REPORT

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Date
17/02/2017

Project ID
6057857

Combined systems and detailed model of the lime kiln

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Contents

Summary

The interest in burning different fuels in lime kilns has increased as mills want to replace fossil oil with renewable fuels. Since all fuels have different combustion characteristics they will affect the process conditions. Then it is important to be able to study how various operating conditions affect the lime quality. In this study a three-dimensional CFD model is coupled with the traditional MesaSim model to get a good model for the whole lime kiln. MesaSim is a fast and established method and is used to model the lime bed as which is used as input to the CFD model. The CFD model gives a better picture of the combustion and gas flow in the kiln and is used to calculate the flame length which is then used as input to MesaSim. The results show that the method works well for oil as fuel, and the results from both models agree well.

1 Introduction

1.1 Background

The lime kiln is an important part of the recycling of cooking chemicals in a pulp mill. A lime kiln is usually a slightly inclined cylinder that rotates slowly around its axis where lime mud slowly flows on the bottom. The kiln is fired with fuel in one end and the flue gases heat the lime mud. The process involves a thermal decomposition of calcium carbonate to calcium oxide with carbon dioxide as the outgoing component and consumes large amounts of energy. This carbon dioxide is neutral from a cyclical perspective when it originates from residues of the timber. The heat in the process, however, has traditionally been generated by combustion of oil. As the mills would reduce the burden of fossil carbon dioxide, carbon-neutral fuels have been evaluated in a number of investigations. The problem is that these new fuels modify the operating conditions in the lime kiln. To facilitate the transition to biofuels, it is of great importance to have reliable tools for calculation of the fuel impact on furnace performance.

ÅF has for many years developed and used a lime kiln simulation program, MesaSim, which calculates the lime kiln performance and is a useful tool to study the effect of different operating conditions. The model solves the heat and mass balances at steady state operation along the kiln axis in a one-dimensional manner. A drawback with the program is that it makes many simplifications on the flame dynamics and the heat transfer around it. The flame characteristics are the most important parameter for the lime kiln performance. Three-dimensional CFD can be used to model the flame and the heat transfer to the lime bed as well as the rotating wall.

A number of projects, including projects funded by Värmeforsk and ÅForsk, have focused on obtaining a complete CFD model of the lime kiln. [1], [2], [3] It has traditionally been very difficult due to that the models needed in the CFD simulation are not fully compatible with each other. The project documented in this report aim to couple a CFD model with MesaSim to utilize the advantages of both models.

1.2 Purpose and objectives

The purpose of this project is to develop a CFD model that models the freeboard hot flow and the rotating wall and uses input from MesaSim as boundary values for the lime bed. The results from the CFD simulations are then used as input for MesaSim in order to get a more accurate prediction of the flame length. This process of information exchange between the models is repeated until a converged solution is obtained.

1.3 The lime kiln

The lime kiln is traditionally a long, slightly inclined cylinder that slowly rotates around its axis. The lime mud is fed in the higher end of the kiln and forms a bed on the bottom of the cylinder that slowly flows towards the lower end. Fuel is fired in the lower end and the hot flue gases heat the lime mud which is fed at the other end.

The causticing process is part of the chemical recovery cycle in kraft pulp mills. Lime mud which consists of calcium carbonate is generated in the causticizing process. The lime kiln converts calcium carbonate in the lime mud to calcium oxide. The kiln product is reburnt lime, which is returned to the causticizing process.

The reburning process can be divided into four steps. First, the lime mud is dried, often in an external dryer, and is then heated to the calcination temperature. Then the lime is calcinated and the calcination reaction, see equation below, is endothermic and a large amount of heat is taken from the hot flue gases.

$$CaCO_3(s) \Leftrightarrow CaO(s) + CO_2(g)$$

In the last step, the lime sinters before it leaves the kiln and can be reused in the chemical recovery process. The lime kiln can be described as a direct-contact counter-flow heat exchanger and can be divided into four zones that corresponds to the steps of the lime reburning process, see Figure 1. There is a large temperature span in the kiln. The lime is heated up from 250 °C to the calcination temperature and is constant during calcination and then it increases again up to around 1000 °C.

