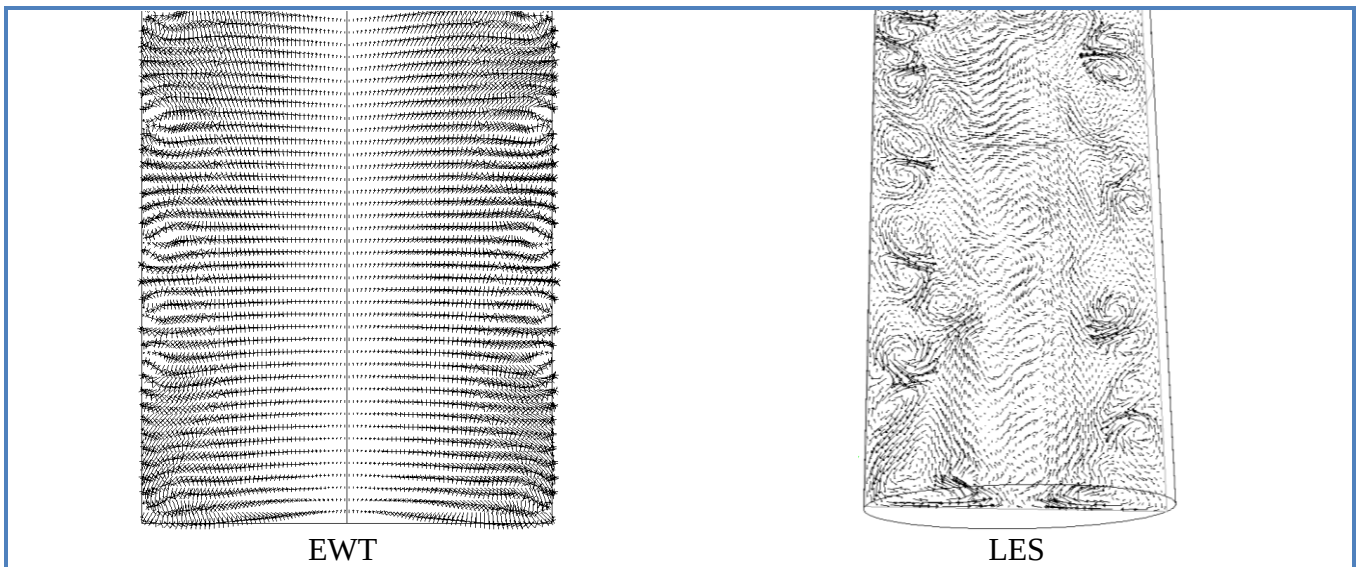


Figure 32. Secondary flows inside the melt

Comparing LES models with the Kolmogorov theory and comparing ε

The Fourier energy spectrum was computed for all LES models - Figure 33. The Cs05 decays much earlier, than the two low-constant models. The effect of the cell size also appears. The mesh density can be understood as a passive-filtering. Better flow resolution can be reached with lower cell volume, so the spectrum decays at a higher frequency.

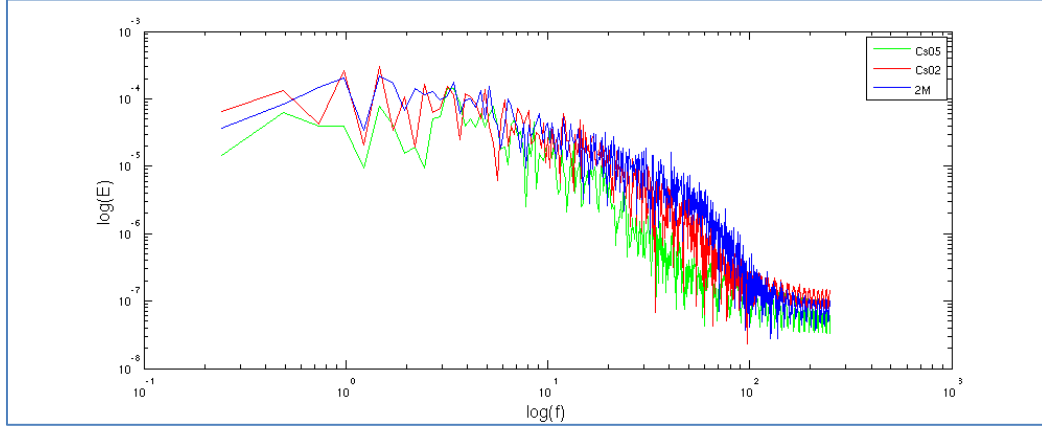


Figure 33. Turbulent frequency energy spectrum of the 3 LES models

The inertial zone was determined for the model, which has the less filtering – 2M. It can be done by the Kolmogorov theory. It says that the function of frequency spectrum in the inertial zone is

$$E = f^{-5/3} \quad (6)$$

and the models spectrum is following the “Kolmogorov line”. It is expedient to use logarithmic scale – see Figure 34. The zone is between about 9 and 30 Hz.

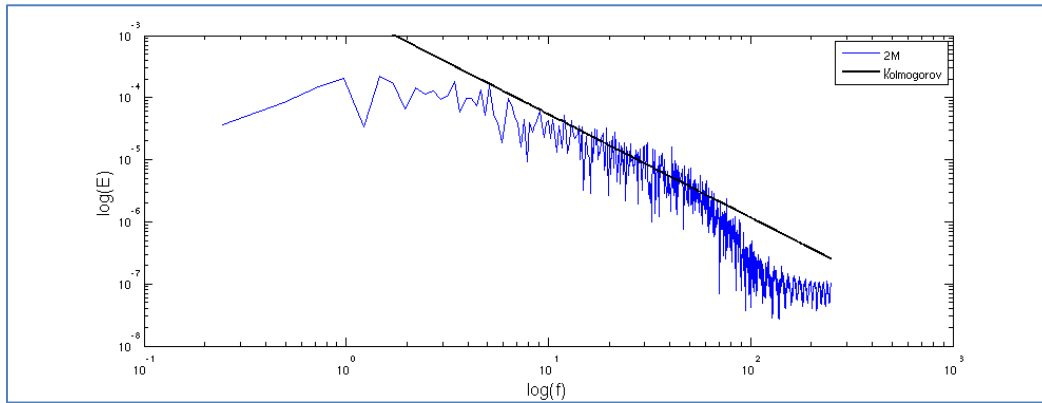


Figure 34. Turbulence frequency energy spectrum of 2M and the “Kolmogorov line”

