MATHEMATICAL MODEL OF HEAT AND MASS TRANSFER IN THE STEEL BELT SINTERING PROCESS

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ABSTRACT

The Outokumpu steel belt sintering technology is used for manufacturing chromite pellets that are charged into smelting furnace for ferrochromium production. Hot air is blown through the moving bed of raw pellets. Direct temperature and flow measurements are difficult to do in the bed of a real scale belt sintering process. Therefore, a tested and reliable mathematical model would be a valuable help for optimising operational parameters of the process and designing new constructional improvements. The aim of this work is to present a mathematical model that calculates the gas flow and temperature distribution in the bed of pellets and the atmosphere. Computational fluid dynamics program FLUENT is used to calculate the gas flow, composition and temperature of the gas in the sintering bed during processing. Energy equation for the bed, containing the effects of evaporation of water and oxidation of carbon and iron oxide, will be added to the model to obtain the temperature of the pellets. The porous media model used for pressure drop calculations in the bed is shortly discussed. A comparison between CFD-calculations and experiments with a pilot scale batch-sintering reactor are also presented. The final model can be used as an engineering tool when developing the process and the equipment further. Different designs can be easily tested with the model and the effects of the changes to the flow pattern and temperature distribution can be studied.

1. INTRODUCTION

The Outokumpu steel belt sintering technology is used for manufacturing chromite pellets that are charged into smelting furnace for ferrochromium production. The sintering furnace is divided into seven sections as shown in the Figure 1. In the first three sections, hot air is sucked through the moving bed of raw pellets. In the last three sections cold air is used for cooling the bed. The energy stored to the cooling gases is utilised in the drying, heating and sintering sections to reduce energy consumption. The gas channeled to the heating and sintering sections is further heated with the gas burners. The gas used in the burners can be carbon monoxide formed in the smelting, natural gas or any other liquefied petroleum gas. Additional energy required by the process is obtained from oxidation of iron within chromite and coke added to the pellets. Direct temperature and flow measurements are difficult to do in the bed of a real scale belt sintering process.

Therefore, a mathematical model is developed for optimizing operational parameters of the process and designing new constructional improvements. The model is still under development, but at least preliminary sub-models have been done for all the main phenomena in the process and the presented model predicts reliably gas flow and temperature distribution in the drying compartment. Further development will focus on chemical reactions.

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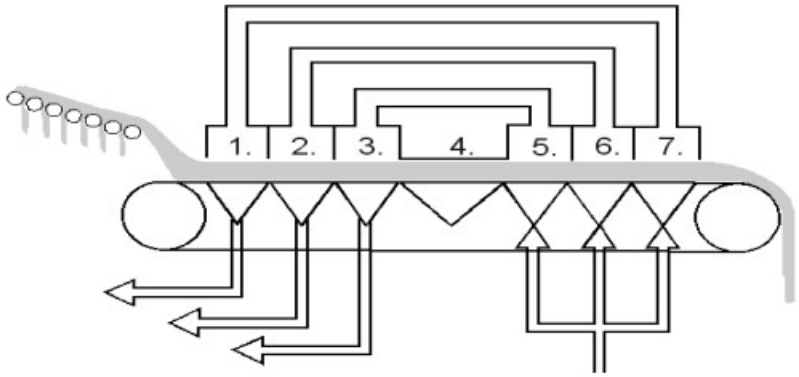

Figure 1. Steel belt sintering process. 1. Drying section, 2. Heating section, 3. Sintering section, 4. Balancing section, 5., 6.and 7. Cooling sections.

2. DESCRIPTION OF THE MODEL

The modelling is carried out with a computational fluid dynamics program FLUENT, which is a finite control volume based computational fluid dynamics program. The steel belt-sintering model is a three-dimensional steady state model. When validating the sub-models with batch sintering experiments, two-dimensional axisymmetric time dependent model is used. Each of the sections of the belt-sintering machine is modelled separately to reduce calculation time required. State of the pellets in the end of each section is used as a boundary condition for the following section. The result of the model mainly consists of state variables (temperature, composition, pressure and velocity) of pellets in the bed and gas in the entire sintering machine.

