CFD Simulations of Silos Content

An investigation of flow patterns and segregation mechanisms

Master's Thesis within the Innovative and Sustainable Chemical Engineering programme

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Division of Chemical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014

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Abstract

When combusting fuel in a combined heat and power plant it is important to have as consistent and time invariant fuel as possible. This thesis aims to simulate the flow patterns in a silo at a combined heat and power plant as well as finding the most important mechanisms for segregation. The fuel is simulated using two Eulerian phases and the interaction effects are neglected. The mesh used is changing in each time step to have high resolution in areas with large gradients of volume fraction and lower resolution where it is not needed. The viscosity is modeled using kinetic theory for granular flow for the rapid regime and an additional term for frictional viscosity in dense regions.

The result shows the potential of using these types of calculation for future development of silos and screws, but there are crucial deficiencies in the way the screw is modeled. The most important segregation mechanisms are responsible for up to 80 % of the segregation and these effects are: kinetic sieving, difference in particle trajectories when falling and sliding, angel of internal friction, fines fluidization and air currents.

Acknowledgements

This Master’s thesis has been performed at Chalmers University of Technology for the consultant company WSP group. The supervisors for this thesis have been Rolf Njurell at WSP group and Prof.Bengt Andersson at Chalmers. This thesis would not have been possible without either one of you, thank you for everything.

I also would like to thank Ronnie Andersson, Mohammad Khalilitehrani and Per Abrahamsson for interesting discussions and useful advice and to Patric Kvist for the help with the UFD. To the division of chemical engineering I would like to express my thanks for an enjoyable working environment, especially to everyone in the diploma worker room.

Finally I would like to send a special thanks to my girlfriend Madelene and our daughter Felicia for making my life magnificent!

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1 Introduction

During the 20th century the energy consumption used by human activities gradually increased and is expected to do so with more and more countries being developed. In order to provide the energy without compromising our earth as we know it, the energy should originate from renewable resources. We need to go from fossil based to a solar based energy production, because the sun is the only source for energy input to the planet. The energy from the sun can be recovered by using several techniques - for example solar cells and wind turbines that are more or less directly driven by the sun. Another more indirect way of using is the solar energy is to grow different types of plants and extract the chemical energy by either direct combustion or to produce liquid fuels such as ethanol or biodiesel.

In combined heat and power plants (CHP) in Sweden it is common to use solid fuels as woodchips or municipal solid waste. A problem with solid fuels is that they tend to be inhomogeneous and vary between batches. Fluctuations in fuel quality will cause variations in temperature inside the boiler and may even cause the fire to get extinguished. With a varying temperature inside the boiler comes variations in the delivered heat to the waterside of the boiler and consequently the delivered amount of both heat and power will be more difficult to predict. Naturally efforts are made to make the fuel more homogenous. Methods that are used originate from coal mining industry and it is unknown how well they work for other types of solid fuel.

A combined heat and power plant is designed to utilize as much of the energy of the fuel as possible. The amount of power produced is less compared to a thermal power station but the total efficiency is considerably higher. A thermal power station is focused on producing the maximum amount of power from the fuel. The ratio between heat and power delivered is an important parameter for a CHP and is usually referred to as the alpha-value. A schematic representation of a CHP plant can be seen in Figure 1.

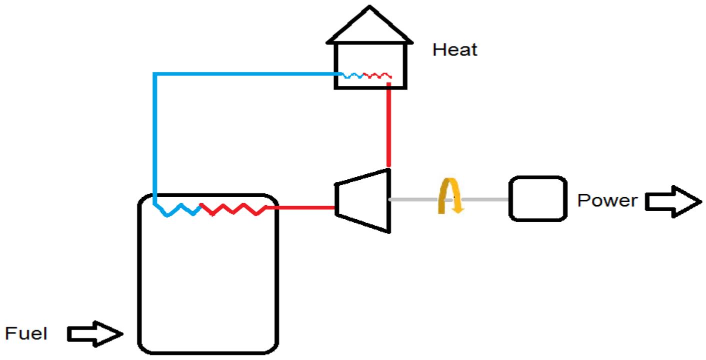

Figure 1 A Schematic representation of a CHP plant

1.1 Objective

As mentioned in the introduction we need to go from fossil to a solar based energy production, this will in some sense involve going from a fluid based energy production to a solid based, at least for the more indirect ways. Chemical processes have traditionally been about mixing, reacting and separating fluid substances. Advanced models and equipment have been developed for such systems but for particle or granular flows the model development is still in an early stage and the equipment still need more refined solutions. This thesis work is focused on how to simulate the flow of woodchips and investigate mechanisms for segregation inside a silo at a CHP plant. Also methods for homogenization of fuel inside the plant were studied.

1.2 Method

To get enough knowledge about how to model such a system a thorough literature study on granular flows was done. Experience of the site was gained through study visits to the CHP during the project. The tool used for calculations was ANSYS Fluent and its pre- and post-processing programs. Measurements of the silo were performed to compare with the calculations. A literature study on what mechanisms are causing segregation was done.

1.3 Limitations

In the real process a wide range of particle sizes exist but in this thesis only one particle size is included for the calculations, this size is set to resemble an average woodchips volume. The aim for this thesis was not to develop new models it was to find out what models exist and use a suitable one.

2 Background

The wood combusted in a CHP plants have varying size, origin, moisture content, shape, heat of combustion etc. To easier be able to control the system it is important to have as homogeneous and time invariant fuel as possible. The size of the fuel particles ranges from a few cubic millimeters to a couple of cubic centimeters. The wood used as fuel is usually residues from forest industry, wood pellets and recycled wood.

When the woodchips enter the site the moisture content of the fuel is measured and the fuel is emptied in a cargo pocket. Depending on the type of woodchips, origin, size etc., it is placed in a specific pocket, shown in Figure 2 c. From the cargo pockets the wood is lifted on to a conveyor belt using a big grapple (Figure 2 a).

Figure 2 Important steps in handling the fuel

The ratios of the different fuel qualities are important in order to have a stable combustion later on; therefore the grappler picks up material according to a recipe. The conveyor belt transports the fuel to the silos (Figure 2 b). The silo acts as a fuel buffer to avoid running out of fuel and it also contribute to the homogenization of the fuel. The woodchips are then fed from bottom of the silo using a rotating screw feeder. When varying the fuel type injected into the silo, layers with different fuel qualities form. When the fuel is driven out of the silo by the screw a volume containing numerous fuel qualities are exiting, as represented by the box in Figure 3. This is a step to get a more homogenous fuel and a more stable combustion, if it is done the right way.

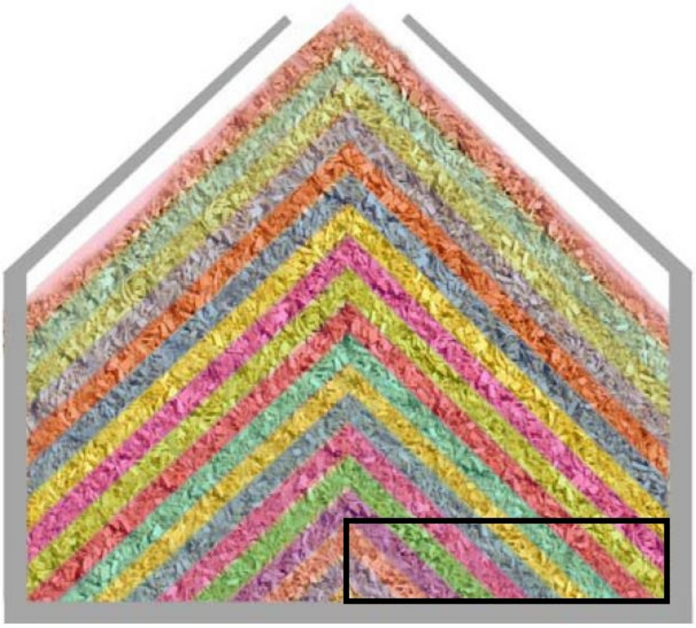

Figure 3 An ideal case of layers formed when varying the inlet fuel and a box representing fuel feed out by the screw during one pass.