The temperature distribution in the lime kiln is important for the lime quality. For example if the temperature is too high the reburnt lime can be overburnt, which reduces its reactivity in the causticizing process. Variations in the temperature profiles can produce reburnt lime with varying quality which makes it difficult to control the

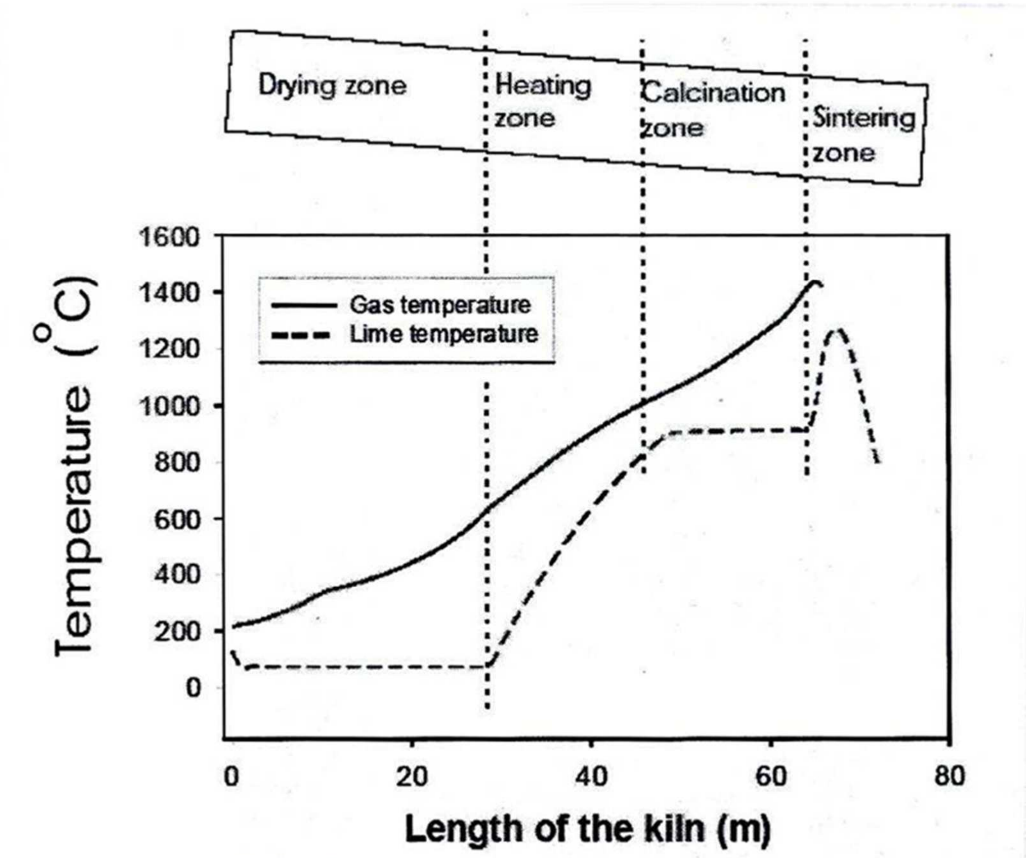

Figure 1 Temperature profile and reaction zones in a rotary lime kiln.

causticing process.

2 Lime kiln at Mönsterås pulp mill

The lime kiln used in this project is one of the lime kilns at the Mönsterås mill. The kiln has an outer diameter of 3.4 m, an inner diameter of 2.8 m and is 73.7 m long. The kiln axis is inclined with an angle of 1.4 degrees and rotates at a speed of 1.6 rpm. See Figure 2 for a sketch of the kiln.

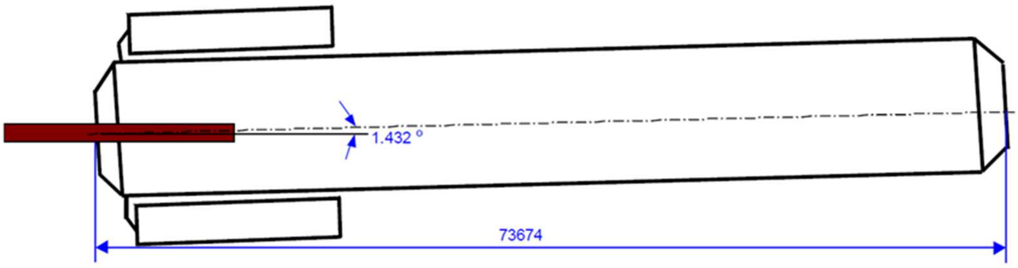

Figure 2 Sketch of the Mönsterås lime kiln.