The phenomena of the sintering process, which are or will be taken into account, are mainly the following:

- structure of the sintering machine and its influence to the gas flow
- gas pressure drop in the bed, formulated by the differential Ergun law
- change in gas composition
- motion of the sintering bed
- heat exchange between gas and pellets
- water evaporation and condensation
- oxidation of coke added to the pellets
- oxidation and reduction of chromite.

The sub-models describing oxidation of coke and oxidation and reduction of chromite are only preliminary at this stage. Although some experiments have already been done, more will be done to find out which physical or chemical phenomenon restricts the reaction inside an individual pellet at different stages. With this information it is easier to make sub-models more reliable.

2.1 Modelling gas composition and flow

Geometries and computational grids of the compartments were made with GAMBIT pre-processing program. Flow calculations were performed with FLUENT. It solves mass conservation equation, the same number of momentum equations as dimensions in the model and two turbulence equations when k-ε model is chosen. The sintering bed is treated as porous media. This means that one extra source term, calculated by the Ergun equation, is added to the momentum equations.

Evaporation and condensation of water and chemical reactions in the pellets change the composition of flowing gas. This affects the speed of these phenomena and also physical properties of the gas. Therefore the composition of the gas has to be modelled. Gas is assumed to consist of four components: nitrogen, oxygen, carbon dioxide and water vapour. Mass fractions of each of the components are calculated with FLUENT's species transport model. In the model conservation equations for oxygen, carbon dioxide and water vapour are solved. Mass fraction of nitrogen can be calculated from the fact that the sum of mass fractions of all

components must be equal to one. User defined functions have been written to add source terms of oxygen, carbon dioxide and water vapour.

2.2 Modelling temperatures of gas and the pellets

Energy equation of the gas is solved to model temperature of the gas. This is a standard feature of FLUENT. In the porous media model it provides, no extra energy equation for the solid part is solved, but its effect is taken into account in the same equation. This can be done when the gas and the solid are locally at the same temperature. This is not a valid assumption in the case of the sintering process. Therefore an energy equation for the pellets is also solved.

When using this approach, heat exchange between gas and the pellets has to be modelled. This is done with the equation

$$S = h_V \left(T_g - T_p \right), \tag{1}$$

where: $S =$ heat transferred from the gas to the pellets per unit volume and time

$h_V =$ heat transfer coefficient between gas and the pellets

$T_g =$ temperature of the gas

$T_p =$ temperature of the pellets.

This term is added to the energy equation of the pellets and subtracted from the energy equation of the gas.

Energy released or absorbed in evaporation and condensation of water and chemical reactions are also taken into account in the corresponding energy equation.

2.3 Water evaporation and condensation

Water content of the pellet is also modelled by solving its conservation equation. Drying is assumed to be restricted by the heat exchange between gas and the pellets and heat conduction inside the pellets. Energy transferred from gas to the pellets is assumed always to follow the equation (1). When the pellets are wet most of the energy is used to evaporate water from the pellets instead of warming them. When the pellets get dryer, the portion of the energy used for evaporation decreases and the portion used in the temperature rise increases.

When the water evaporates in the upper parts of the sintering bed the gas becomes humid. A necessary condition for the drying to take place is that the water vapour pressure has to be smaller than the saturation water vapour pressure, which is strongly dependent on the temperature of the gas. As the gas is cooled in the lower parts of the bed, this condition is not fulfilled. When the relative humidity exceeds 100%, water will condense on the pellets. The phenomenon is taken into account in the model.

2.4 Oxidation of coke

A lot of models for oxidation of coke can be found in the literature. Most of those treat coke particles that diminish as the burning progresses. The case is different for chromite pellets since the coke is inside the pellets as fine dust, which is mixed with the chromite ore before pelletising. The temperature of the pellets restricts the speed of oxidation in the beginning, but as the burning progresses, diffusion of gases inside the pellet starts to restrict the reaction. A simple preliminary sub-model is created to describe the phenomena, but further development and experiments are needed.