For further investigation, the compensated spectrum was made also, by the means of Kolmogorov theory. Here, the original frequency spectrum is converted into a wave-number spectrum by the laws of Taylor hypothesis:

$$\eta = 2\pi/v_{av} f \quad (7)$$

From this the original wave-number spectrum is generated – $E(\eta)$. The compensated spectrum is:

$$\varepsilon^{-2/3} \eta^{5/3} E(\eta) \quad (8)$$

Where ε can be calculated from the following integral:

$$\varepsilon = 2\nu \int_0^{+\infty} \eta^2 E(\eta) d\eta \quad (9)$$

Or from the velocity and the characteristic wave-length:

$$\varepsilon = u'^3 / \lambda \quad (10)$$

Solving the integral is a very difficult task and in our case not very important, so equation 10 was used for determining ε . The characteristic wave-length is computed from the characteristic wave-number (which can be approximated from Figure 34) as the following equation:

$$\lambda = 2\pi / \eta \quad (11)$$

The turbulent dissipation rate is at about $0,101 \text{ m}^2/\text{s}^3$, 50x higher than with the EWT model, which has the average of $0,002 \text{ m}^2/\text{s}^3$. The original and the compensated wave-number spectrum can be seen on Figure 35. The compensated spectrum has a wide range over the line of Kolmogorov constant, so the model has a wide inertial range [2]. This wide inertial range comes from the low cut off frequency and the higher density mesh, which seems to be fine enough to finely resolve the flow. The wave-number linked to the mesh size is at about $5.7 \cdot 10^4$, so it is far away from the cut off frequency. With the geometry of Cs02 and Cs05, the linked wave-number is $\sim 3.4 \cdot 10^4$. It is still far from the cut off.

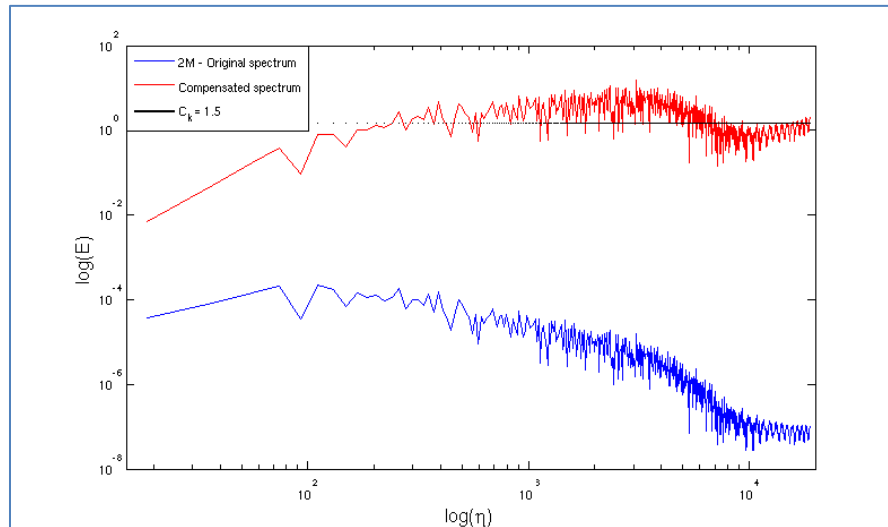


Figure 35. The compensated and the original spectrum, and the Kolmogorov constant

Regarding the results, the LES models seem to be fairly accurate with the mean flow – see Table 3 – and the lower scales should be well resolved. Other induction values, crucible sizes should be investigated to get enough information about this type of flow. Also should be good to research the induction value, which is at the border of laminar and not truly laminar flow.

The epsilon values of EWT in the points across the radius and the Kolmogorov length scale can be seen on Figure 36. The average value of epsilon is 50 times smaller, than with 2M ($0,101 \text{ m}^2/\text{s}^3$). The length scale of EWT is between 0,005-0,024 m. With Large Eddy Simulation it is between 0,002-0,0091 m, so the model can provide better flow resolution with nearly the same mesh size, than EWT – mesh size of LES is $110 \text{ }\mu\text{m}$, in case of EWT it is $100 \text{ }\mu\text{m}$.

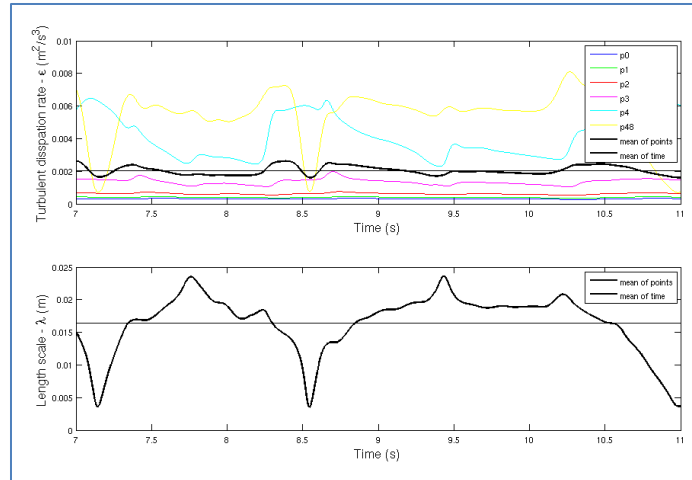


Figure 36. Turbulent dissipation rate and Kolmogorov length scale as a function of time with k-ε model

The Kolmogorov theory is applicable mostly for isotropic turbulence. To check the anisotropy/isotropy of our model, see Figure 37 and Table 5. The diagram shows the velocity fluctuations for each component as a function of time. If the turbulence is isotropic, the fluctuations of the components are similar at each time step. In our case it seems to be a bit anisotropic, mostly with the radial component. However the average values are not too different, so the theory is adaptable.

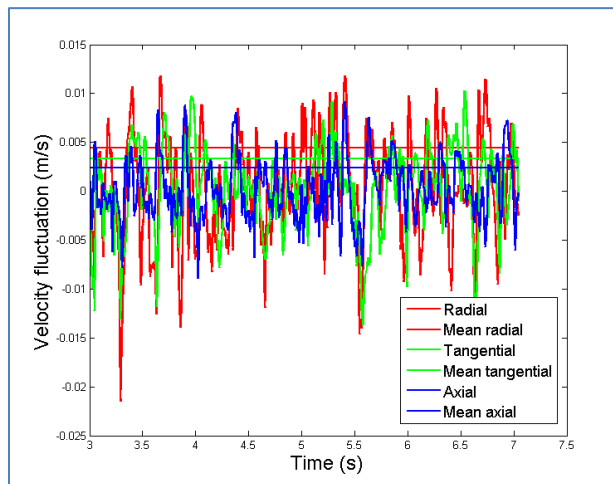


Figure 37. Velocity fluctuations for each component as a function of time

Table 5. Mean velocity fluctuations

Velocity component	Fluctuation (m/s)
Axial	0,0024
Radial	0,0044
Tangential	0,0033

LES model with higher induction

A model was made with higher induction to see the effects on the flow. The setup was same as the 2M, but with $B = 57,4 \text{ mT}$ induction. With stronger magnetic field, stronger Lorentz force is induced, so the melt rotates faster and the flow settles earlier. With 22,6 mT the flow needs ~ 3 seconds to develop, with 57,4 mT, it is just 1-1,5 seconds.