The kiln walls are lined with two layers of refractory bricks that are divided into three regions with different material and thickness of the layers. See Figure 3 for the layout of the refractory regions and Table 1 for the thickness and conductivity of the layers. The outer shell of the kiln is made of steel.

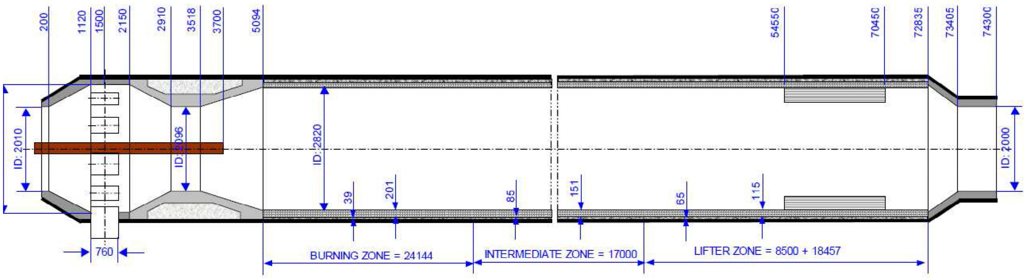

Figure 3 Layout and refractory lining of the Mönsterås lime kiln.

Table 1 Refractory thickness and conductivity for the two layers in the different zones.

	Burning zone	Intermediate zone	Lifter zone
Layer 1: Thickness [m]	0.12	0.15	0.2
Layer 1: Conductivity [W/Km]	1.8	1.8	1.8
Layer 2: Thickness [m]	0.07	0.09	0.04
Layer 2: Conductivity [W/Km]	0.3	0.3	0.3

Below the burner there is a threshold to increase the lime retention time. There are nine satellite coolers that cool the lime product and heat the combustion air with secondary air.
The kiln co-fires oil and biofuel and uses a multi-fuel burner. Figure 4 shows the burner design with dimensions. In this project, only firing with 100% oil is considered.