2.5 Oxidation and reduction of chromite

Most of the iron in the chromite ore is in the form Fe^{2+} but it oxidises to Fe^{3+} during the process. The speed of oxidation varies a lot depending on the conditions inside the pellets. In fact, when coke is burning, carbon monoxide content in the pores inside the pellets increases and reduction of Fe^{3+} occurs. The task of creating a sub-model simple enough to be imbedded in a computational fluid dynamics program is challenging. A sub-model that describes the phenomenon tolerably for the pellets without coke has been added to the model, but further development is needed.

3. DETERMINATION OF PHYSICAL PARAMETERS

Physical parameters of gas components like specific heat, thermal conductivity, viscosity and molecular weight were taken from FLUENT's database. Some of those were calculated by assuming temperature dependence to be piecewise linear. Some physical parameters like viscous and inertial resistance coefficient of the porous media model, specific heat and thermal conductivity of the pellets and heat exchange coefficient between gas and the pellets, had to be measured. The sensitivity of the model with respect to the parameters was tested.

3.1 Viscous and inertial resistance coefficients

Cold gas was blown through a 40 cm thick sintering bed to find out viscous and inertial resistance coefficients for the Ergun equation. The speed of the gas was increased and the pressure drop over the bed was measured. The resistance coefficients were adjusted to fit the data. When the inertial resistance coefficient was increased and decreased by 10% the total pressure drop over the bed was increased and decreased by only 0.15% respectively. When the viscous resistance coefficient was increased and decreased by 10% the total pressure drop over the bed was increased and decreased by 9.8% respectively.

3.2 Specific heat of the pellets

The specific heat of the pellets was measured as a function of temperature with a differential scanning calorimeter. According to the experiments, specific heat of the pellets ranges between 550 and 1200 J/kgK in the conditions of the sintering process. The propagation speed of the heat front in the bed is quite sensitive to the specific heat of the pellets. When it is too small the heat front propagates too fast and when it is too big the propagation is too slow.

3.3 Thermal conductivity of the pellets

Thermal diffusivity of the pellets was determined by heating a pellet and measuring temperatures inside it at different distances from the surface. The thermal conductivity was calculated from the thermal diffusivity and the specific heat of the pellets. According to the experiment the thermal conductivity ranges between 0.1 and 0.55 W/mK in the conditions of the sintering process.

3.4 Heat exchange coefficient between gas and the pellets

The heat exchange coefficient between gas and the pellets was determined with the following experiment. A chemically inert pellet was placed inside a sintering bed. Temperatures were measured inside the pellet and in the gas a few millimetres away from the surface of the pellet. The heat transferred to the pellet per unit time was calculated from the temperatures of the pellet. By knowing the surface area of the pellet, total area of the pellets in a unit volume of bed and the temperature difference between the surrounding gas and the pellet, it was possible to calculate the heat exchange coefficient. Different gas speeds and temperatures were used. With temperatures ranging from room temperature to 1500K and gas speeds ranging from 0.4m/s to 1.2m/s the heat enhance coefficient was between 15 and 90 kW/Km^3. The total energy balance of the bed is not very sensitive to the heat exchange coefficient. The errors in the parameter affect more to the temperature gradient inside the bed. If the heat exchange coefficient is too big, the heat front in the bed is too thin and vice versa.