From the silo the fuel is transported using conveyor belts to the boiler where the wood is combusted (Figure 2 d). The heat is used to heat and evaporate water. The evaporated water is expanded is a turbine to produce electricity. The water is also used to provide district heat to houses and other facilities.

3 Theory

Development of models for granular flow is an important area of research, since many flows in industry are in fact granular. Modeling of granular flow is complicated and it requires a deep understanding of the system to make sure that the most important phenomena are included. The behavior of the particles varies with numerous parameters, where perhaps the most important property of granular flow is the volume fraction of particles. At low volume fractions particles behave very differently from when there are high volume fractions. At low volume fraction the interaction between particles is much like the one between gases. But when the Volume fraction is close to the packing limit it is almost static and bears a resemblance to that of a solid and when the volume fraction of the flow is moderate the particles behaves much as a liquid. Granular flows are usually divided into dense and rapid regimes and are modeled with completely different approaches. Figure 4 shows a system containing all regimes much as the system of interested in this thesis.

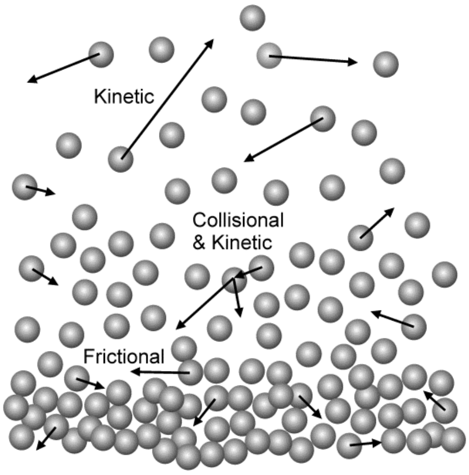

Figure 4 System containing all different regimes

3.1 Continuum Modeling of Granular Flow

Simulations of multiphase flows can be done in different ways. In this Master's thesis work it has been found most reasonable, due to the high loading and size of the equipment, to simulate the system using an Euler- Euler approach. The Euler-Euler approach means that all phases are modeled as fluids, with properties equivalent to those of the granular phase. Transport equations for each phase are solved and the sum of all volume fractions must be equal to one. A multiphase flow is modeled as a homogeneous mix of quasi-fluids within each cell, the cells average is used for calculations. The Euler-Euler model solves momentum and continuity equations for each phase; however it is also a necessity to specify how the phases interact.

3.1.1 Rapid Granular Flow

When the particle volume fraction is low one usually models the flow behavior using the kinetic theory for granular flow (KTGF). KTGF have a lot in common with the kinetic theory for gases, for instance that only binary collisions are occurring and that the collisions are instantaneous. One major difference is that the collisions in KTGF are not assumed to be elastic as anticipated for gases. The random velocity fluctuations of the particles give rise to a granular temperature (Θ_s), which is corresponding to the thermal temperature. The transport equation for granular temperature below is derived from the KTGF. The equation has similar terms as an ordinary heat balance with for example conductive, diffusive and production terms. (Andersson et al 2013)

$$\frac{3}{2}\left[\frac{\partial(\rho_s\alpha_s\Theta_s)}{\partial t}+U_{j,s}\frac{\partial(\rho_s\alpha_s\Theta_s)}{\partial x_j}\right]=\kappa_s\frac{\partial^2\Theta_s}{\partial x_i\partial x_j}-P_s\frac{\partial U_{j,s}}{\partial x_j}+\tau_{kj,s}\frac{\partial U_{k,s}}{\partial x_j}-\gamma_s \tag{1}$$

The dissipation term (γ_s) describes how fast the fluctuation energy decays .

3.1.2 Dense Granular Flows

When particles are densely packed the interactions between particles will not be instantaneous, as assumed by KTGF. Solid-like or quasi-static are behavior are seen when a system approach the particle packing limit. The systems are more or less immobile and if the system is exposed to external forces, the added energy will cause the volume to expand before accelerating.

At intermediate volume fractions particles will instead slide against each other and momentum transfer between particles will mostly be due to friction, the particles will also depend on how the neighboring particle moves and this dependence lead to a collective behavior (Abrahamsson 2012). The collective behaviors of the dense flow give rise to properties that resembles that of a (Bingham) plastic. Since frictional forces are dominating the system at these condition it is often referred to as the frictional regime or granular liquid regime.

3.1.3 Pressure

In fluids it is usually easy to calculate pressure, using gas laws for gases or using P=ρgh for liquids. The pressure calculated by these models are isotropic, it is uniform in all directions. Using the equation for liquids for granules may at a first seem to be reasonable but inside the bulk cavities can be formed. The force from above the cavity is divided into components to keep the cavity intact, therefore forces (and pressure) will not be uniform in all direction. The strategy for how to describe the pressure in dense systems usually involves volume fractions, α_s, and how close to the maximum packing limit the region is. The Johnson and Jackson (1987) model suggest that the frictional pressure can be calculated from:

$$P_{s,friction}=\frac{Fr(\alpha_s-\alpha_{s,min})^n}{(\alpha_{s,max}-\alpha_s)^p} \tag{2}$$

Where n=2 , p=5 and Fr=0.1α_s is suggested by an experimental study by Ocone et al.(1993) resulting in the final expression:

$$P_{s,friction}=\frac{0.1\alpha_s(\alpha_s-\alpha_{s,min})^2}{(\alpha_{s,max}-\alpha_s)^5} \tag{3}$$

The value for $\alpha_{s,max}$ is set to 0.63, that is the number close random packed spheres can reach. $\alpha_{s,min}$ is the volume fraction limit for when the software starts calculating the frictional pressure, this value is set to 0.45 in the calculations in this thesis. This value must not be higher than the inlet volume fraction and must be lower than $\alpha_{s,max}$.

The solids pressure in regions with low to intermediate volume fractions is calculated using KTGF (Lun et al. 1984). The solids pressure that arises due to streaming and collision is calculated using the following expression:

$$P_{s,kinetic}=\alpha_s\rho_s\Theta_s+2\rho_s(1+\varepsilon_s)\alpha_s^2 g_0\Theta_s \tag{4}$$

Granular temperature (Θ_s) is the random movement of granules, ε_s is the restitution coefficient, ρ_s is the particle density and g_0 is the radial distribution function that describes how close to maximum packing the cell is, and prohibit the packing to get denser than the maximum value. For mono-disperse system g_0 can be calculated using the following equation (Lun et al. 1984):

$$g_0 = \frac{1}{1 - \left({}^{\alpha_s}/_{a_{s,max}} \right)^{1/3}} \tag{5}$$

The total solids pressure,P_s ,is the sum of frictional pressure and kinetic pressure, that is:

$$P_s = P_{s,friction} + P_{s,kinetic} \tag{6}$$

This summation has no scientific reason but it has shown to provide reasonable results. In dense areas pressure from KTGF should be close to zero and the value from the frictional regime will be negligible in areas with low volume fraction.

3.1.4 Viscosity

Perhaps the most important factor for determining how a fluid will flow is the viscosity. Viscosity calculation is calculated for the different regimes and are in a similar way as for pressure first calculated individually and then added to a total solids granular viscosity (Andersson 2009)

$$\mu_s = \mu_{s,kinetic} + \mu_{s,collision} + \mu_{s,friction} \tag{7}$$

The kinetic and collisional parts of the viscosity are calculated according to Gidaspow et al. (1992) who suggest the following formulations:

$$\mu_{s,kinetic} = \frac{10\rho_s d_s \sqrt{\pi\Theta_s}}{96\alpha_s(1+\varepsilon_s)g_0}\left[1 + \frac{4}{5}g_0\alpha_s(1+\varepsilon_s)\right]^2 \alpha_s \tag{8}$$

$$\mu_{s,collision} = \frac{4}{5}\alpha_s^2\rho_s d_s g_0(1+\varepsilon_s)\sqrt{\left(\frac{\Theta_s}{\pi}\right)} \tag{9}$$

Frictional viscosity is calculated using the following expression by Schaeffer (1987) this is used in dense regions.

$$\mu_{s,friction} = \frac{P_{s,friction}\sin\phi}{2\sqrt{I_{2D}}} \tag{10}$$

The particles internal angel of friction (ϕ) determines the slope of a pile in equilibrium will have, this property is material specific and depends on friction, shape and cohesion among other things. I_{2D} is the second invariant of the stress tensor which is related to the Jacobian matrix for stresses.