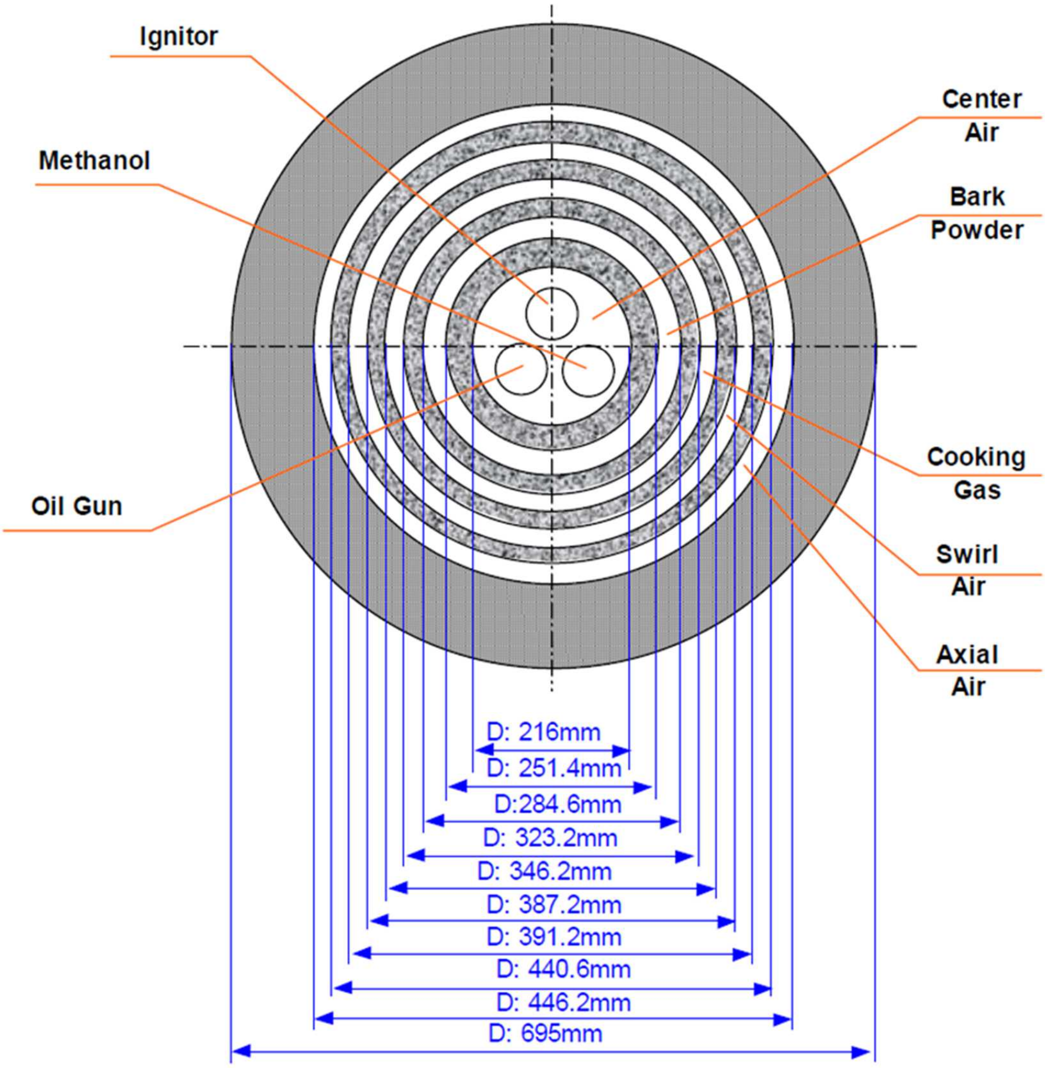

Figure 4 Burner design.

Primary air is supplied through central air, swirl air, axial air and transport air inlets. The air properties are listed in Table 2. The kiln has an external lime mud drier. Dry lime mud is fed at a temperature of 250 °C and at a rate of 5.18 kg/s, yielding a production rate of 9791 kg/h of reburned lime.

Table 2 Primary and secondary air properties.

	Central air	Swirl air	Axial air	Transport air	Secondary air
Mass flow [kg/s]	0.145	0.349	0.478	0.522	6.288
Temperature [K]	300	300	300	300	600
Swirl angle	-	45 °	-	-	-
Total mass flow of air [kg/s]	1.524				6.288

3 Method

The modelling of the lime kiln is divided into two coupled sub-models using Computational Fluid Dynamics, CFD, and MesaSim. This is done in order to utilize the advantages of both methods.

MesaSim models the mass and heat balances in the kiln in a one-dimensional manner. The kiln is divided into a number of segments in the longitudinal direction. This means that there is no variation in the kiln cross section. MesaSim also makes approximations on the combustion characteristics by using a simplified correlation to calculate a flame length. These approximations are not true for a rotary kiln where there are large temperature and concentration gradients in the kiln, especially in the freeboard gas flow. In the lime bed these approximations are acceptable. The advantages with MesaSim are that it is easy to implement and provides instant results on how different operating parameters affect the lime production.

CFD is a useful tool to study the flame and gas flow inside the kiln since it solves the governing Navier-Stokes equations numerically in 3D. The modelling of the lime bed has been studied in previous studies without success due to that the models needed are not compatible. The flame characteristics and the gas flow have a great impact on the lime bed and need to be accurately modelled. At the same time, the temperature on the lime bed surface and the release of CO_2 from the calcination reaction in the bed affects the flame and the gas flow.

The lime kiln is divided into two parts in order to utilize the advantages of both models. See Figure 5 for an overview of how the kiln is divided. The freeboard flow and rotating wall is modelled using CFD and the lime bed is modelled using MesaSim. There is an exchange of information between the models. MesaSim provides boundary conditions for the lime bed surface that are input to the CFD simulation. The flame length is calculated in the CFD model and is input to MesaSim. The models are solved in an iterative manner until a converged solution is obtained. The simulation procedure is further described in Figure 6.