4. VALIDATION OF THE MODEL

Many error sources like bad quality grid, too big time steps, numerical errors, bad convergence and too heavy consumptions when deriving equations, must be taken into account when developing a mathematical model. Qualities of the computational grids were tested with tools available in the pre-processor. Grid independence tests were also made for the geometries used in the calculations to estimate minimum number of cells needed. Typically for each of the compartments of the steel belt sintering machine it was around 500 000. Different time step lengths were tested to find out maximum accurate time step in the time dependent calculations. It was also verified that the pressure drop in the sintering bed could be modelled with the porous media model. Calculations were performed with two two-dimensional geometries. In the first one pellets were treated separately. In the second one the bed was treated as a porous media. Good agreement was found as shown in the Figure 2. In discretization of equations, second order accuracy was used whenever possible to minimize numerical errors. Assumptions of the heat exchange model were tested with a simple

one dimensional single pellet heat conduction model. More complex single pellet chemical reaction models will be used for further development of oxidation sub-models.

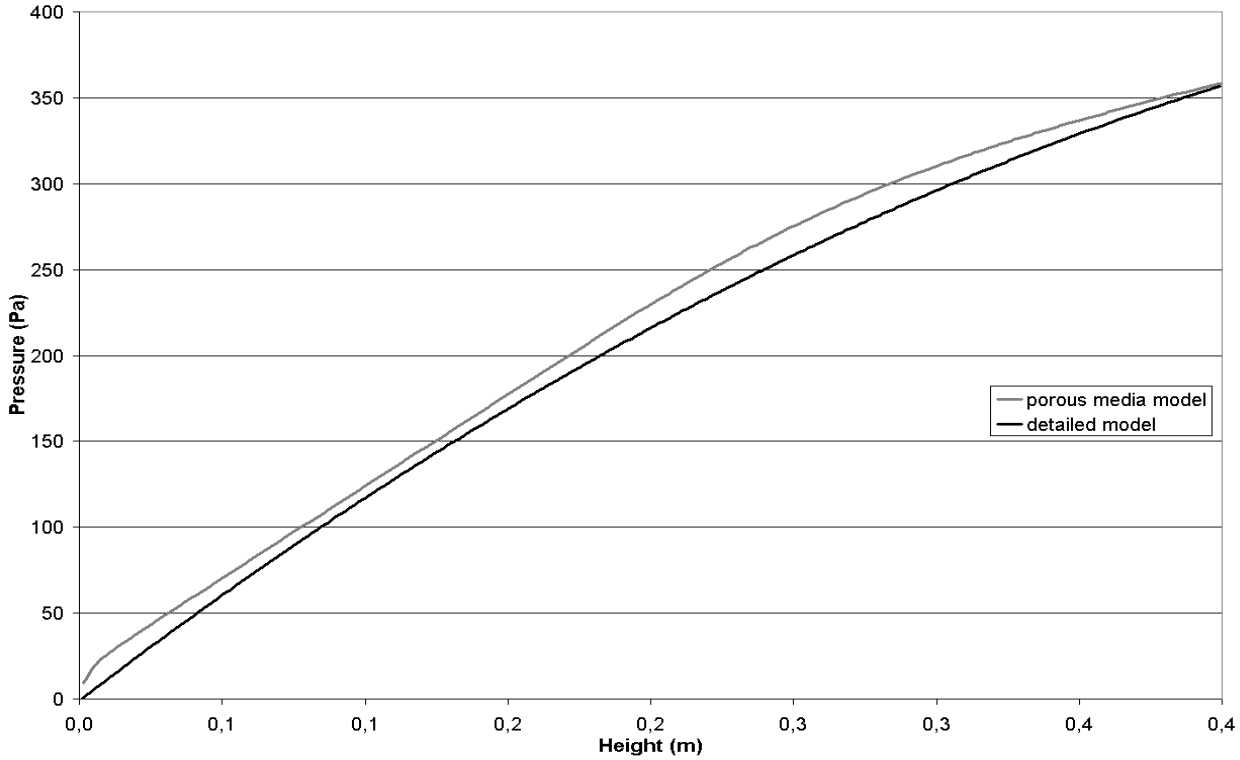

Figure 2. The comparison of the pressure drop inside a sintering bed when detailed and porous media models are used.