The flow pattern doesn't change compared to the lower induction models, just the values different - Figure 38. The mean tangential velocity is $\sim 0,245 \text{ m/s}$ but 0.48 m/s can appear. The induction is 2,5x bigger and the velocity values are also 2,5-3x higher with all the components. The fluctuations are also the same as in 2M – Figure 39.

The accuracy of the model was checked with comparison to the measurements in [1], like it was done with the other models. The fluctuations on the radius are 4 times bigger, than with 2M, but with volume method no major difference appears. The values has the maximum of $0,4 \text{ rad/sec}$ difference, but at about 109 rad/sec angular velocity it can be neglected. The error of the model is shown in Table 6.

Table 6. Relative error of the 57mT model

	ω (rad/sec)	Relative error (%)
Measurement	106,50	-
57mT	109,71	3,01

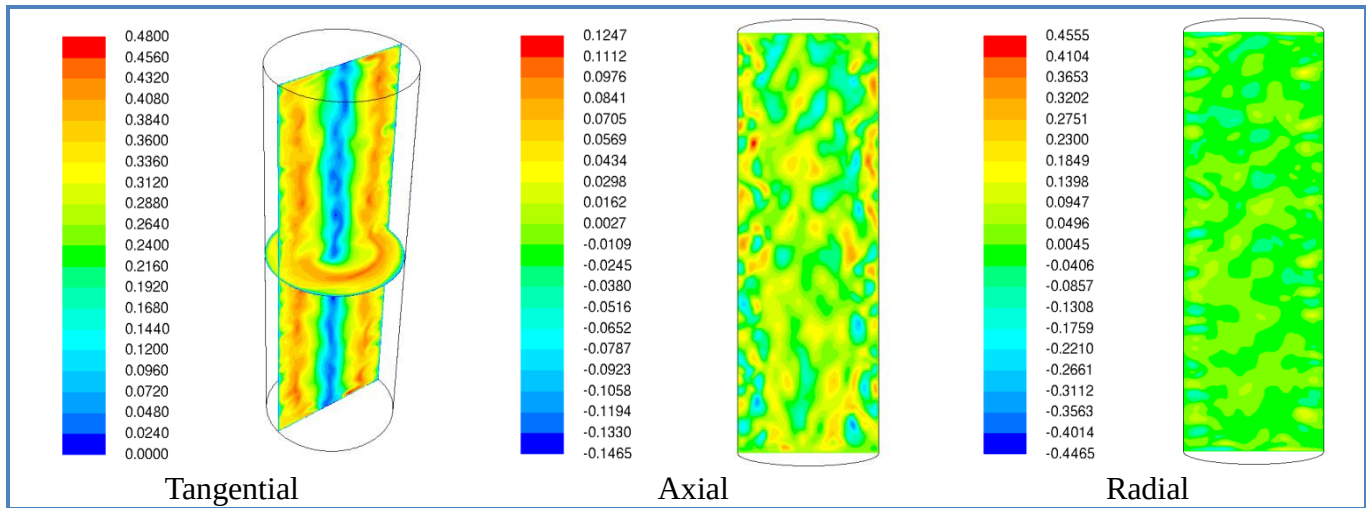


Figure 38. Contours of velocity components - 57mT – colormap is in m/s

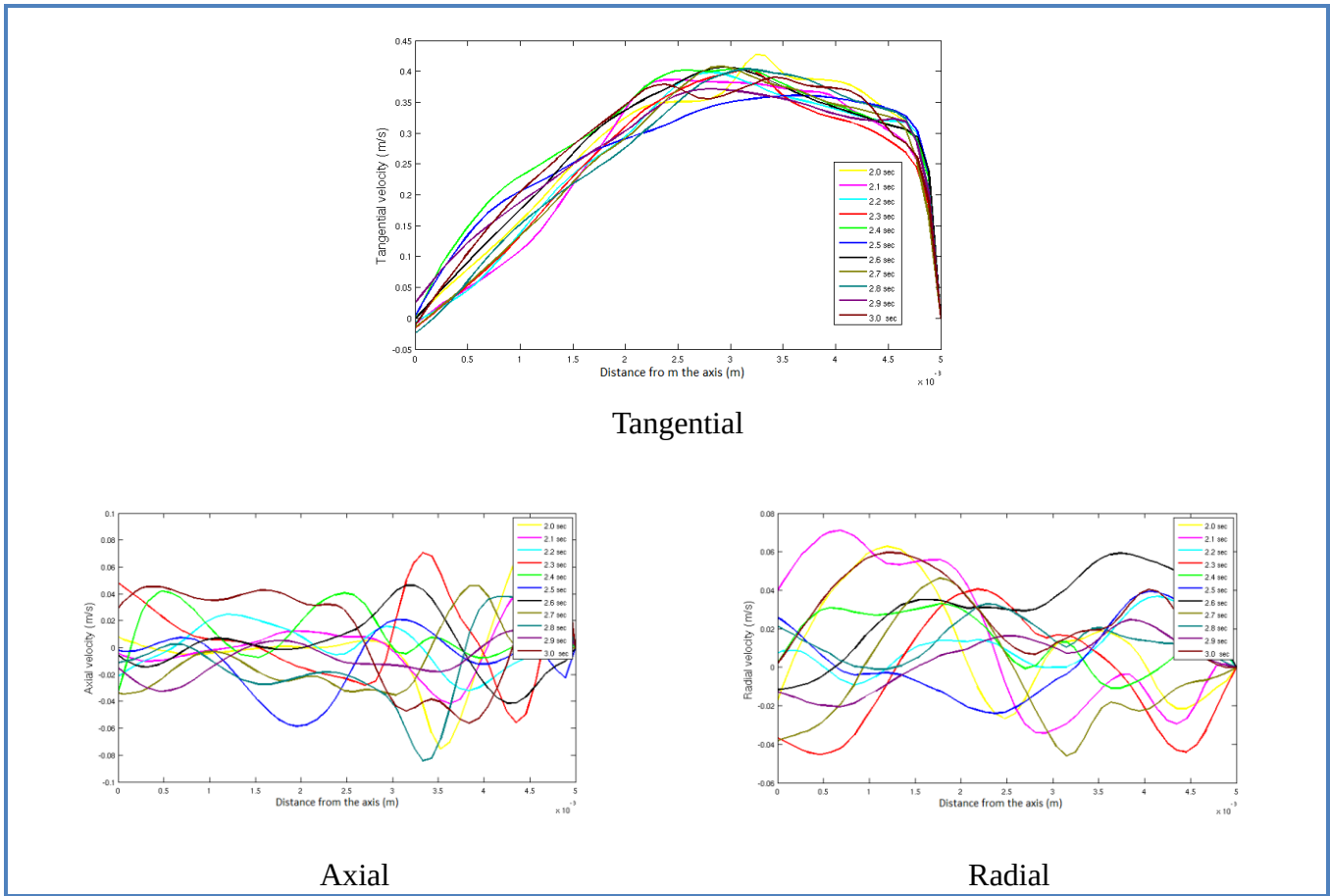


Figure 39. Velocity distributions along the radius at various time steps - $h = 15$ mm

Figure 40 shows the angular velocity, the turbulent kinetic energy as functions of time. The turbulent kinetic energy is 10 times higher than in the case of 2M.