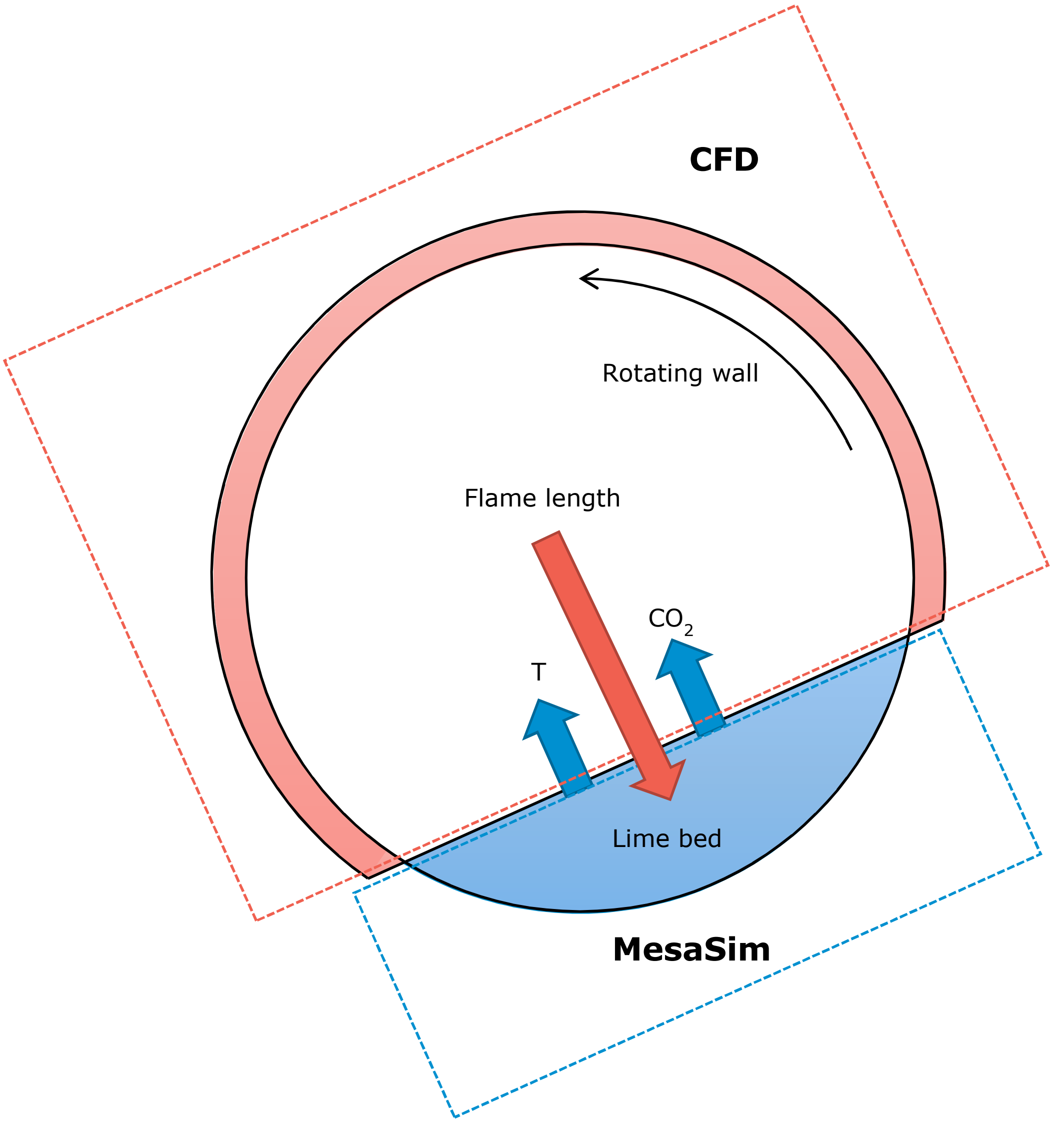

Figure 5 Overview of how the lime kiln is divided between the two models and the information exchange between them.

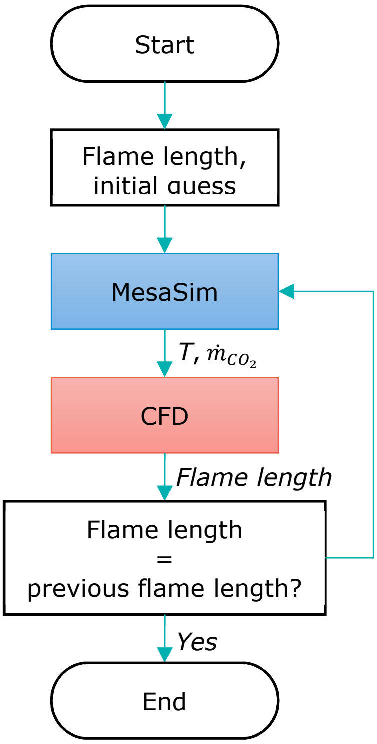

Figure 6 Simulation procedure for the method used in this report.