4.1 Pilot scale batch sintering reactor

The most reliable way to validate the model is to compare its results to experimental measurements. Since Outokumpu has done a lot of pilot scale batch sintering experiments at Outokumpu Research Oy in Pori, those experiments were also modelled. This could be done with only small changes to the model. The model was changed to a two-dimensional axisymmetric time-dependent model and convection terms were removed from the equations. The batch sintering reactor used in the experiments was the same as used by Daavittila et. al.[1]. The grid used in the model of batch sintering reactor is shown in the Figure 3.

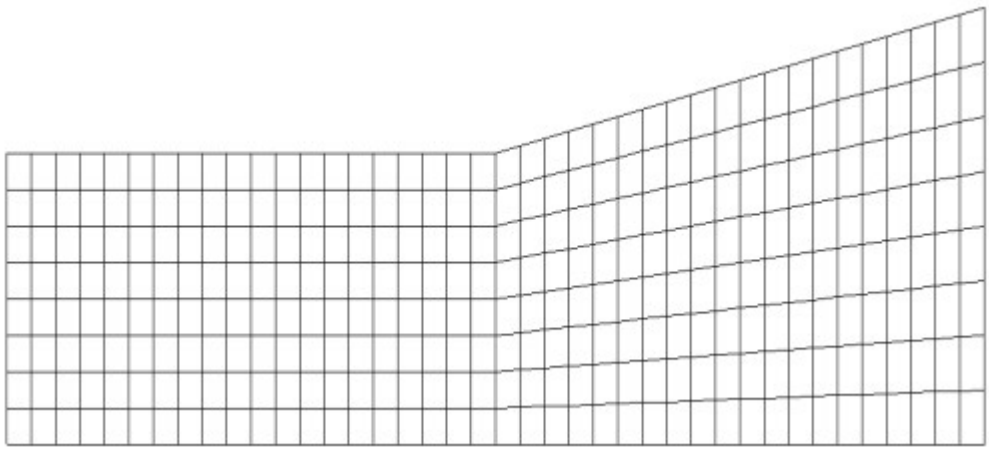

Figure 3. The grid for the pilot scale batch-sintering reactor.

The temperature of the gas blown through the surface of the bed (right in the Figure 2) in the batch sintering experiment was set as a boundary condition in the calculations. Heat flow through the walls was assumed to be negligible to the temperatures in the centerline of the reactor where the temperatures were measured. The mass flow rate and the gas composition in the calculations were also set to match the experiments. First the

model was tested with dry and chemically inert pellets to see how the heat exchange sub-model worked without water and chemical reaction sub-models. The measured and predicted temperatures are plotted in the Figure 4. During the heating sections the agreement was excellent. In the cooling section the model predicted slightly too low temperatures, but in general the model works well.

The drying and condensation model was tested with normal chromite pellets. The results are shown in the Figure 5. In the experiments the gas temperature rises rapidly between 50 and 100 seconds. This is due to the heat released in the condensation of water. As the temperature rises to 320 K the saturation water vapour pressure rises also and condensation stops. In the model the condensation front is not as thin as in reality, but the difference in the temperatures is small and hence not significant for the whole process. According to simulations the model predicts temperatures well in the drying compartment.