Granular bulk viscosity is how resistant the granular phase is to compression and expansion, an expression for how it is calculated is given by Lun et al (1984).

$$\lambda_s = \frac{4}{3}\alpha_s \rho_s d_s g_0 (1 + \varepsilon_s)\sqrt{\left(\frac{\Theta_s}{\pi}\right)} \tag{11}$$

3.1.5 Forces

One important criteria for how two a fluid and a granule interact is the Stokes number. The stoke number in a quota of relevant timescales. If the Stoke number is much larger than 1 the particles are unaffected by the continuous phase

$$St = t_d / t_s \tag{12}$$

Simulations in this thesis are focused on how the granules flow inside the silo. For the particles sizes simulated the terminal velocity is much higher than the maximum velocity reached and since the air flow is not of interest it is acceptable to neglect drag forces in between these two phases. With no interaction in-between air and granules the air flow patterns will be very different from how it would have been with drag included, but the flow pattern for the wood would be more or less unchanged.

3.1.6 Turbulence

Turbulence is a property of the flow that is commonly thought of as random deviation from the mean flow value. Turbulence will normally enhance heat, momentum and mass transfer due to that random motion. Turbulence generally arises at high Reynolds number, i.e. when the inertial forces are much greater than the viscous. If no energy is fed to the turbulence the energy in the turbulent eddies will decay and in time end up as heat.

Solving the Navier-Stokes equation directly comes with an extremely high computational cost and is therefore not done in engineering flow simulations. Instead one usually models the turbulence in some way. The simulation in this thesis disregards the effect of turbulence due to that the particles are not that effected by the air and the flow pattern of the air is unimportant

3.2 Mesh

Eulerian multiphase models require a control volume that is bigger than the particle size but small enough to resolve the macroscopic flow structures. Figure 5 illustrates how the cell size influences the averaging process done when using Eulerian simulations. If the cell size is too small, much smaller than the particle size, fluctuations in properties will differ dramatically in between cells (Abrahamsson 2012). On the other hand if the mesh is to coarse, the equations for granular pressure, and viscosity etc. is not solved correctly since the models are very dependent on *local* volume fractions. Therefore the cell volume and consequently the averaging volume should be small enough, especially in areas with high gradients. Consequently a mesh independent solution does not exist, but an optimal mesh can exist.

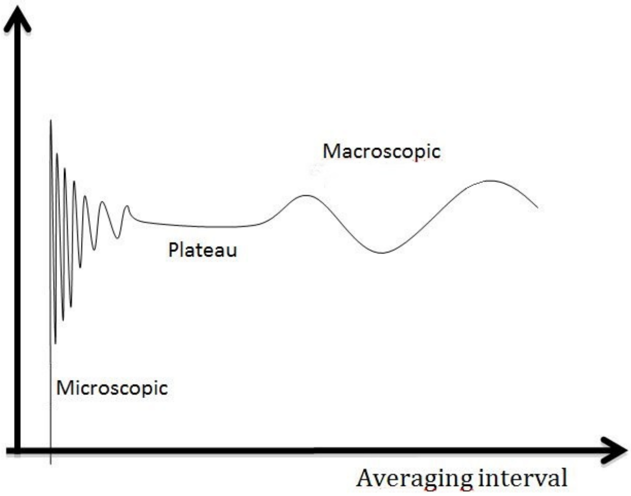

Figure 5 showing the dependency of averaging volume (Abrahamsson 2012)

3.3 Segregation and Mixing

In real processes dealing with granular flows the granules are not perfect spheres and are not of the same size, this fact may lead to particle segregation. When mixing two fluids it usually result in a lower concentration gradient after it has been mixed than before. This is not always true when mixing two granular phases; the added energy may actually cause the particles to separate instead of homogenize (Gyenis 2001).There are numerous mechanisms for this segregation but there are five major contributors to this separation. The following five effects are accounting for about 80% of the segregation: (Diamondback technology 2005)

- Kinetic sieving: The first phenomena generating this separation is when a mixture of particles with different sizes is agitated the smaller particles tend to move down the bulk, this is due to that when particles are in motion all particles will not have the exact same velocity and therefor gaps in between particles will form. Small particles needs a smaller gap to fit inside and will be pulled down by gravity to greater extent, this will cause segregation of particle sizes. This segregation is what is referred to kinetic sieving. Distinct element method (DEM) simulations by Jullien Meakin and Pavlovitch (1992) and experiments by Canoli and Manga (2005) have both confirmed this separation due to size. Canoli and Manga also show that not only size is important but also the material properties.

- Trajectory: Particles may have different shape, size, density etc. The difference in these properties will result in different frictional forces for the particle types, both for the drag- and particle-particle friction forces. Since smaller particles have higher area to volume (and mass) ratio, smaller particles will be influenced to larger extent by frictional forces resulting in separation of sizes. The area to volume ratio also varies due to the shape of particle; that is a separation of shapes will arise due to this phenomenon. A DEM-simulation by Jullien and Meakin (1990) shows this separation of particle sizes when forming a pile, the simulations show how the large particles roll of and accumulates in in the borders of the pile. In the same article Jullien and Meakin do a simulation inside a cylindrical vessel to investigate if size segregation is occurring, the result clearly show that the concentration of large particles increase in radial direction. This separation is due to the different trajectories when falling and rolling during the filling procedure.

- Angel of internal friction: The third effect is that different materials that are in the same pile may have different angel of internal friction. This effect causes the material with lower angel of internal friction to roll or slide of the pile.

- Fines fluidization: The fourth effect is fines fluidization this effect is important when a mixture has high share of small particles. The small particles form a layer that can be penetrated by a bigger particle flowing towards the pile. This causes the small particles to top of the container and to dust.

- Air currents: Air current may cause the fine fractions to get airborne and follow the air flow and accumulate in some regions.

3.4 The Silo

The silo is run throughout the week and it is continuously being both filled and emptied of woodchips. The level of woodchips inside the silo is varying a lot during the week and the silo is almost empty on Monday morning since no or almost no fuel is put in during the weekend. The maximum volume in the silo is generally at Friday afternoon.

When designing a silo it is important to make sure that the silo can withstand the forces and the pressure acting on the walls due to the contents mass. Generally a method that is averaging over horizontal direction is used and only the height is important. These methods neglect the fluctuations, cavity formations, non-uniform loading etc. And according to Schaffer (1985) complete collapses of silos, especially for hoppers, are not rare due to these incorrect assumptions when the flow is unbalanced.

3.4.1 Screw Feeder

In order to the push the wood out from the silo a screw feeder is placed at the bottom of the silo. The screw is rotating around its own axis to force the granular material towards the outlet. The screw also rotates around the center of the silo with an angular velocity, ω. Since the volume of a cylinder increases proportionally to r^2, so should the screw capacity in order to have the same volume uptake throughout the radial direction. The capacity is the volume of material that is pushed. Constructing a screw that has an infinitely small capacity at the edge is not possible therefore an initial capacity at the edge is used. Figure 6 shows a screw that is pushing the material towards the center of the silo from where the material is loaded onto a conveyor belt.

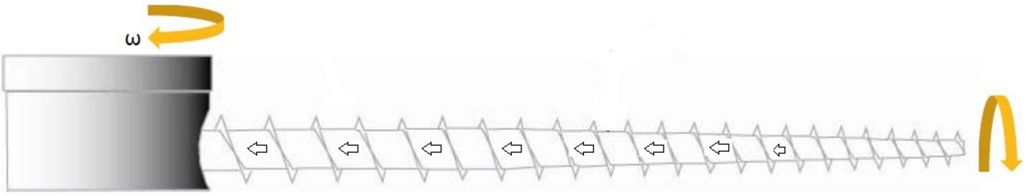

Figure 6 the screw pushing the material towards the outlet

4 Method

Transient simulations were run using two Eulerian phases, with air as the primary phase and wood granules as a secondary phase. The models for solids pressure, frictional viscosity etc. described in equations 2-11 were used to simulate the behavior of the granular phase. Section 4.1 describes the geometry and 4.2 the mesh. In section 4.3 the numerical set up is presented.

