CFD MODELLING OF THE STEEL BELT SINTERING PROCESS

J. Keihäs, P. Mäkelä, J. Ollila[1] and L. Hekkala[2]

Outokumpu Technology Research Centre, P.O. Box 60, FIN-28101 Pori, Finland
[1]Outokumpu Technology Oy, P.O. Box 103, FIN-02201 Espoo, Finland
[2]University of Oulu, Laboratory of Process Metallurgy, P.O. Box 4300, FIN-90014 Oulu, Finland
E-mail: juha.keihas@Outokumpu.com

ABSTRACT

The Outokumpu Steel Belt Sintering (SBS) Technology is used for manufacturing chromite pellets that are charged into a smelting furnace for ferrochromium production. One of the main elements in successful furnace operation is the control of gas flows inside the furnace, giving improved temperature distribution in the bed during the process. Computational Fluid Dynamics (CFD) gives excellent opportunities for studying these phenomena. An investigation using CFD can be performed relatively fast. For example, implications of different configurations can be studied within a day and an optimum design chosen. Therefore, Outokumpu Technology has developed a Steel Belt Sintering Model (SBSM), which takes advantage of a commercial CFD code.

Each main physicochemical event occurring in a steel belt sintering furnace is incorporated independently in the SBS model as a sub-model, enabling every event to be studied separately. The commercial CFD code solves mass, momentum, species and energy equations for determination of the gas flow, composition and temperature. In addition, the Outokumpu SBSM takes into account the moving pellet bed, drying of pellets in terms of water content, coke combustion, oxidation and reduction of chromite and the decomposition of carbonates and silicates.

During the development of the model, numerous laboratory-scale tests were performed. The sub-models were validated against the laboratory tests. The reliability of the Outokumpu Steel Belt Sintering Model was validated against a pilot-scale batch-sintering furnace by comparing the modelling results against measurements.

The aim of this paper is to give a brief presentation of the Outokumpu steel belt sintering model by showing some general modelling examples. Emphasis has been placed on demonstrating some of the main features of the model.

1. INTRODUCTION

Since 1989, Outokumpu has been using the Steel Belt Sintering process (SBS) for the production of sintered chromite pellets at the company's Ferrochrome Plant in Tornio, Finland. The SBS plant produces spherical, hard and porous chromite pellets with constant physical and chemical properties for use as a charge material in FeCr smelting in the submerged-arc furnace. The pellets are a superior feed material compared to lumpy ore and briquettes. Outokumpu Technology has supplied eight SBS processes to the Republic of South Africa, Kazakhstan and Brazil since 1998. The capacity is now up to 700 000 t/a sintered chromite pellets.

Each SBS plant is custom-designed to ensure the quality of the pellets and productivity of the plant. Outokumpu Technology's R&D Centre in Pori (ORC) has comprehensive facilities for testing the sinterability of different chromite grades. Manganese and niobium oxides have also been successfully sintered using SBS technology. Outokumpu is continually developing the SBS process to increase process efficiency. As a consequence, Outokumpu has an on-going development programme using CFD modelling to optimise SBS furnace performance.

Heat transfer inside the pellet bed is the critical factor influencing sintering process efficiency. Heat transfer affects moisture evaporation, decomposition of hydroxides and carbonates, ferrous iron oxidation, and partial softening and melting of gangue minerals. The final strength of sintered chromite pellets is based the formation of a molten silicate phase.

The gas velocity profile and temperature field inside the porous pellet bed is very difficult to determine in existing production. Thus, CFD modelling is an attractive alternative, providing a detailed understanding of the mass and energy transfer in the sintering furnace. Outokumpu has been developing mathematical submodels to study the SBS furnace performance since the year 2000. Calculations are carried out with the commercial CFD-code Fluent 6.2.

2. DEVELOPMENT OF THE STEEL BELT SINTERING MODEL FOR CFD

The steel belt sintering model (SBSM) is implemented in the commercial Computational Fluid Dynamics code FLUENT. The Fluent software bundle includes GAMBIT, which is a CAD-like pre-processor and geometry creation tool. The pre-processor allows you to make geometrical changes to the sintering furnace model relatively easily. Therefore, it is easy to compare the implications of geometrical changes against the performance of the sintering furnace.

Gas flows in the bed are modeled with the porous media-model and the gas composition is solved with the species transport-model. These two models are standard models within the FLUENT code. In addition to the standard models the SBSM solves 1) gas flows and composition, 2) temperatures of pellets and gas 3) drying of pellets 4) coke combustion and 5) chromite oxidation-reduction and 6) decomposition of carbonates and silicates.

The real challenge with the development work of the SBS model is the fact that the most important process phenomena are taking place on many different scales. With the SBS model, the whole steel belt sintering process can be solved simultaneously, although the largest flow dimensions can be up to tens of metres whereas, in the pellet bed even over a distance as small as a couple of centimeters, temperature changes of hundreds of degrees of Celsius are not uncommon. Important heat and mass transfer phenomena regulating drying, coke combustion and chromite oxidation occurs at pellet scale. In addition, the pores with dimensions typically of a couple of micrometers affect these phenomena. The smallest chromite particles are at the same scale where mass diffusion occurs. The smallest scales are represented by the kinetics of chemical reactions and thermodynamics.