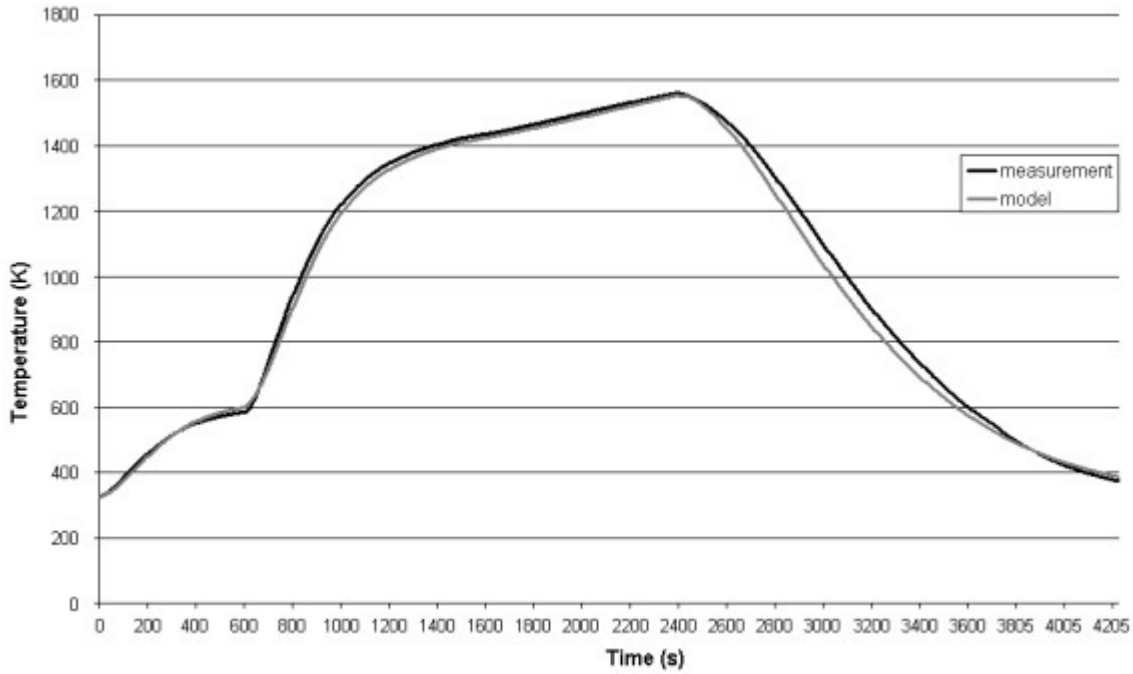

Figure 4. Comparison between measured and modelled gas temperature in batch sintering experiment with chemically inert and dry pellets.

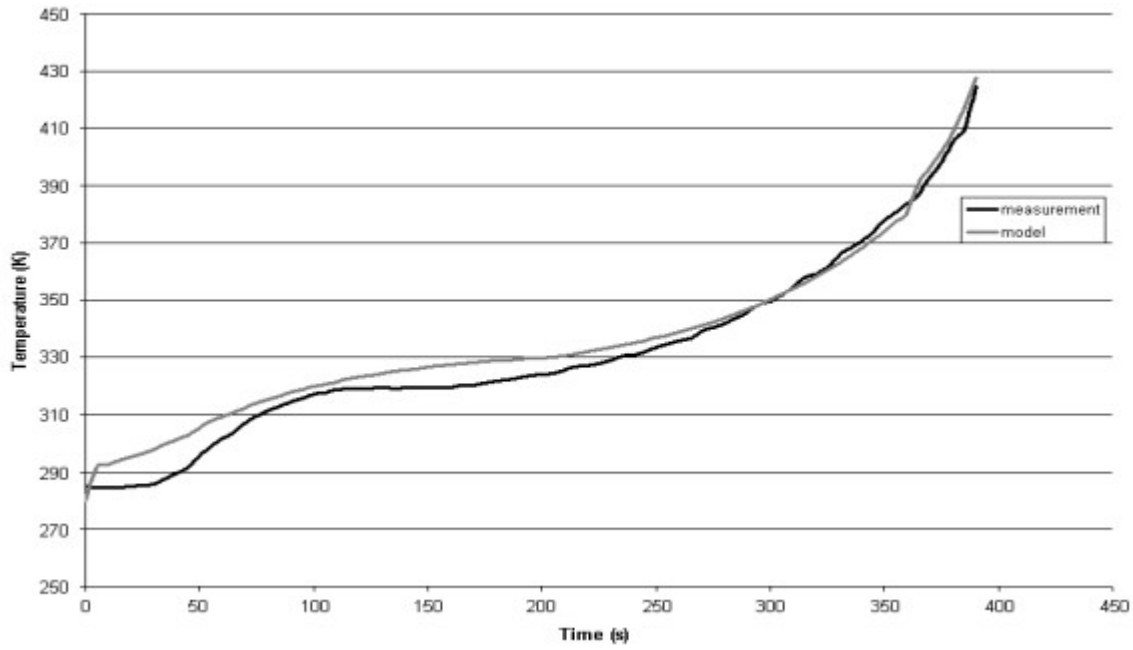

Figure 5. Comparison between measured and modelled gas temperature in batch sintering experiment in the drying compartment.