3.1 CFD model

The calculation method for the CFD model consists of three parts. First, a computational domain is defined which consists of the parts of the system that is to be included in the simulation. The domain is then discretized by dividing the domain into a large number of smaller volumes, constituting the computational mesh used in the simulation. In the third step the boundary conditions and models required to capture the physical phenomena of interest are defined. Then the models are solved numerically.

3.1.1 Computational domain

The domain is presented in Figure 7 and includes the whole lime kiln except for the part that is filled with lime mud.

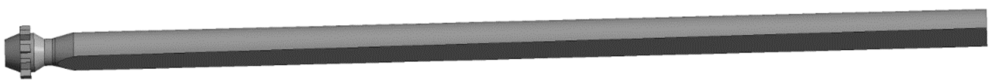

Figure 7 Computational domain of the lime kiln.

3.1.2 Computational mesh

The domain is then divided into smaller volumes, cells, making up the computational mesh. To accurately capture the flame characteristics, the cells are concentrated around the burner and in the first part of the lime kiln. The cell size increases towards the outlet. See Figure 8 and Figure 9. The mesh used in the simulations consist of 3.8 million cells.

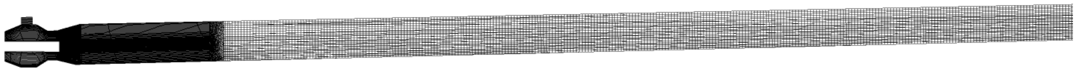

Figure 8 Overview of the mesh in a cross section of the kiln.

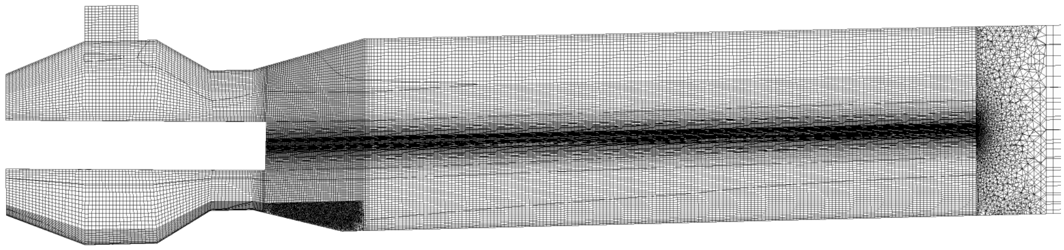

Figure 9 The mesh in the region around the oil burner and air inlets.

3.1.3 Models and boundary conditions

The software used for the simulations is ANSYS Fluent 17.0. It solves the steady state continuity, momentum and energy equations numerically using the finite volume method in three dimensions. [4]

3.1.3.1 Freeboard hot flow model

The gas flow in the kiln is modelled in a Reynolds Averaged Navier-Stokes (RANS) framework, with the Realizable k-epsilon model for the turbulent viscosity. Wall-functions are used on the no-slip boundaries. Since the flow at the walls are not of primary interest, the y+ vales does not meet the requirement for valid wall turbulence.

Convective and diffusive heat transfer are included in the transport equations. The radiative heat transfer is calculated by the DO model.

The discretized equations are solved in a steady state manner. A second order accurate upwind scheme is used for the discretization of the convective terms in the momentum and turbulence model equations.