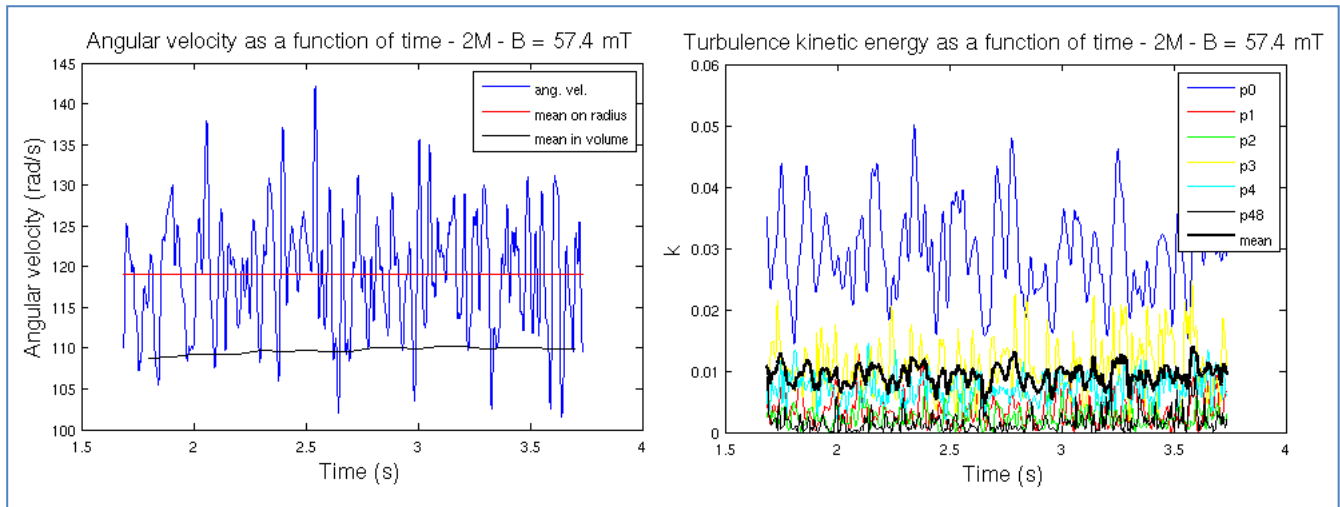


Figure 40. Angular velocity and turbulent kinetic energy as functions of time - 57mT

The Fourier frequency energy spectrum, the wave-number spectrum and the compensated spectrum was also made for this model – see Figure 41. The model has a much narrower inertial range than the 2M – the compensated spectrum doesn't reach the Kolmogorov constant line and also on the left

diagram, the Kolmogorov line is followed on a very narrow scale. The inertial range is between about 954 and 2546 1/m. For 2M (22,6 mT) it is between~690-3100 1/m. Much more turbulent energy is contained in the media with higher induction – see left diagram on Figure 41 – the energy containing part of the flow is before the inertial range on the spectrum [4]. The turbulent dissipation rate (ϵ) is 3,69 m^2/s^3 – 37 times more than the lower induction model. It is expected, because of the high turbulent energies.

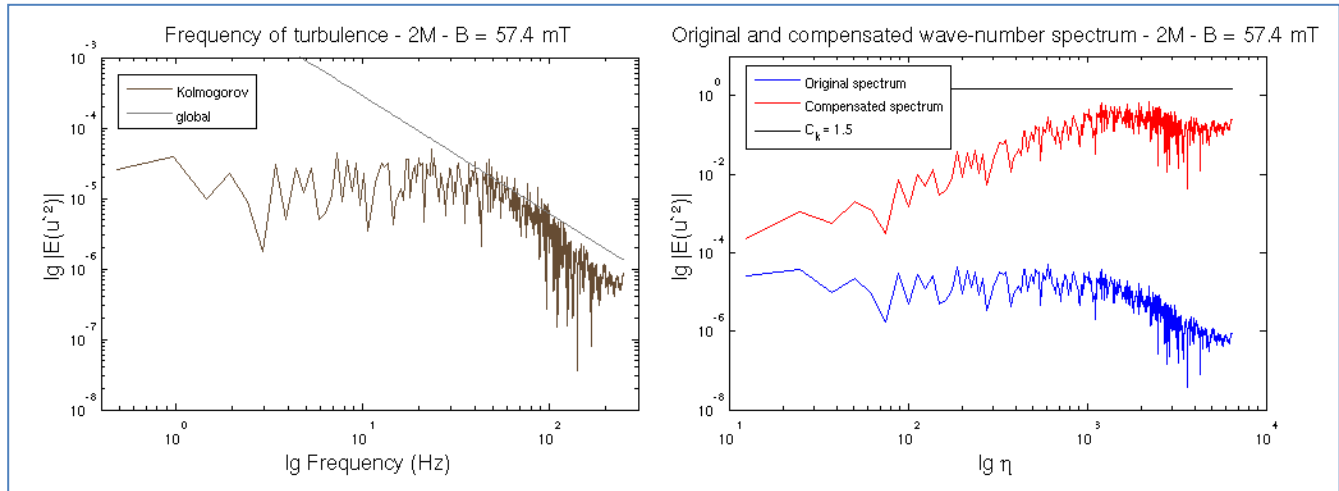


Figure 41. Fourier spectra of 57mT model

These spectra were made of a data of 2 seconds, so it would be good to have a longer data range to check if the turbulence needs more time to develop. The spectra of other models were made with 8 seconds of data.

Model with free surface

The last LES model was a multiphase model. The aim of this job was to investigate the effect of free surface on the flow. The setup was the same as in 2M, but a Volume of Fluid multiphase model – for 2 phases: air and gallium – was used to calculate the free surface of the melt. The geometry was kept, but the top of it has been opened with a pressure inlet on zero pressure. The melt has been added to the model with patching method from 0 to 20 mm of height, so there was 10 mm of air in the crucible. A new UDF had to be made to make the force appear just on the melt.

I concentrated on the differences in the flow pattern. Figure 42 and Figure 43 shows the settling of the flow without and with free surface. The shear, what provides eddies in the flow appears earlier at the free surface. These shears also seem to be stronger than at the bottom of the crucible.