During the development work of the sub-models for the SBSM, a vast number of laboratory tests were done. During these tests each phenomenon and its limiting factors were studied carefully. Sub-models describing drying and chemical reactions were first developed for a separate pellet and generalized to the computing cells representing the pellet bed in a numerical grid. The density of the grid also limits the accuracy of the model. The dimension of a computational cell is at the best a couple of centimeters in each dimension. This also gives an idea of the accuracy of the model. In future, finer grids are expected due to more efficient computers.

2.1 Sub-model for the Drying of the Pellet Bed

Based on experimental observations it can be shown that pellet drying goes through three separate stages, namely: 1) during the first phase the temperature of the pellet is moderate, water content high and pellet surface moist. A vast amount of the energy transferred to the pellet is consumed for heating the pellet. 2) During the second phase, the heating rate decreases and drying rate increases. During this process, the energy consumed for drying is almost equal to the heat energy transferred from gas to pellet. The moisture of the pellet is still relatively constant in radial direction. The drying rate is steady during the whole phase provided that the environment of the pellet does not change. 3) During the third phase, the moisture content of the pellets starts to reach the critical moisture level~~,~~ which is determined by laboratory experiments. It can be observed from measurements that the surface temperature rises rapidly at the beginning of this phase. This is a consequence of the fact that liquid water is not transferred by capillary forces to the pellet surface, in which case the surface dries and the boiling temperature of water does not limit the temperature. The drying front approaches the centre of pellet. The temperature of the wet core according to measurements cannot reach temperatures much above 100 °C. Therefore, it can be assumed that the water in the pellet core is not strongly bonded and acts like free water. The drying model takes into account the internal and external heat and mass transfer.

Figure 1 shows a comparison between the modeled and the moisture measurement with a TG furnace based on pellet temperature and mass when the furnace temperature was kept at 200 °C and gas flow rate at 0.05 m/s. It can be noticed that the SBS model predicts the drying process well. The predicted heating rate of pellet is slightly rapid in the beginning and rather slow towards the end of the period, compared to the observed values. However, the shape of the surface temperature curve is correct.

The drying time with different furnace temperatures is shown in Figure 2. At low temperatures the model predicts a slightly faster drying, but already at temperatures of 200 °C the prediction is excellent.