5. RESULTS

As an example of the use of the model, it was applied to the drying compartment. Hot gas with a temperature of 625 K was sucked through the sintering bed as the bed was moving with a speed of 1 cm/s. The gas temperatures in the sintering bed in a plane along the centreline of the bed are shown in the Figure 6.At the end of the compartment the gas temperature was nearly 625 K at the surface of the bed, while in the bottom the temperature was around 320 K, only a few Kelvins higher than the temperature of the pellets fed in to the compartment.

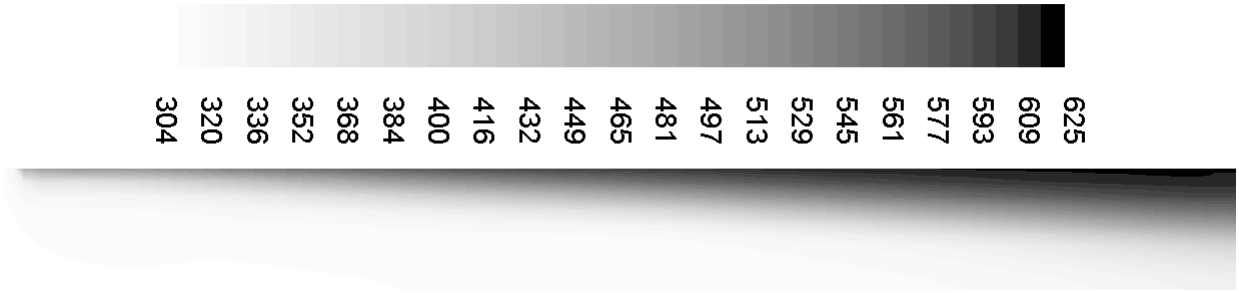

Figure 6. Gas temperature (K) in the drying compartment along the centreline of the sintering bed.

The mass fraction of water in the pellets in the same plane is shown in the Figure 7. A layer of pellets that are already sintered is placed to the bottom of the bed to protect the steel belt so the mass fraction of water was zero at the bottom in the beginning of the compartment. The mass fraction of water in the raw pellets was 0.09 in this particular case. The pellets at the surface began to dry immediately. Due to condensation the mass fraction of water increased to 0.095 at the bottom of the layer of raw pellets. In the pellets that were already sintered the water content increased to 0.01. At the end of the compartment the surface had dried and the maximum mass fraction of water was 0.02 at the bottom of the raw pellets.

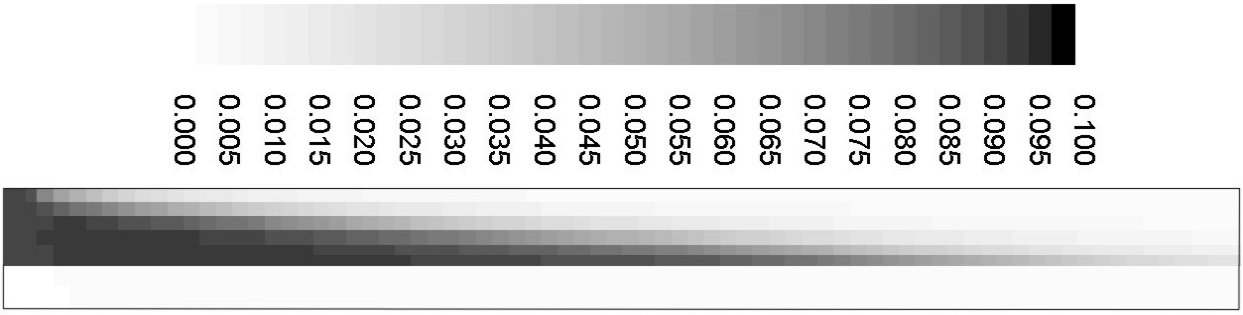

Figure 7. The mass fraction of water in the pellets in the drying section along the centreline of the sintering bed.