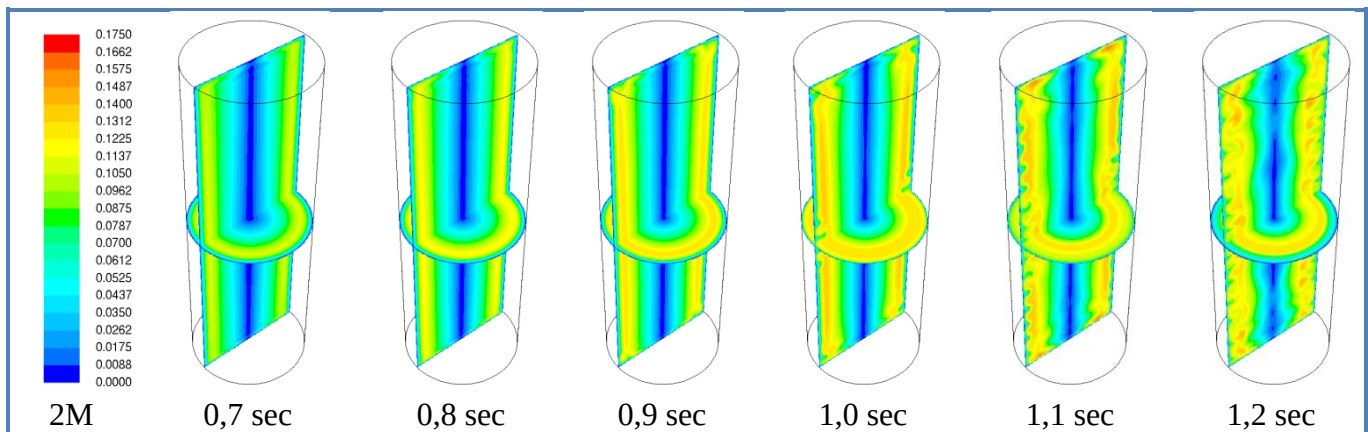


Figure 42. Settling of the flow - 2M, without free surface – colormap is in m/s

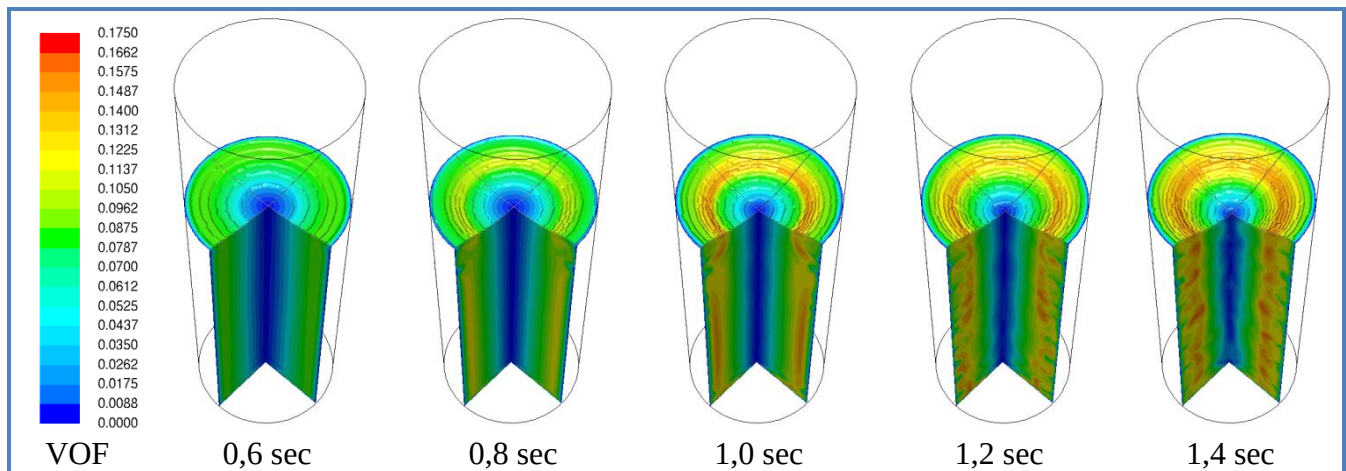


Figure 43. Settling of the flow - VOF, with free surface – colormap is in m/s

The velocity distribution has been plotted near the bottom and near the free surface, where eddies appear. The place of the lines and the fluctuations can be seen on Figure 44. The pulsating effect appears later at the bottom and the level of fluctuations are also smaller, than near the free surface, but it gets equal during the settling of the flow. No other effect appears from the surface.

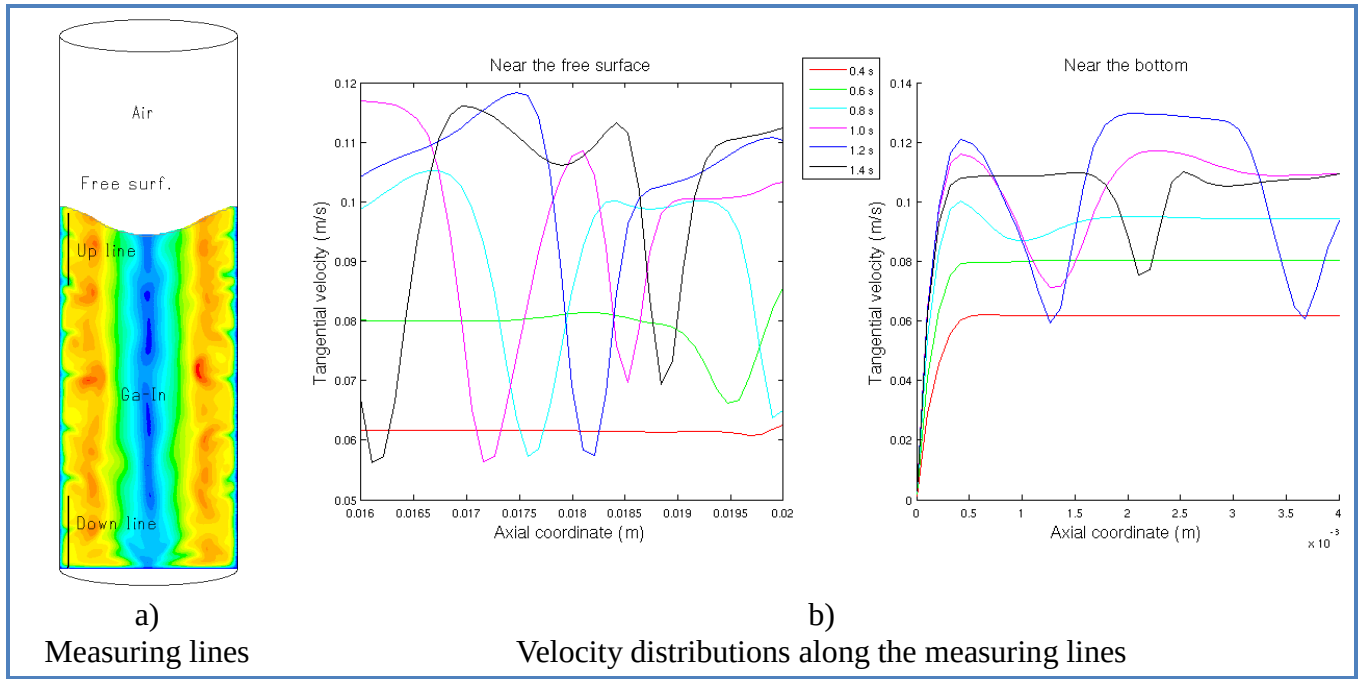


Figure 44. Velocity distributions during the settling of the flow

The accuracy of the free surface sedimentation was checked with the following equation:

$$d_s = \frac{R^2 \omega^2}{2g} \quad (12)$$

Where

- d_s is the distance between the highest and the lowest point of the free surface,
- R is the radius of the crucible,
- ω is the average angular velocity of the melt,
- g is gravitational acceleration.

The ω is gathered from the media, and the theoretical sedimentation is computed with eq. (12), then it is compared to the sedimentation value, what is measured in FLUENT. The results and errors can be seen on Table 7.

Table 7. Angular velocity and free surface sedimentation results and their error in VOF model

	ω (rad/sec)	Relative error (%)	d (mm)	Relative error (%)
Measurement	38,83	-	-	-
VOF	38,47	0,94	2,06	-
Computed from ω in volume	-	-	1,89	8,30

The free surface deformation can be seen on Figure 45. The results are acceptable, but a finer mesh would make better surface resolution.

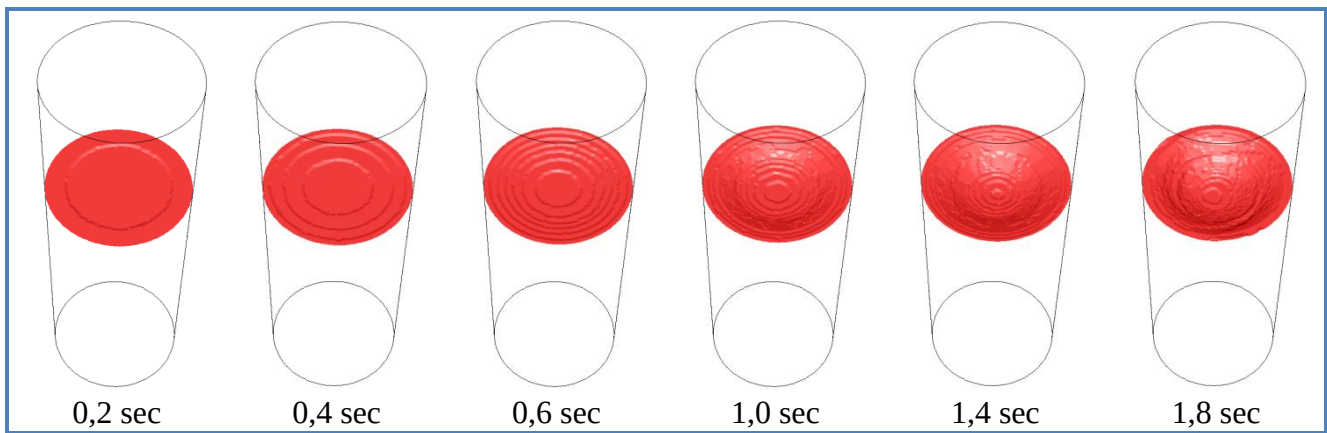


Figure 45. Deformation of the free surface

Additional models

Effect of temperature

A 2D k- ϵ model was made to see if there is significant effect of temperature on the flow. The EWT model was used as a base. Energy equation has been turned on, the temperature of the melt was set to 483 K, and the bottom wall of the crucible was set to 283 K to induce a temperature difference. The angular velocity was plotted during the calculation, but it did not change compared to the iso-temperature model – see Figure 46 – just the eddy fluctuation visible. Also no differences appeared in the flow pattern – see Figure 47.

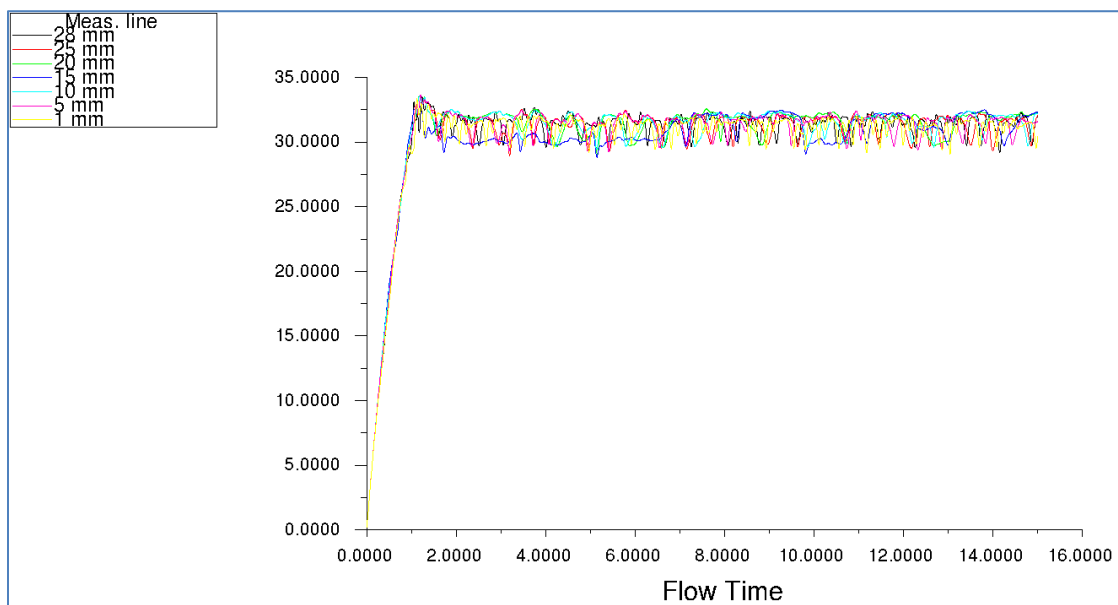


Figure 46. Angular velocities as functions of time on several measuring lines – temperature model