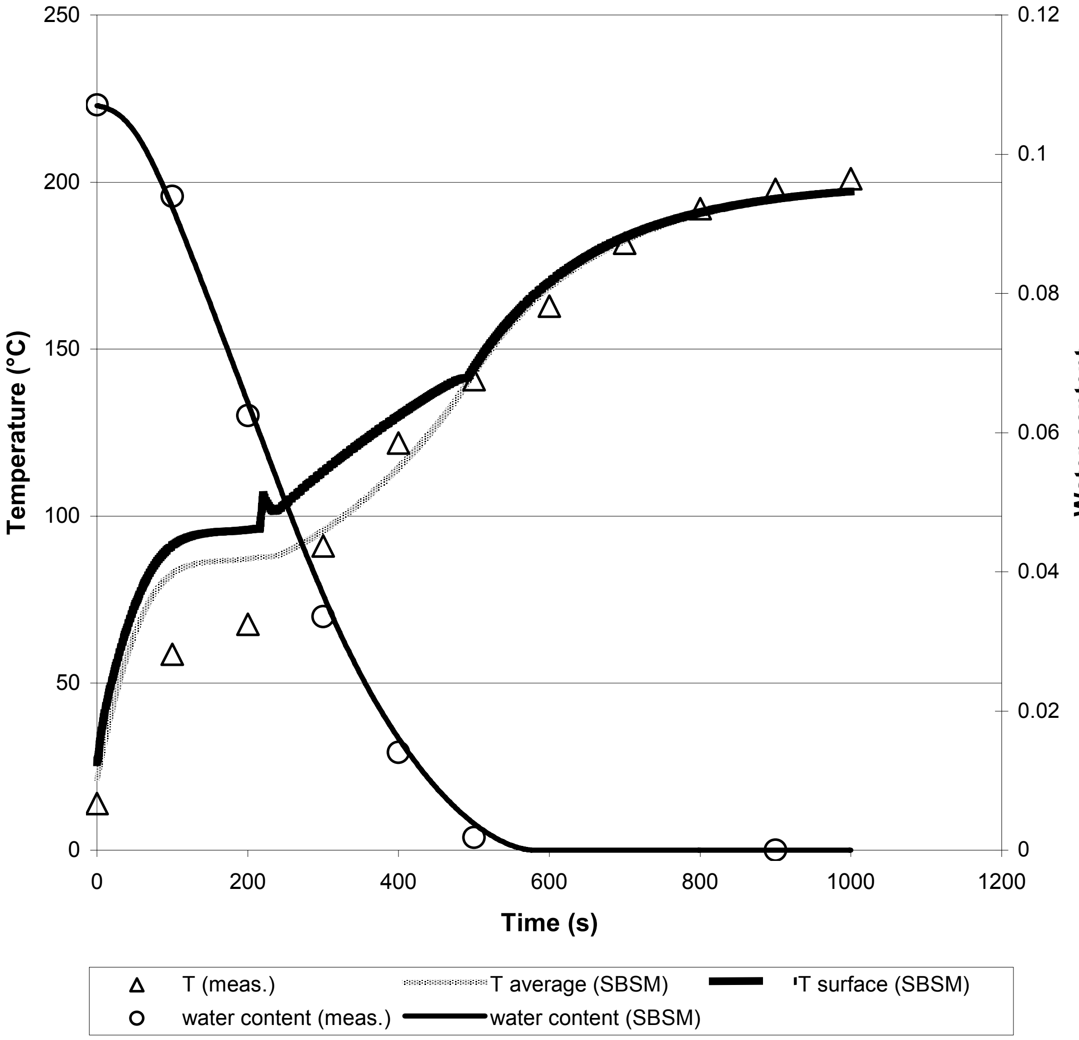

Figure 1: Comparison of the sub-model for drying against experiments. Pellet temperature and moisture. Furnace temperature kept constant at 200°C

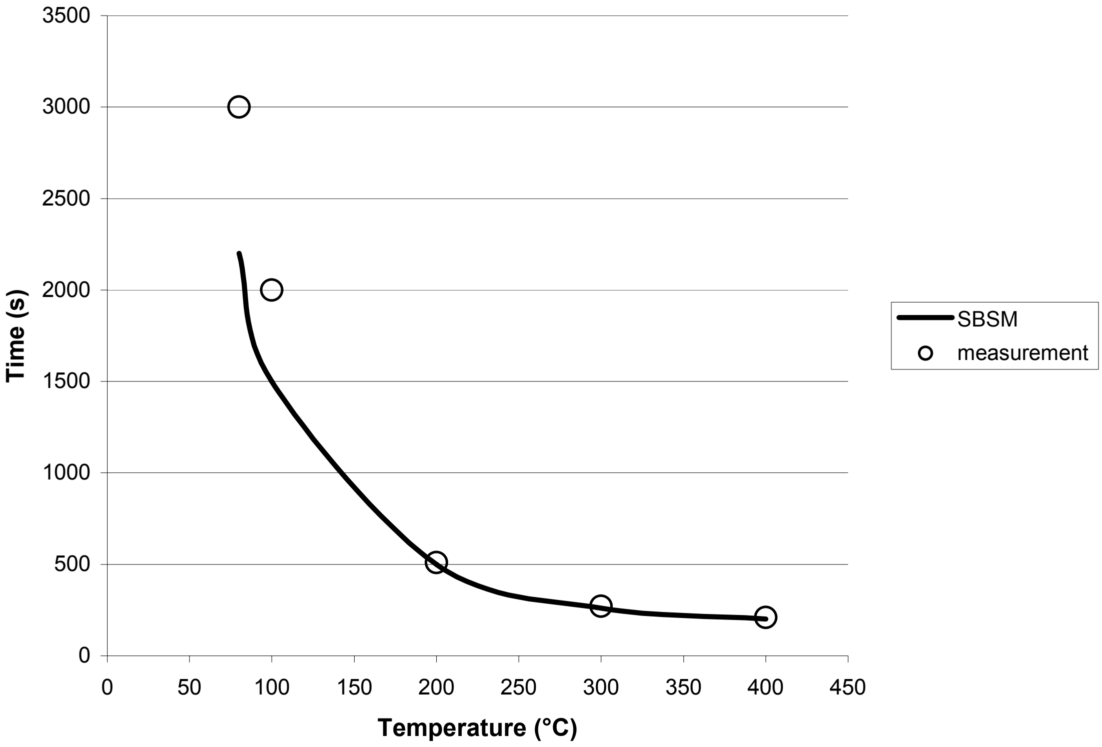

Figure 2: Drying time of pellet with different furnace temperatures, drying time vs. furnace temperatures

2.2 Dual-shell (layer) Model for the Burning of Coke and Chromite Oxidation-reduction Reaction

Results of interrupted tests with the TG furnace proved that the combustion of coke takes place in a thin layer, in a reaction front when the temperature exceeded 850°C. This fact made it possible to describe the oxidation of coke by the shrinking core-model [1].

A visual examination of the reaction front is not as straightforward as it is with coke. Isothermal experiments with chromite powder were made with a DSC furnace. Based on these experiments it was concluded that the oxidation of the chromite powder is very fast at the beginning. This implies that for the chromite too, the majority of the oxidation takes place at the reaction front. After this it was noticed that the rate of oxidation decreased rapidly while the mass increased and it was concluded that the oxidation was limited by the diffusion of oxygen between single chromite particles, which supports the assumption of a reaction front. Finally, the front assumption was proved with a detailed pellet-model [2]. Chromite and coke oxidation starts at different temperatures and for this reason, a dual layer oxidation model was developed. At high temperatures the layers propagate simultaneously.