The model is also able to predict the flow pattern in the entire compartment. As an example of this a detail from the side of the bed on a plane across the bed is shown in the Figure 8. The length and the colour of a vector represent the speed of the gas at the beginning point of that vector. In some areas the vectors are closer to each other. This is due to a finer grid and it does not mean that more gas is flowing there.

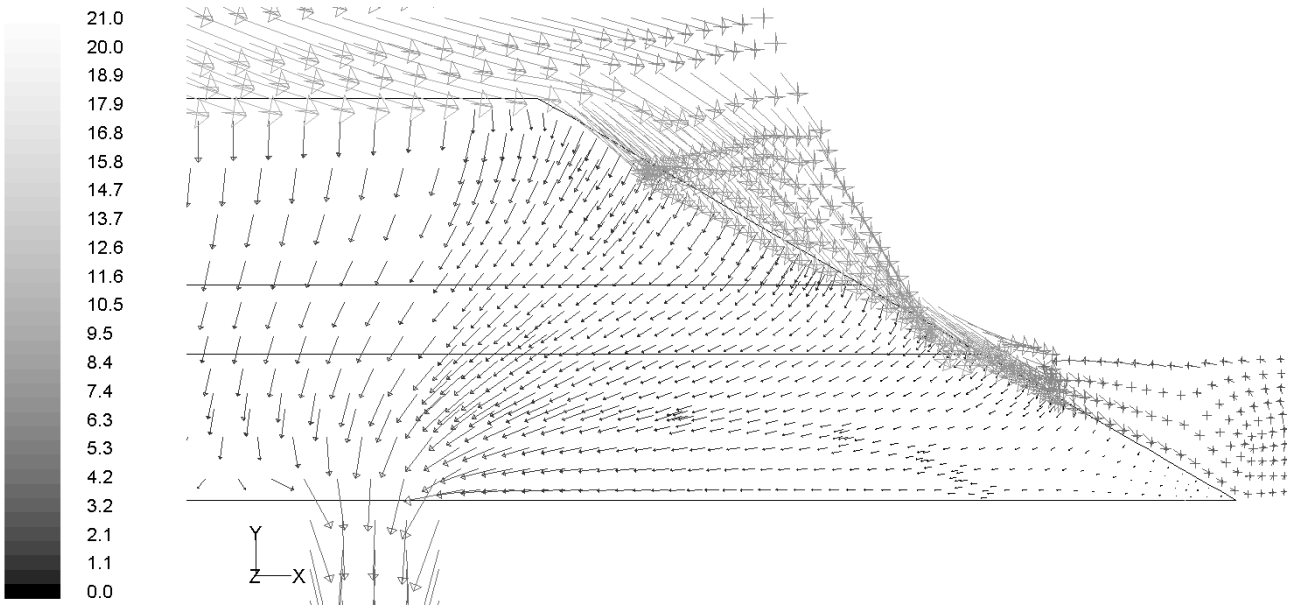

Figure 8. Velocity vectors of the gas in the drying compartment. A detail from the side of the bed on a plane the across the bed.

6. CONCLUSIONS

The mathematical model of the Outokumpu steel belt sintering process developed at University of Oulu is able to predict pressure drop and flow in the sintering bed and also the composition and temperatures of the pellets and gas. The results are proven to be accurate in the drying compartment and in the case of chemically inert pellets. The model also gives qualitative information from other compartments, but to get accurate quantitative information, further development of the chemical reaction sub-models is needed.

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