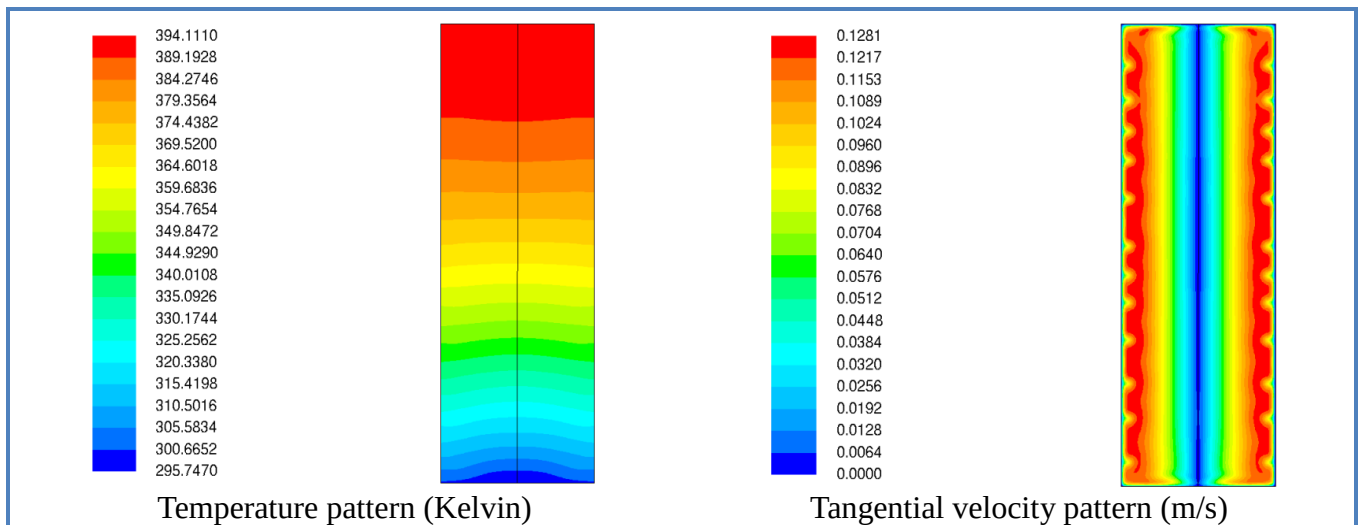


Figure 47. Temperature and flow pattern – 14 s of flow time

This job wasn't the main task of my internship. I focused on the LES simulations, so more tests needed in this task to see effects of temperature. Additional temperature dependent material data is also needed for the simulations.

Incomplete computations

Two models have been started, but couldn't be finished because of the enormous computing time. These models are:

- Investigation of the effect of *wall roughness*
- Space experiment with $B = 1 \text{ mT}$ and no gravity

Wall roughness

First is based on the paper of Rónaföldi et al. [4]. The effect of wall roughness on the mean flow – sedimentation of free surface and angular velocity – was investigated. Reconstruction of the system in FLUENT seems to be a good task and also should be useful during modeling crystallization. Just think about the interface between the solid state and the mushy zone and/or the liquid phase alloy. The surface of the solidified alloy is absolutely rough and should have bigger effect on the flow. There is no working near wall model which can take the roughness in account, so two other methods have been made with LES:

- Using Volume of Fluid multiphase
 - Separating the roughness with volume fraction
- Making real wall roughness with mesh separation

Using VOF, a UDF was made for initialization – to set up volume fraction nearby the wall and make the wall roughness with setting air in the separated regions. For the calculations, the equation of volume fraction has been turned off.

The model showed several convergence problems and the flow hasn't been affected as expected. The interface of the two phases is not real block in the flow without the equation of volume fraction. No valid result can be reached with this result – see Figure 48.

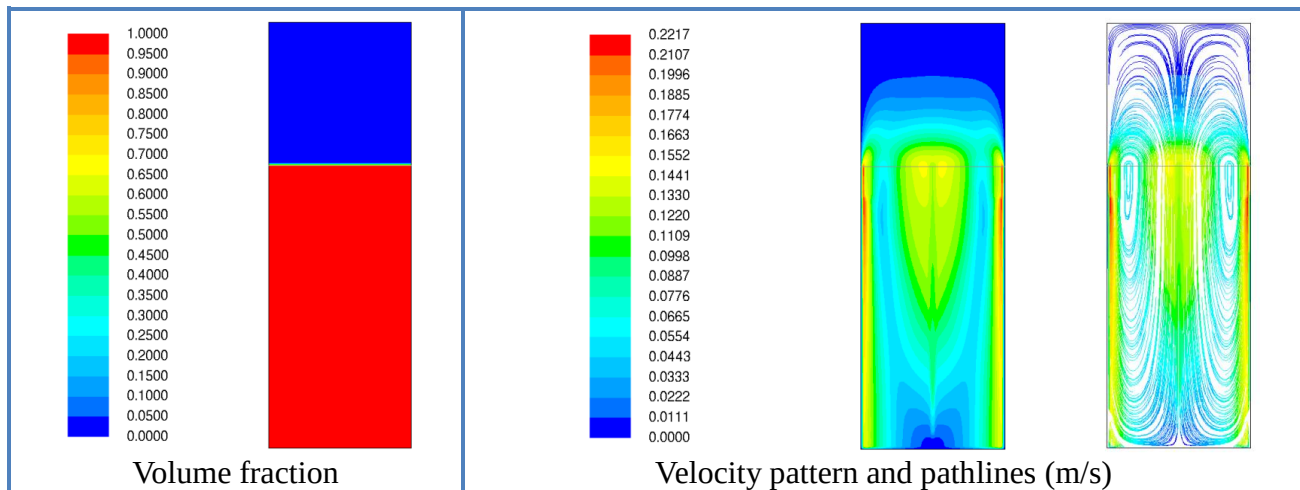


Figure 48. Result of “multiphase method”

To be able to see some differences in the flow with the mentioned problem, real wall roughness has been made in 2/3 of the cylindrical wall. A journal was used to separate cells from the media on the wall – see Figure 49. After the separation, the unused volumes have been deleted. For acceptable flow resolution, the mesh has been adapted – a model with 3.5 million cells was made. The work with this model is very slow because of big amount of cells and enormous number of walls.