Experiments with DSC furnace showed that after the rapid oxidation of chromite at the beginning it slowed down considerably. This is due to two factors: 1) there is a large size distribution in the chromite powder. The small particles oxidise significantly faster than the larger ones. 2) On the other hand, the sesquioxide layer formed on the surface limits the mass transfer in a single particle and therefore limits the overall reaction. A chromite powder-model, which takes into account both phenomena during the last phase of the oxidation of chromite was developed and implemented in the SBSM.

When the temperature reaches its maximum the already oxidised chromite starts to reduce, just as the law of thermodynamics predicts. The chromite powder model can also predict this phenomenon and likewise the re-oxidation when the temperature decreases.

3. MODELLING THE STEEL BELT SINTERING PROCESS

The SBSM model was tested with a sintering machine model for all the different zones individually and in simplified furnace geometry where all the zones were modeled simultaneously. The results were compared against laboratory tests [3].

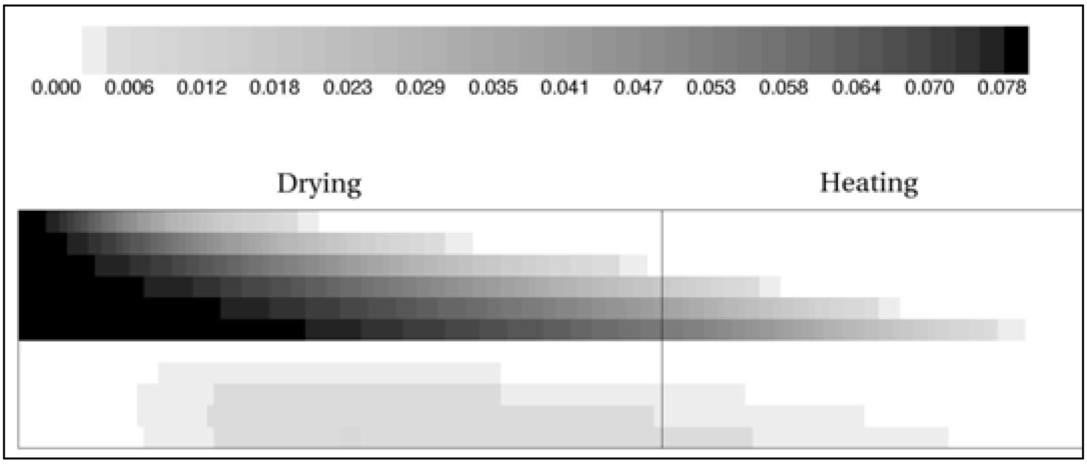

Figure 3: Water content of pellets in the drying zone

The water content in the drying and heating zone is shown in Figure 3. The surface of the bed dries already in the drying zone, while the bottom of the wet bed dries in the heating zone. Furthermore, Fig. 3 shows that water is condensed at the beginning of the lower layer. The condensation of water can also be seen in the figure below (Fig. 4), which shows the mass fraction of water vapour in the gas phase.

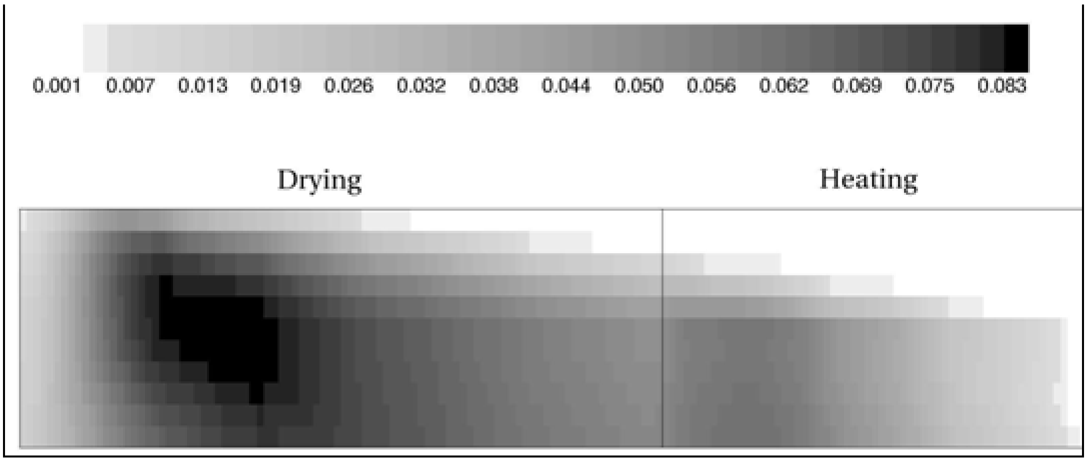

Figure 4: Mass friction of water vapour in the gas phase in the drying zone

The gas temperature distribution and the average temperature of the pellets are shown in Figures 5 and 6, respectively. It can be noted that the bed is heated up reasonably during the first three zones and cools in the cooling zones. The maximum temperature of the gas according to the model is 1399°C (1672K) and for the pellets 1400°C (1673K), while the temperature of the entering gas is 1357°C (1630K). The temperature difference between gas and pellets is shown in Figure 7. The gas temperature is at maximum 215°C (215K) higher in the pre-heating zone and 110°C (110K) lower in the cooling zone.