4.1 Geometry

The geometry used in the simulations is based on the drawing used when building the actual silo. For 2d simulations a rotation symmetry line was set in the middle of the silo to reduce computational time, shown in light blue in Figure 7. The inlet is at the top marked with green and the outlet is located in the bottom center. The screw can be seen at the bottom of the silo as dark blue region.

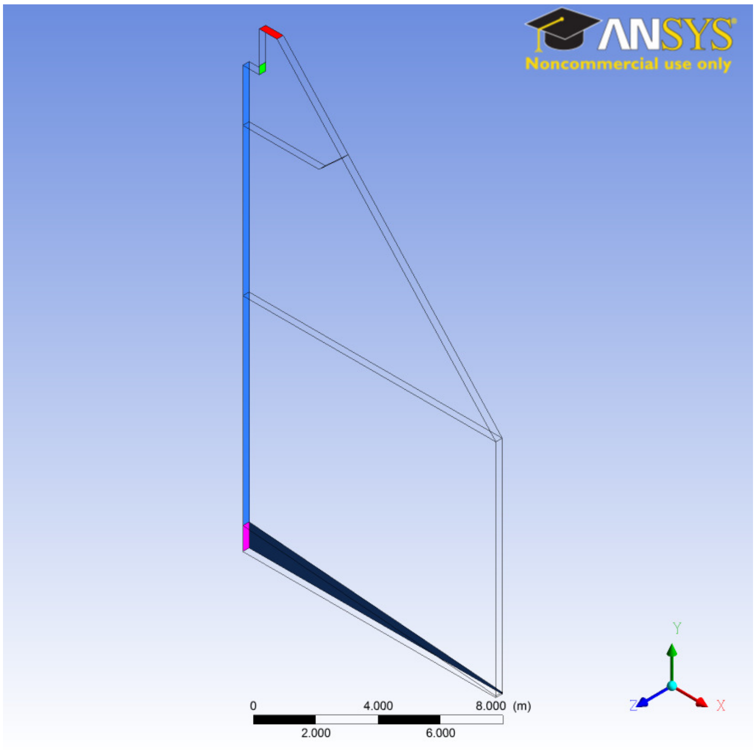

Figure 7 The geometry used in 2d simulations

To be able to capture more of the behavior of the granular material when the silo is emptied, a full three dimensional simulation was planned. The geometry of the full 3d simulation is illustrated in Figure 8.

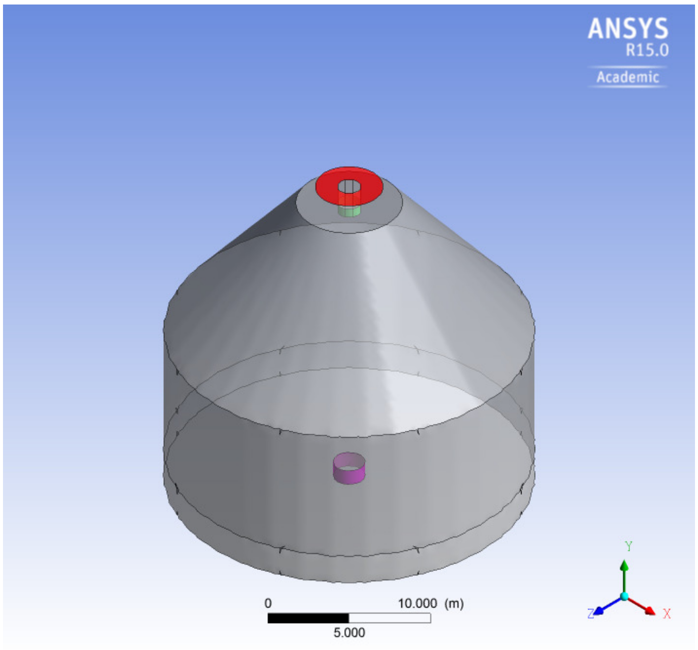

Figure 8 The geometry used in 3d simulations

The screw in the 3d case is not included in the geometry as in the 2d case. The screw zone is instead defined by a User Defined Function, UDF. The UDF finds cells corresponding to the screw zone in each time step, since screw is rotating as shown in Figure 6. This is to decrease the complexity of the mesh and to increase calculation efficiency.

4.2 Mesh

Having small cells all over the volume would result in high computational cost, due to the high number of equations to be solved. To decrease the computational cost a coarser mesh is used initially nevertheless the mesh is adapted in each time step in areas with high gradients of volume fractions; that is in areas where a lot is changing, the cell volume is small, and more precise result than in the rest of the volume is acquired.

The non-refined 2d-mesh is a quadrilateral mesh with cell size of 0.3m with ~2000 cells; the mesh is refined by cutting the cell into four new cells, this procedure is repeated a maximum of three times in order to avoid problems with averaging over too small cells. For 3d simulations each cell is split into eight volumes, so for each level of refinement the number of cells will increase rapidly as can be seen in Figure 9. The original 3d mesh was a Cut cell mesh with ~200000 cells.

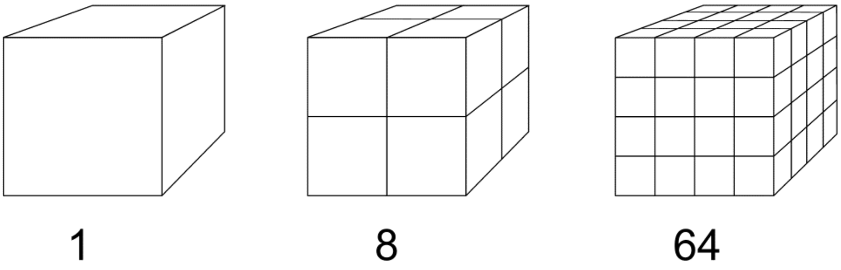

Figure 9 Displaying the way cells are dividing and multiplying for the 3d case

Since the pile is growing during the simulation the region of interest is changing, therefore the program is also allowed to make the mesh coarser in areas with low gradient. The volume fraction is, as can be seen in the equations 1-11, the most important parameter in simulating granular flow. Therefore the mesh is adapting to gradients of solid volume fractions. If the gradient is larger than 0.01 the region is refined, and if it is smaller than 0.001 the mesh is made coarser. The minimum allowed volume for a cell in the 3d case was set to 209.44cm^3. The particle volume, 4.2 cm^3, is 50 times is smaller than the smallest possible cell size.

4.3 Numerical Set up

The woodchips were model as spherical particles with a diameter of 0.02 m. The density of the wood, restitution coefficient and the angel of internal friction were set to 850 kg/m^3, 0.001 and 45° respectively. Due to high Stoke number the drag was neglected so was the effect of turbulence, for more information regarding this see appendix. For calculating the momentum equations with high accuracy and to avoid numeric diffusion a second-order upwind scheme is used. Standard criterions in Fluent for convergence were used. The time step used was 0.001 seconds and the number of iteration was limited to a maximum of 30 in each time step.

The material enters the silo at the top falling down and accumulating in a pile at the bottom of the vessel. This is done by having a velocity inlet with a volume fraction of wood corresponding to 0.4.The outflow of wood is at the bottom in the center of the silo and the material is pushed there by the screw. The screw is modeled as a volume with a velocity toward the outlet. In the 2d-case a constant value is set throughout the zone, and as can be seen in Figure 7 the cross sectional area increases towards the center. For 3d calculations the granule velocity is instead greater closer to the outlet. The velocity in that case is calculated using equation 13 for the granular phase.

$$V(r) = V_0 - \beta r^2 \tag{13}$$

Equation 12 satisfies the r^2 dependence described in the previous section. The velocity equation is included in the UDF that is defining the screws position and gives the granules the velocity in each cell and time step.