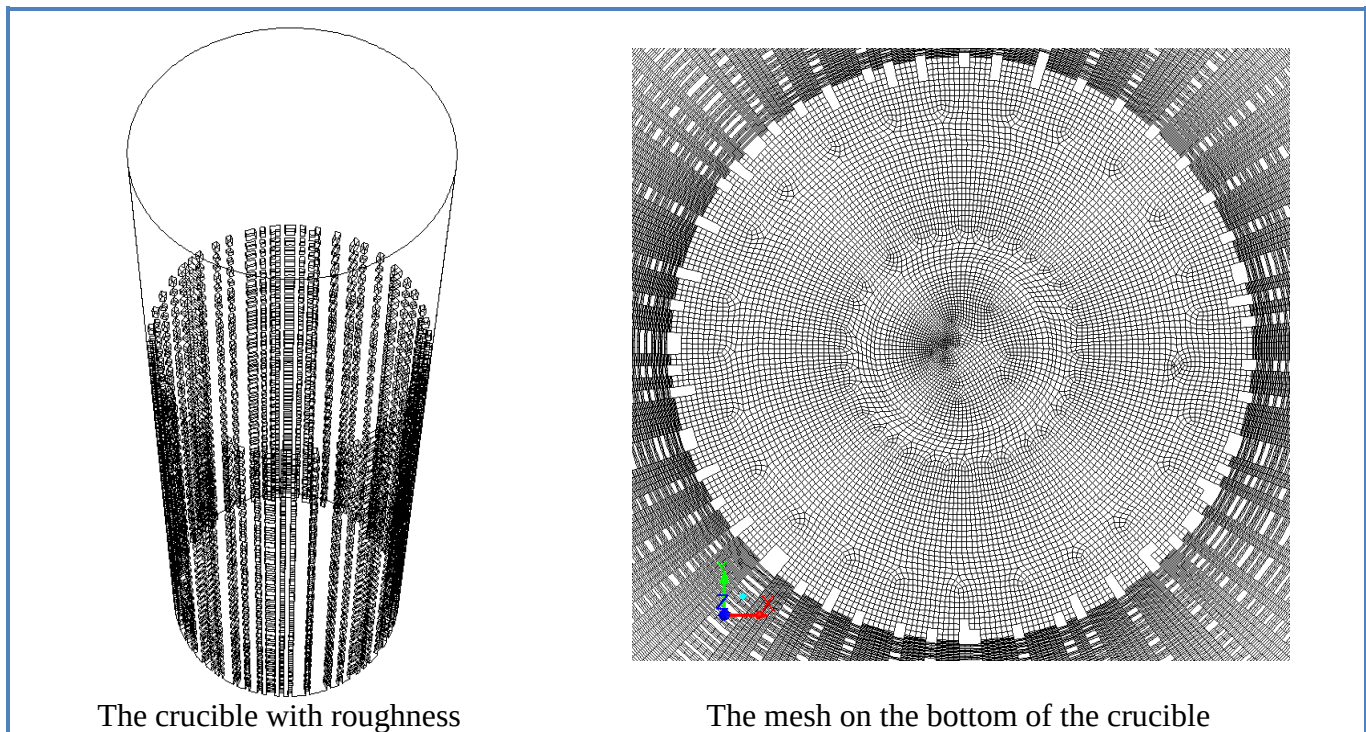


Figure 49. Geometry and mesh of the “real roughness” model

The intermediate results show what is expected. The flow is a bit slower in the case of the rough wall than with simple boundary. Figure 50 shows the contours of angular velocity in different transverse planes. The slowing effect is purely visible. Table 8 also shows the average angular velocities on each plane.

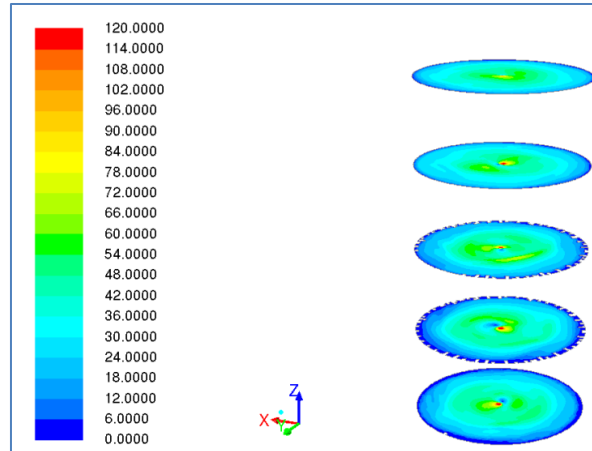


Figure 50. Angular velocity distribution on planes of height = 5, 10, 15, 20, 25 mm – rad/s

Table 8. Average angular velocities on planes of height = 5, 10, 15, 20, 25 mm

Height (mm)	ω (rad/s)
5	29,53
10	29,10
15	31,30
20	32,32
25	32,94
Average	31,05
Measured (no-rough)	38,83

Low induction

The second model has been started to see the flow field of space experiments. The model is the same as 2M, but with 1 mT induction and with no gravity. The contours and pathlines of the main flow and the vectors of secondary flow can be seen on Figure 51. The flow is totally laminar. The secondary flows on the top and the bottom are made by kind of end effects in the melt.

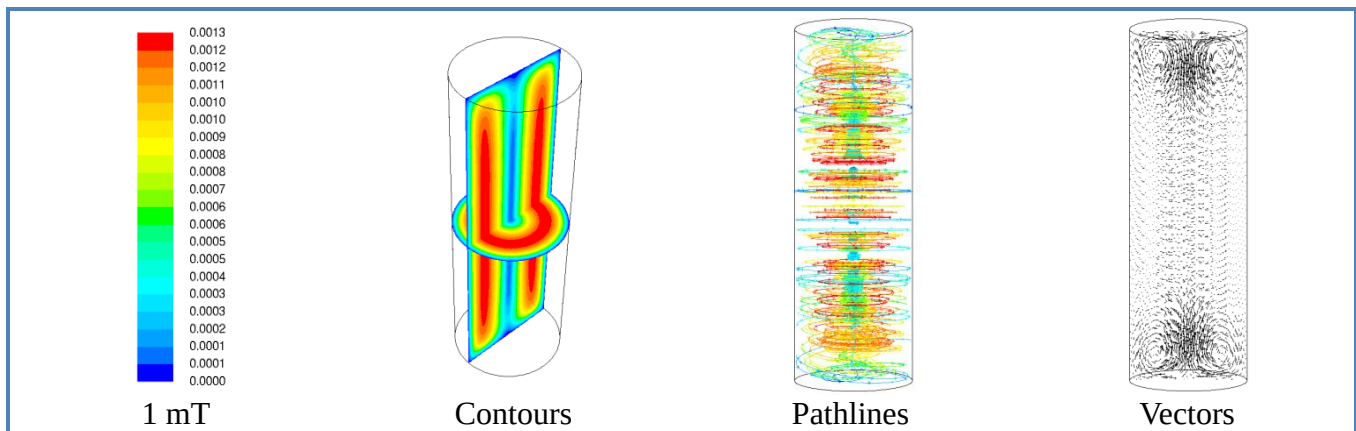


Figure 51. Contours and pathlines of the main flow and vectors of secondary flow - 1mT model – colormap is in m/s

Summary

Several phenomenons have been investigated during the internship. The biggest works were the LES simulations, with the long computing time and the big post processing requirements. The comparison results between the Realizable k- ϵ and Large Eddy Simulation turbulent models will be useful for later works with modeling crystallization. For future works with the flow, the crucible of the crystallization – 8 mm ID x 120 mm – should be used and more computations should be done with other alloys.

Acknowledgements

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