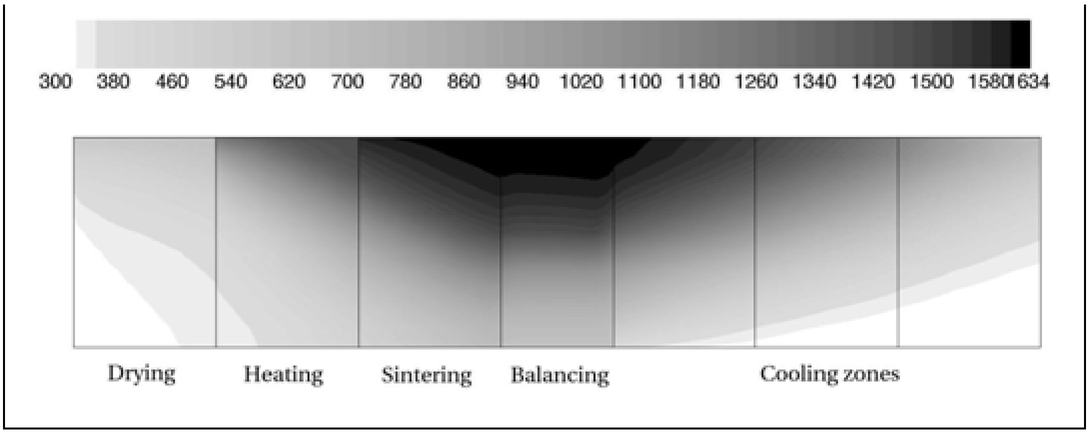

Figure 5: Temperature distribution of the gas in the bed

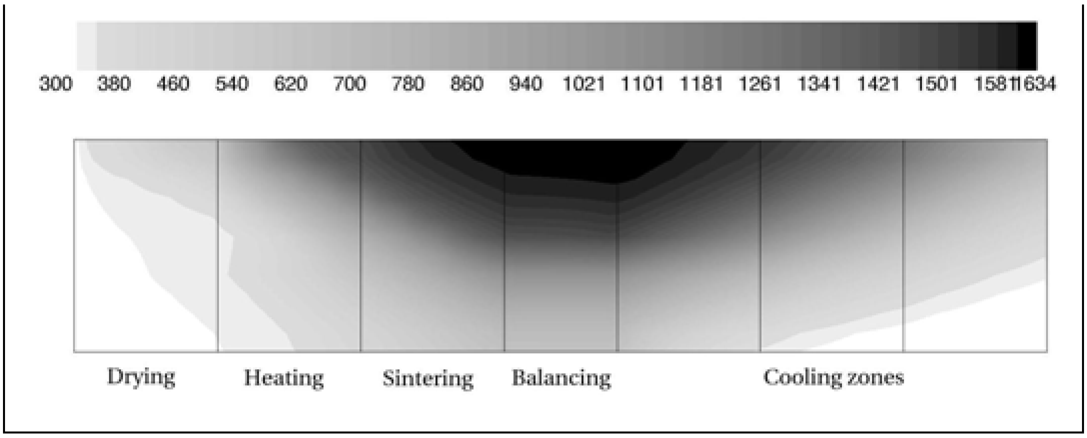

Figure 6: Average temperature of pellets

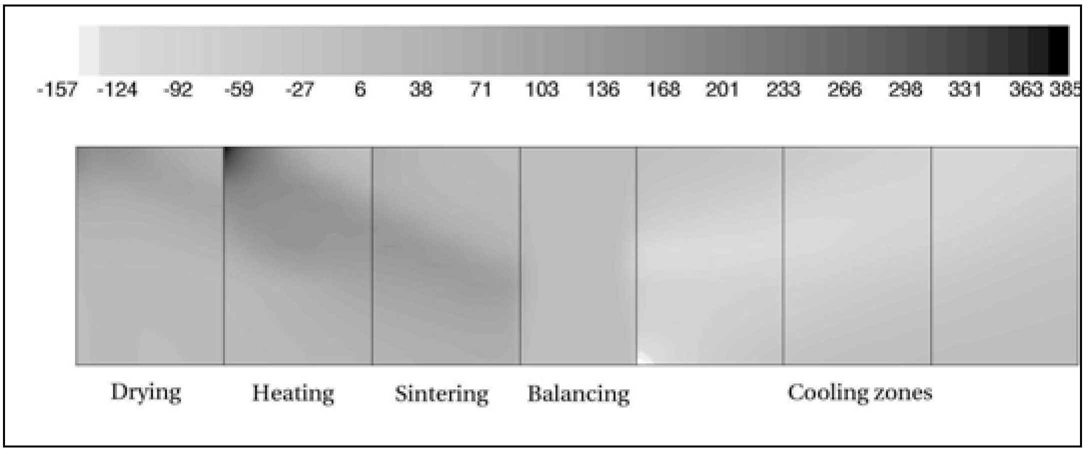

Figure 7: Temperature difference between gas and pellets

The carbon content and the consumption rate of oxygen for combustion of carbon in moles per cubic metres of bed are shown in Figures 8 and 9, respectively. According to these results the carbon combustion is complete. The combustion rate in Figure 9 does not appear to be a completely even front but in the different layers of the computational cells the fastest rates appear in separate spots (as well as in Figures 12 and 13). The reason for this can be seen in Figure 14, which shows oxygen concentration and Figure 15, which shows the concentration of carbon dioxide. In the balancing zone, oxidation concentration decreases under the level needed for combustion and this in turn leads to a high carbon dioxide concentration. The oxidation of Fe^{2+} and the unreacted chromite core volume fraction of the whole pellet volume are shown in Figures 10 and 11, respectively. These both seem to proceed as expected.