5 Results

The result section first presents the simulation of a silo being filled, after that the simulations of emptying the silo. In section 5.3 additional simulations of the system were run to validate the models and investigate segregation effects. Finally, in section 5.4, result from the measurement of the actual silo is presented.

5.1 Fill up the Silo

Simulations of filling the silo were done using the setup described in the method chapter. During this part no wood was fed out of the silo. Figure 10 shows the filling procedure and you can clearly see the shape of the pile. The red color represents granules at maximum packing and blue only air, other color have got an intermediate value. The residuals for continuity equation was generally after each time step somewhere in-between 10^{-3} to 10^{-4}.There were deviations in the level of convergence, especially during the first few time steps and when the pile started forming.

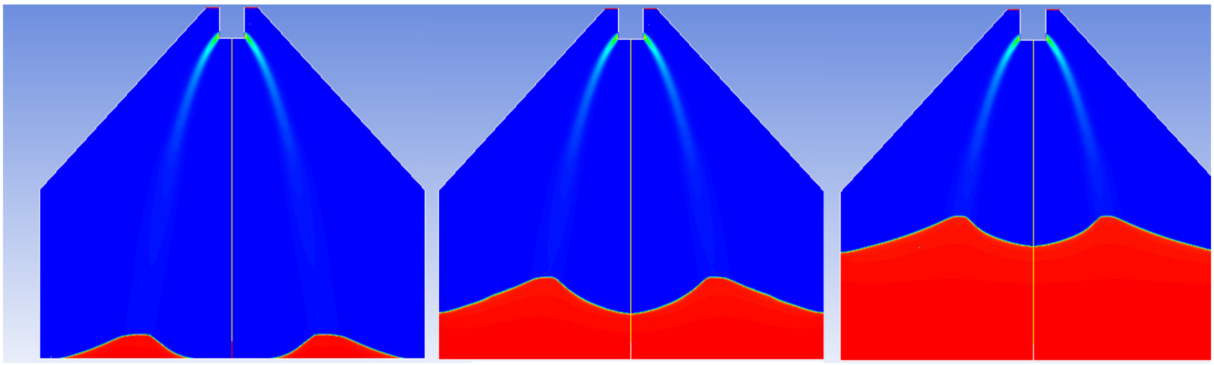

Figure 10 the material filling up the silo, snapshot from three different time steps.

The mesh during adaption is shown in Figure 11. Notice how the mesh size has gradually decreased in areas closer to the air/wood interphase. In regions deeper into the pile the cell size in bigger since the need for small averaging volume is unnecessary due to the smaller gradients.

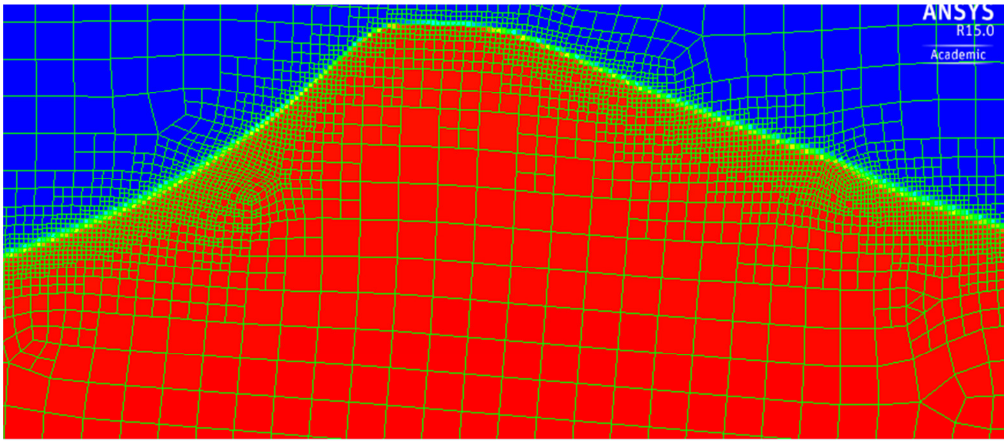

Figure 11 the adaptive mesh

Figure 12 shows the values of frictional viscosity from the simulations, the red represents a maximum frictional viscosity of 10^5 Pa*s, typical values for a liquid have a viscosity of 10^{-3} and very viscous liquid may have values close to 1 (Welty et al 2008). This suggests that only the outer layers are moving.

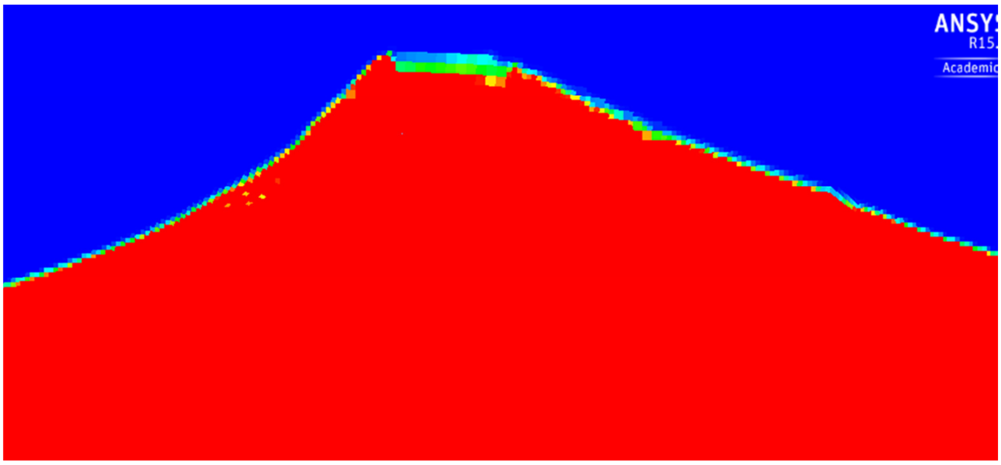

Figure 12 cell values for frictional viscosity

Cell values of granular temperature is shown in Figure 13, this plot shows how only the top few layers of the pile has a granular temperature, that is only the top few layers are vibrating and the rest of the pile is still. The maximum value is at the top of the pile, this is where most of the particles land and cause vibrations.

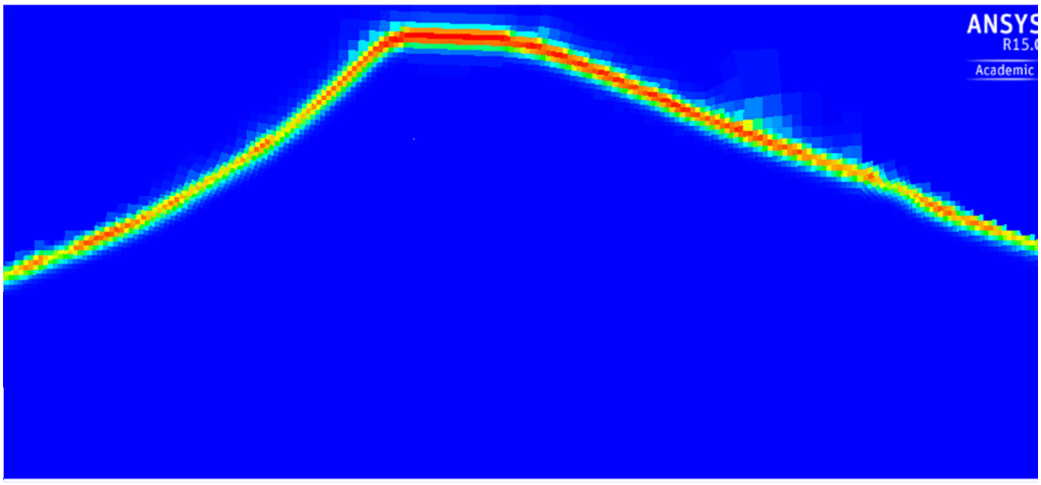

Figure 13 Cell values for granular temperature

5.2 Emptying the Silo

After the silo is filled, the outlet is opened and the screw zone is set for forcing the wood out and no more wood is entering trough the inlet. The flow pattern is displayed in Figure 14 and the deformation of the content is shown. The flow from pattern shows the impact the screws initial capacity has. The material closer to the silo walls will be fed out to greater extent than the material in the center. Further investigated of the flow pattern in section 5.3.2 shows that the screw is modeled somewhat wrong and these flow patterns should be interpreted with caution.