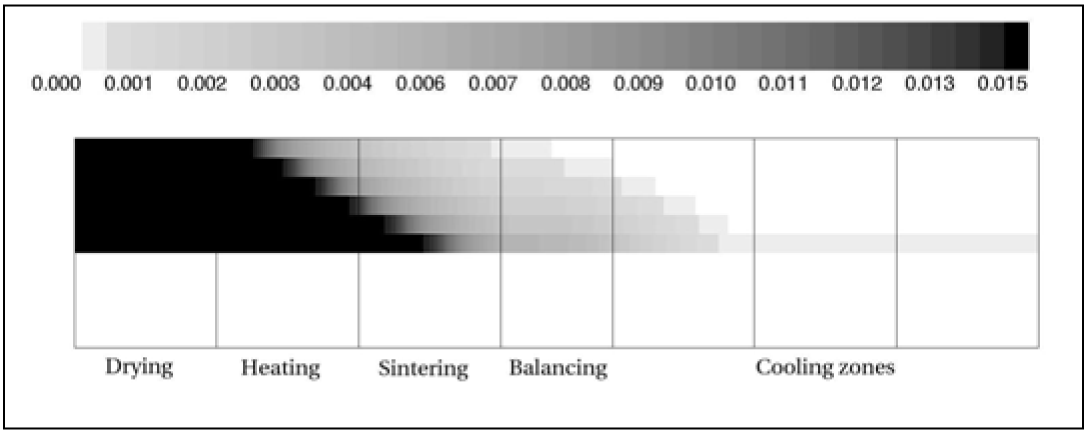

Figure 8: Carbon content of the pellets

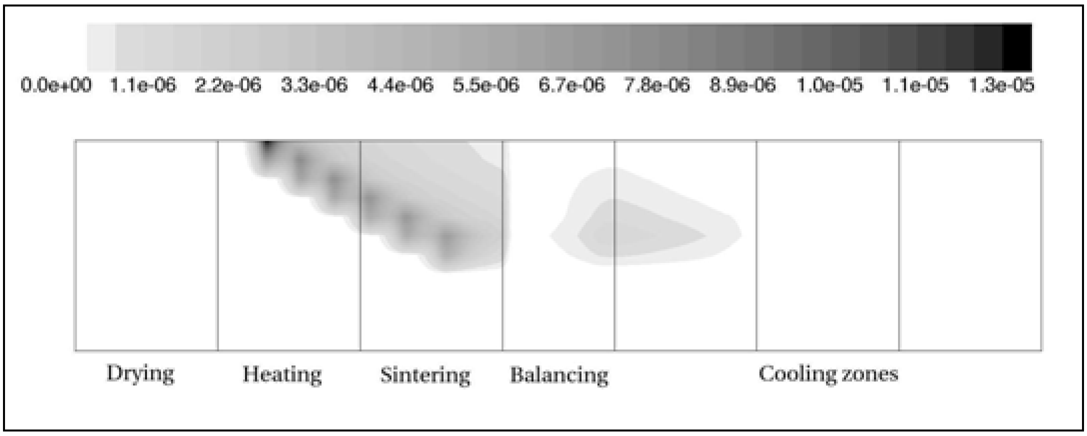

Figure 9: Combustion rate of carbon

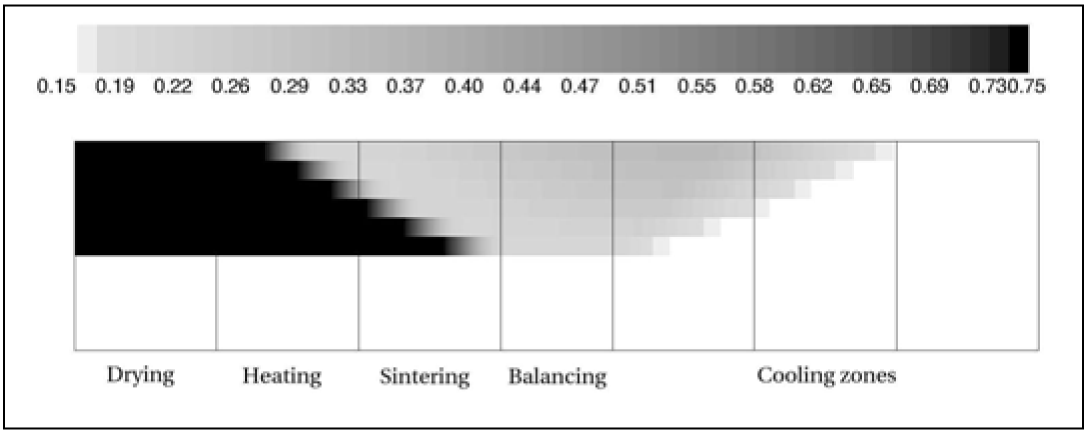

Figure 10: Fe^{2+}/Fe_{tot} ratio at pellet surface

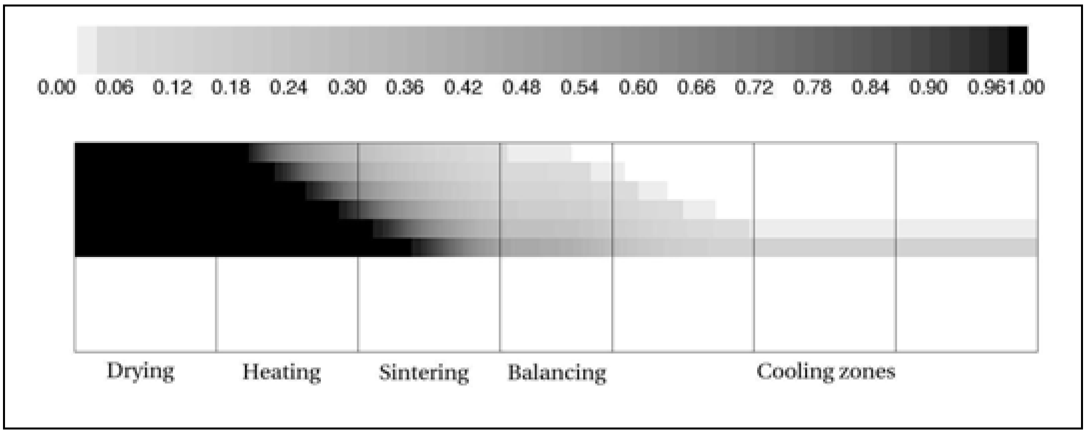

Figure 11: The volume fraction of the unreacted chromite core in the whole pellet volume