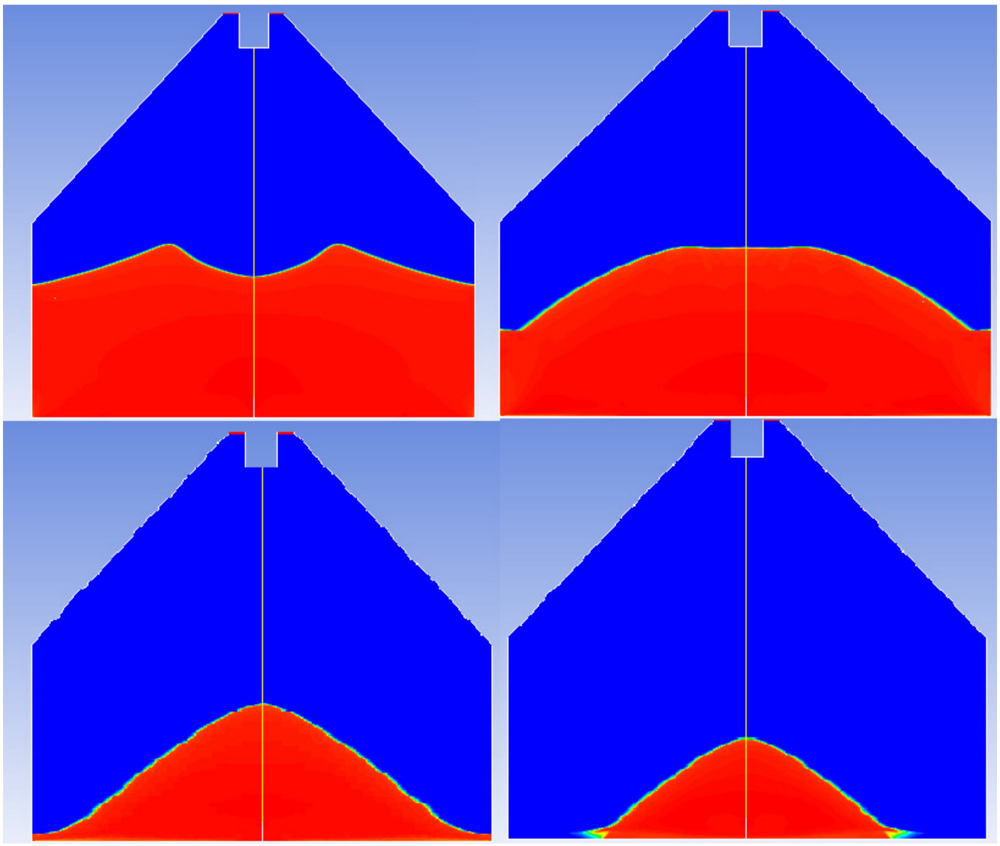

Figure 14 showing how the material is reforming during the emptying procedure

5.3 Additional Simulations

Additional simulations to investigate effects of different factors were performed. Firstly a study of the drag and turbulence is done for two different particles sizes. Then a simulation when an investigation of how layers in the silos are deforming during withdrawal of fuel. In section 5.3.13 a validation of the models used against experiment are done.

5.3.1 Effect of Size, Drag and Turbulence

During the main simulations the interactions with the gas phase was neglected, to study the effect of these factors additional simulations where run. It was decided to investigate the maximum particle velocity in vertical direction as well as the distance traveled in horizontal direction before impact. The Gidaspow and k-ω models were select for drag and turbulent viscosity calculations. Particles diameters used where 2cm and 3mm, this is to represent woodchips and sawdust. Values taken after 1.6 second of simulation time for all calculations, this value was chosen to represent the time when the first particles approach the silo bottom. Another reason is that the first particles will have higher drag resistance before the particles have accelerated the air. The results are presented in Table 1.

Table 1 showing the result from in section 5.3.1

Settings	$V_{y,max}$	Impact from center[m]
2cm	18.9	5.2
2cm with drag	15.6	4.8
2cm with drag + turbulence	15.48	4.8
3mm	18.9	5.2
3mm with drag	15.30	4.20
3mm with drag +turbulence	15.37	4.24

5.3.2 Mixing of Layers

As it would be a major benefit in predicting the mixing degree between two fuel layers a simulation with the different particles were run. The particles are really the same but have got a difference in temperature, temperature that is a property that is irrelevant for how the granules behave. The particles, with different temperatures, were fed in to the silo one at the time one to form layers. Three different temperatures where used and the layers formed can be seen in Figure 15. To reduce heat transfer between the layers the value for thermal conductivity and specific heating capacity was set to 10^{-9} [w/m*K] and 10^{9}[j/kg*K] respectively.

Figure 15 shows the snapshot from when the layers are forming; the background color shows the current inlet temperature. The deformation of layers is shown in Figure 16. Notice that the shape of the layers has altered slightly during the filling procedure due to the impact from particles landing on top.

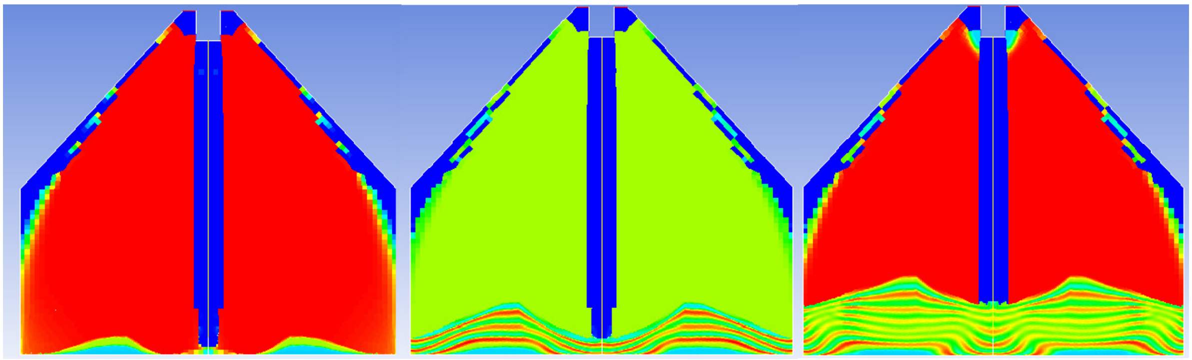

Figure 15 Formation of layers with different temperature

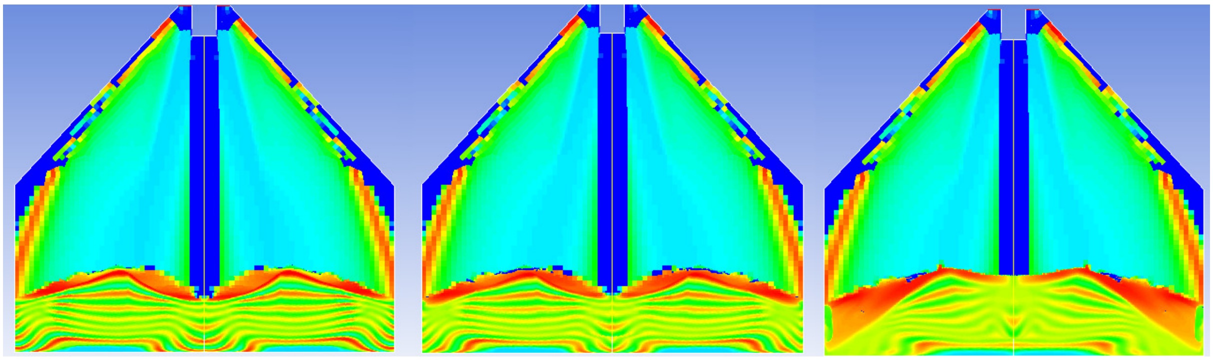

Figure 16 Deformation of layers when the material is fed out

A strange pattern emerged when the material was fed out, and it could only be explained by that the modeling of the screw was wrong. The velocity vectors in Figure 17 shows how the material is moving. This flow profile suggests that the material above the screw is accelerated and reaches a velocity almost as high as the material in the screw. This velocity vectors shows how the particles are moving, at first they move towards the center and when they get to the center particles move upwards. The screw is modeled in the same way as in 5.2 and those simulations are also wrong due to this.

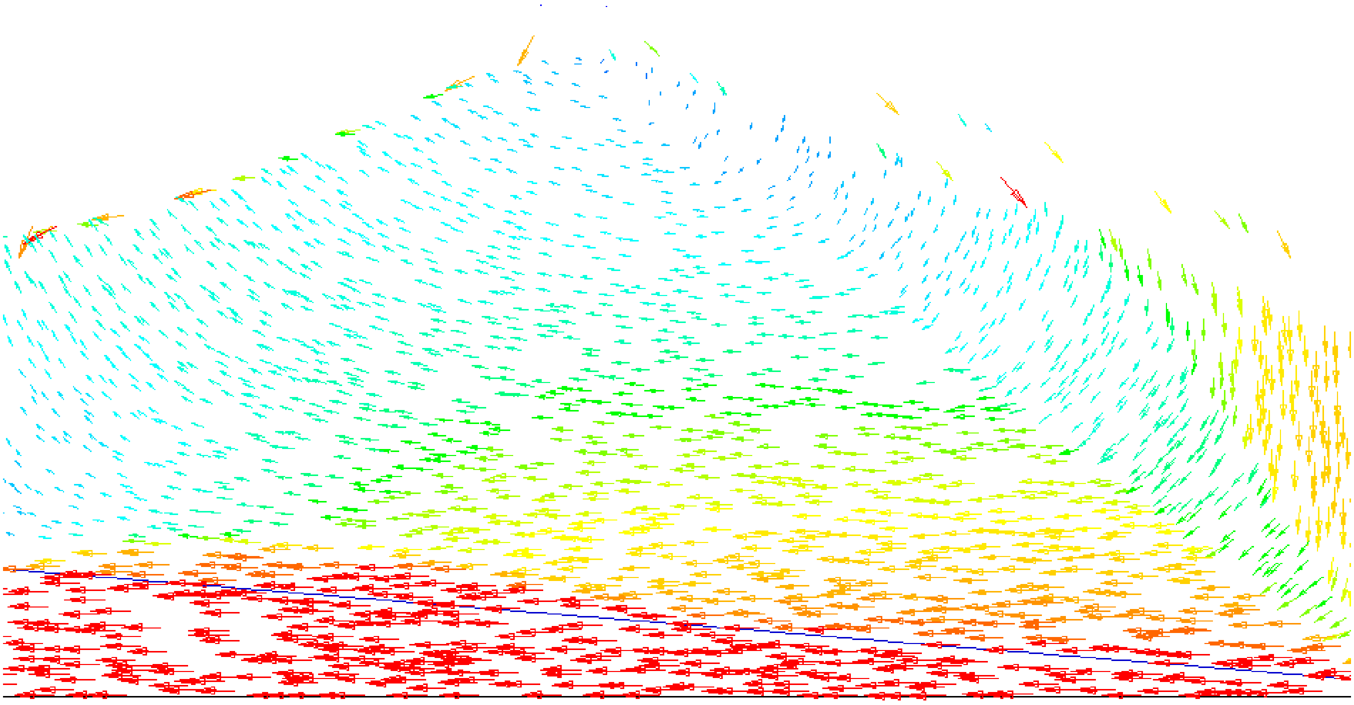

Figure 17 velocity vectors when the material is fed out

5.3.3 Verifying Model Selection

To validate the models used in the main simulations a comparison with experiments by Jaeger and Nagel (1992) was done. In their experiment, a pile with granules with slopes at the internal angel of friction is produced. After that they tilt the pile to increase the angel beyond the maximum stable angel. With a high speed camera it was shown that only the outer ten particles where moving. To simulate this, the direction of gravity was changed instead of tilting the silo. The solid volume fraction and contours lines of velocity are shown in Figure 18. The steep change in velocity shows a clear resemblance to what the experiments showed. Each contour line represents 0.1 m/s.

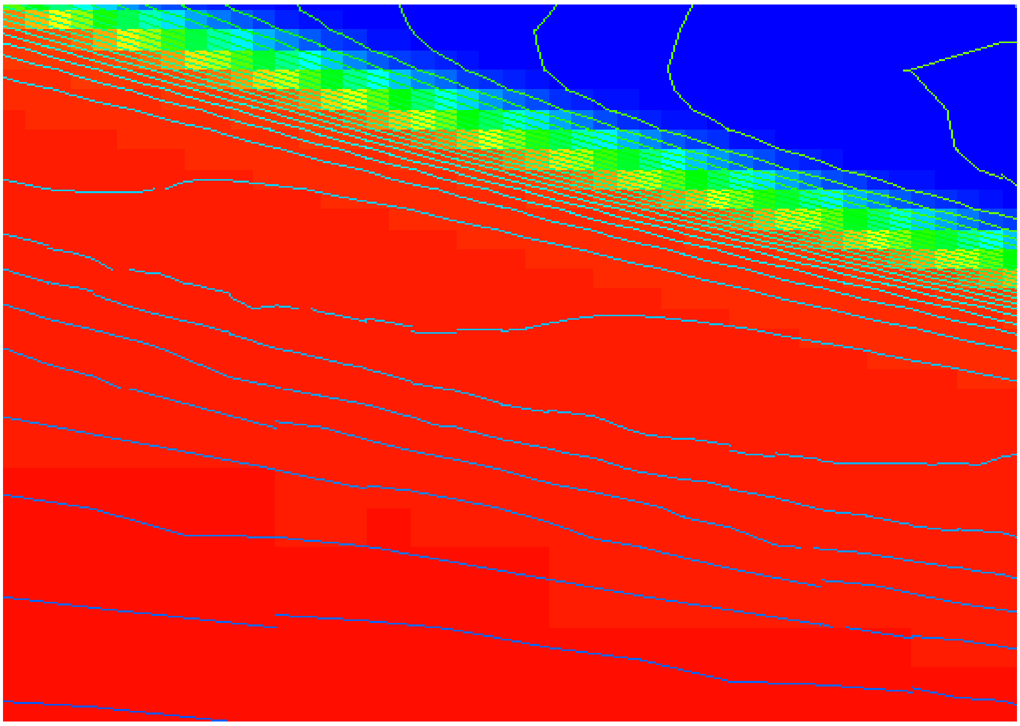

Figure 18 Velocity contours near the surface of the pile after the direction of gravity changed

5.3.4 Full 3d Simulations

The simulations of the system using a full 3d simulation was unfortunately too time demanding to run in the limited time of this thesis, even though the geometry, mesh, case and UDF is done and the initial time steps seems promising. The 3d simulations were necessary to be able to simulate how the screw is working in a correct way. In Figure 19 the screw volume and the velocity defined by the UDF is shown.

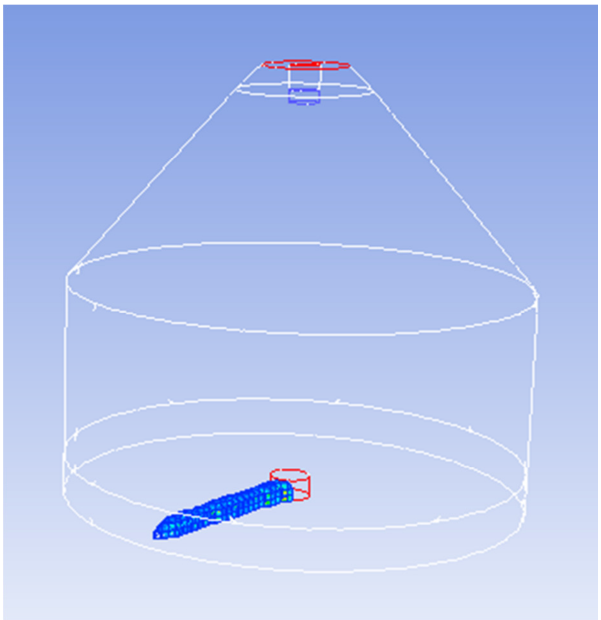

Figure 19 3d geometry with screw

5.4 Silo Measurements

To study the behavior of a real silo measurement on the site in Mölndal was done. The Figure 20 shows the curvature of the top fuel layer inside the silo. The real silo, compared to the simulated has both inflow and outflow simultaneously. The pictures were taken when the silo was about 70% full. The screw is located at a position below where the pit has formed. An ocular inspection inside the silo clearly showed that the pit shape in these pictures is slightly wrong; the pit is actually located from the center all the way to the wall in radial direction, otherwise the pattern is representative.