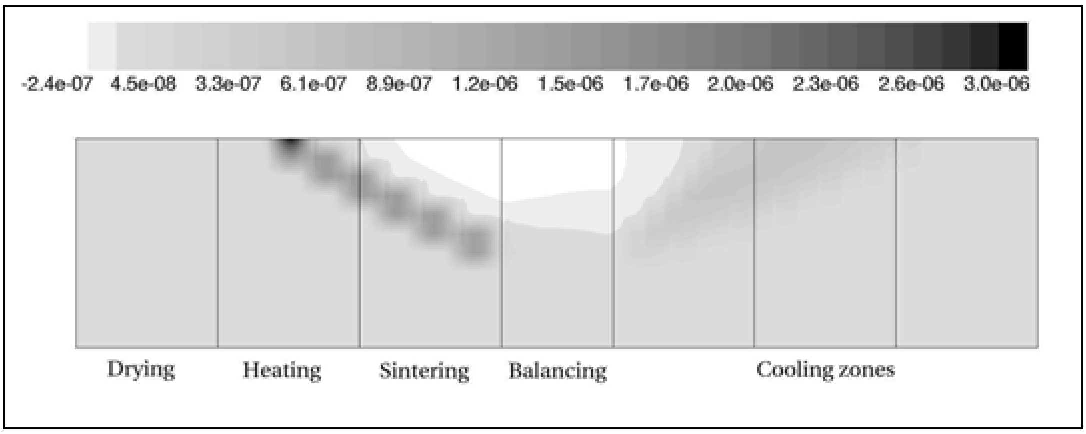

Figure 12: Consumption rate of oxygen during final oxidation of chromite

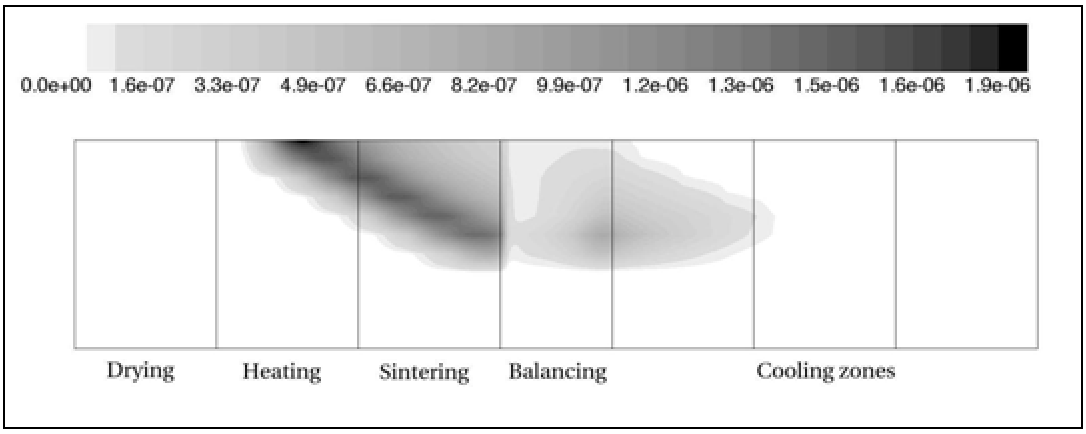

Figure 13: Consumption rate of oxygen at reaction shell of chromite

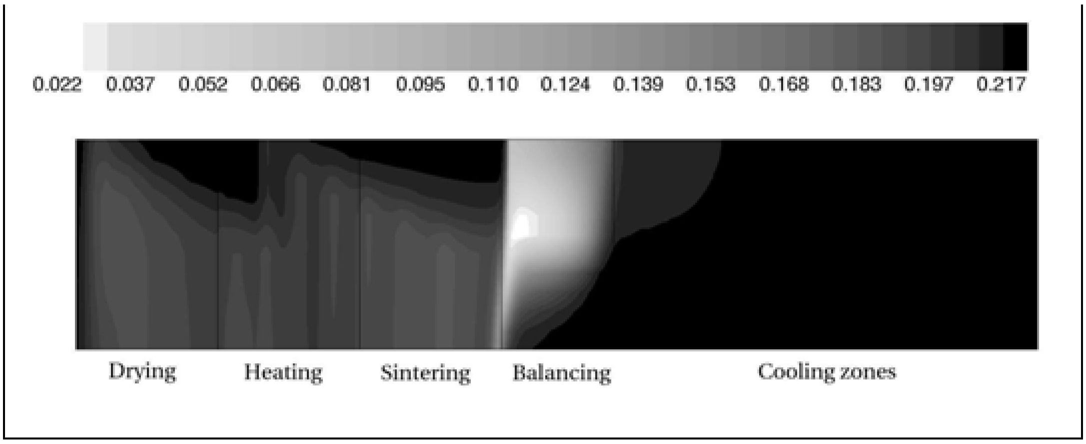

Figure 14: Concentration of oxygen in the gas phase

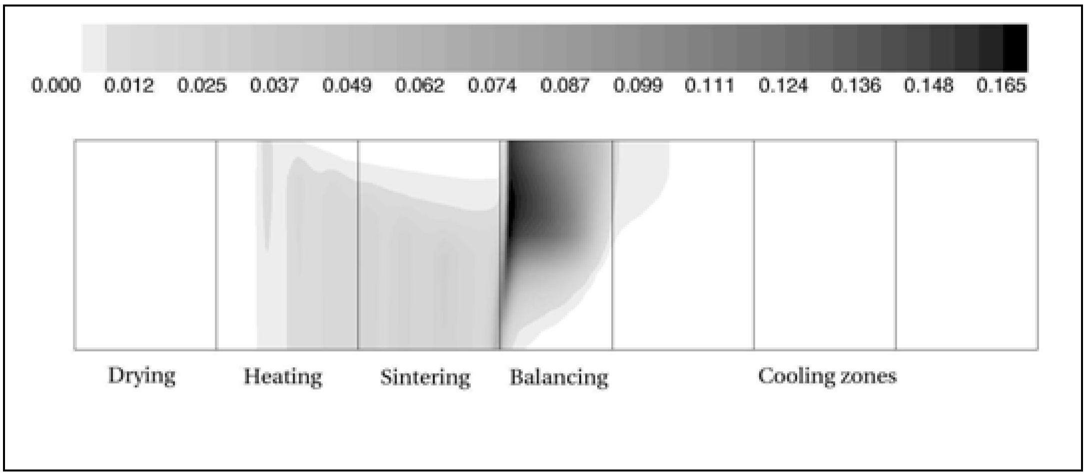

Figure 15: Concentration of carbon dioxide in the gas phase

4. CONCLUSIONS

The SBSM makes use of the commercial CFD code FLUENT. The model solves the fluid flows in the bed and its surroundings, the heat transfer between pellets and gas, the drying of pellets, carbon combustion and oxidation and the reduction of chromite. The results show clearly that SBSM can be successfully used for predicting the steel belt sintering process. However, the development work will continue by incorporating more materials in the model in order to improve applicability.

REFERENCES

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