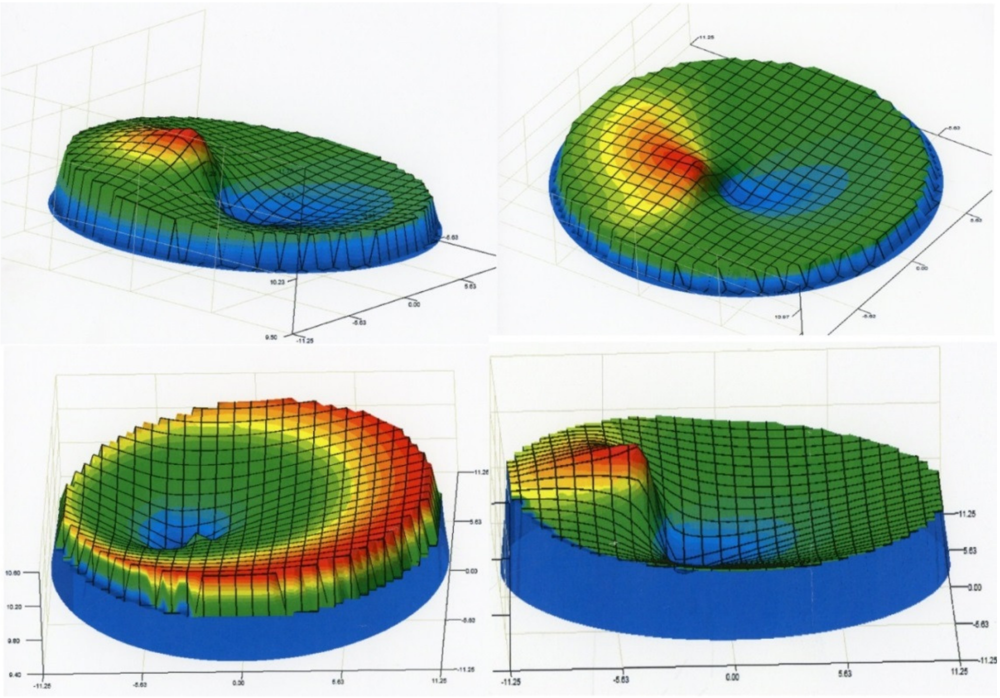

Figure 20 the shape of the top layer from the measurements

6 Discussion and Conclusion

The trustworthiness of these CFD simulations is important to discuss since models use experimental data for calculating the frictional pressure and since the summation of viscosities is somewhat unscientific, it is just known to work.

The simulations for filling the silo shows a reasonable shape of the material if one compares those pictures with the ones from the silo measurements. The simulation in 5.3.3 shows that velocity gradient is very steep and that only the outer layers are moving when changing the direction of gravity. This corresponds well to experiments by Jaeger and Nagel (1992). Therefore it can be suggested that modeling the granules with one term from KTGF plus one for the frictional regime for the viscosity is suitable for this type of system. The actual value of viscosity in the bulk is irrelevant in this static type of system but values of 10^5 Pa*s will definitely put these areas in the categories of a granular solid.

The flow pattern suggested by the simulations in section 5.2 would suggest that the center of the silo contains a stationary zone from where the material more or less never exits unless the silo is totally drained of wood. The way the screw is modeled is wrong as simulations in 5.3.2 showed but the presence of a stationary zone might still be there. In order to model the screw correctly a source term (or fixed value) using a UFD for granular temperature should be added to the screw zone´s conditions. This would lower the viscosity inside the screw and in neighboring cells.

It can be concluded that using this type of gradient adapting mesh is a very powerful tool when dealing with Euler-Euler multiphase systems but whether the mesh used is of optimal size or not is not investigated. The exact decrease in computational time is unknown but compared with having small cells throughout the volume it is really efficient.

Neglecting the drag forces results in a different location for the peak of the pile, but other than that the effect is negligible. The effect of turbulence did not show any major impact and the assumption that its effect could be ignored seems valid. When having more than one size or shape of particles it is not suitable to ignore the drag forces, as shown in section 5.3.1.

The device for measuring the level of fuel inside the silo is flawed which was shown by an ocular inspection in to the silo, even though the generally features were correct, something is wrong with the measurements close to the walls.

The particle size segregation inside the silo is expected to be mainly due to five mechanisms: kinetic sieving, trajectories, angel of internal friction, fines fluidization and air currents. As long as the silo is continuously being filled the segregation effect of kinetic sieving should be insignificant due to that the flow will be in axial direction will be same in time. But when only extracting material, as done during weekends, the extraction of fines will decrease with time because of this effect. The effect of trajectories will have large and dense particles to accumulate in areas closer to the walls then smaller and lighter. The effect of different angel of internal friction is suspected to have minor impact, but more insight is needed. The effect of small particles following the air currents and fines fluidization are suspected effects that should be taken into account especially when evaluating the safety aspect of the plant and the imminent risk of dust explosions.

The five segregation phenomena will also have major impact during the other stages of fuel handling. During the transport to the factory in trucks the effect of kinetic sieving will be were prominent and cause a separation. During discharging from the trucks and when loading the material from one conveyor belt to another causes segregation due different particle trajectories. So when loading the material from one conveyor belt to one, make sure that the conveyor belt have the same velocity direction. An improper design will cause unwanted segregation very much as the one shown in section 3.3 and by Jullien and Meakin (1990) where the bigger particles roll easier then smaller.

7 Future Work

For the future I would recommend to create a UDF that give the screw zone a granular temperature in order to provide the vibrations that exist in the real silo. This would probably solve the problem described in 5.3.2. The 3d simulations should also be run, to be able to more clearly understand the flow patterns of woodchips, as wells as trying to run it as with both inlet and outlet at the same time to resemble the actual system better.

A different way of modeling the granular flow instead of kinetic +frictional as done in this thesis work is using the so called rheology model which has shown promising results . The approach to this model is completely different and uses a different set of equation. But since it was unavailable in the software used it was not tested but could be included using UDFs.

The models used in this simulations is only valid for using one granular phase, therefore segregation mechanisms were not detectable, but simulating a small scale version of the system using a DEM approach could possibly give more insight into the segregation. Using this approach would complement the findings of this thesis to get better understanding of the system. Additional particles sizes and more accurate inlet conditions could be included in the study of drag and turbulence and the whole trajectory to be able to evaluate where different particles sizes will land.

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9 Appendix

9.1 Hand calculations

Calculations of stoke numbers for two different particle sizes

$$t_{d1} = \frac{800 \ast 0.02^2}{18 \ast 10^{-5}} = 1777s$$

$$t_{d2} = \frac{800 \ast 0.003^2}{18 \ast 10^{-5}} = 40s$$

t_s~2s

St>>1

9.2 Notations

CHP	*Combined Heat and Power*
DEM	*Discrete Element Method*
UDF	*Used Defined Function*

α	*Volume fraction*
ε	*Restitution coefficient*
ϕ	*Angel of internal friction*
λ	*Granular bulk viscosity*
μ	*Granular Viscosity*
Θ	*Granular temperature*
ω	*Angular velocity or Specific dissipation*

d	*Diameter of the particle*
g_0	*Radial distribution function*
I_{2D}	*Second invariant of the stress tensor*
P	*Granular pressure*
r	*Radius of silo*
St	*Stoke number*