3.1.3.2 Modelling oil combustion

The oil is injected into the kiln as small droplets. The discrete-phase model, DPM, which uses the Euler-Lagrangian framework is used. The fluid phase is modelled as a continuum and for the dispersed phase, a large number of droplets are modelled. The trajectories of the droplets are calculated and they exchange momentum, mass and energy with the continuous phase, two-way coupling. The injection is modelled as a cone spray with a Rosin-Rammler size distribution. The injection properties are listed in Table 3. The combustion of an oil droplet is considered as a three step process. First, the drop is heated to the evaporation temperature and then it evaporates. The gas-phase combustion of the oil vapour is calculated with the eddy-dissipation model where it is assumed that the rate of reaction is dependent only on the mixing rate of reactants. The fuel used in this case is $C_{19}H_{30}$ and the reaction takes place in two steps according to the reaction schemes below.

$$C_{19}H_{31} + 18CO_2 \rightarrow 19CO + 17H_2O$$

$$2CO + O_2 \rightarrow 2CO_2$$

Table 3 Injection properties for the oil burner.

Injection properties	
Mass flow	0.46 kg/s
Temperature	353 K
Velocity	50 m/s
Droplet mean diameter	50 µm
Droplet max diameter	75 µm
Droplet min diameter	25 µm

3.1.3.3 Rotating wall

The two layers of refractory of the kiln wall are modelled as two solids with different thickness and conductivity to account for the heat transfer through the walls to the surroundings. The heat transfer from the outer kiln wall is modelled with a convective wall boundary condition. The rotation of the lime kiln is accounted for by applying a moving wall boundary condition on the refractory walls. The rotational speed is 1.6 rpm or 0.167 rad/s.

3.1.3.4 Lime bed

The lime bed is set as a wall boundary with a temperature profile that is calculated in MesaSim. The mass flow of CO_2 that is released from the calcination reaction is applied as a source term in the cell layer closest to the lime bed surface. The boundary conditions are applied with the help of User Defined Functions, UDFs.

3.1.3.5 Inlet and outlet conditions

The primary and secondary air inlets are set as mass flow inlets and the outlet as a pressure outlet.

3.2 MesaSim

MesaSim was developed in the late 80s in collaboration between Chalmers University and ÅF-IPK. The program has been used by ÅF in several lime kiln studies. It is a useful tool for trouble shooting and process optimization of existing kilns, as well as evaluation of proposals for new kilns. It has also been used in several research projects, for example investigation of alternative fuels, development of CFD models for kiln simulation.

MesaSim is a one dimensional model which calculates the lime kiln's overall mass and energy balances, from which the kiln fuel demand is calculated. [5], [3]

The program also calculates temperature profiles, and heat losses in the kiln. The temperature profiles are for lime, flue gas, inner wall temperature, and outer shell of the kiln.

The model is solved by numerical iteration with an integration step of 0.1 m.

Results from the simulation also include profiles for:

- Flue gas composition (H2O, SO2, CO2, N2 and O2) and velocity.
- The reaction of CaCO3 to CaO.
- Bulk transport - degree of fill and overall retention time in the kiln.

MesaSim is described in more detail in earlier studies. [1]

3.2.1 Required data

Data required for MesaSim includes key parameters related to the kiln design such main dimensions of the kiln, specification of equipment which affects heat transfer within the kiln such as thresholds, lifters or chains, specification of product coolers, and refractory characteristics.

Properties of the incoming lime mud, reburnt lime, combustion air and fuel are also required. Fuel properties determine flame characteristics, and are an especially interesting parameter in many studies.

4 Results

Numerical simulations using the developed CFD and MesaSim models are performed for one kiln operating point. The two models are coupled and provide input to each other. The results from the CFD simulations are presented and compared to the results from MesaSim. The simulation procedure, described in Section 3 is iterated until a converged solution is obtained. Two simulation loops are presented and discussed in this section.

4.1 Flame length

The flame and its propagation into the kiln have a great influence on the temperature distribution in the kiln. Different fuels have different flame characteristics during combustion and it is important to study the flame propagation. There are different ways to visualize where the flame front is located. Here, the turbulent reaction rate for the combustion is used to define where all the fuel is combusted in the CFD simulation. In MesaSim a correlation is used and for the first simulation a flame length of 7.8 m is calculated. The corresponding value that is obtained from the CFD simulation is 8.0 m. In the second simulation loop, the flame length of 8 m is used in the MesaSim simulation, resulting in new boundary conditions for the lime bed. In Figure 10, the flame front from the second simulation loop is presented. The flame length is 7.75 m and the simulation loop is considered to have converged.

The result shows that the method works well for oil, which has well-known combustion properties. For other fuels that do not have that good combustion data it will be very useful to simulate the combustion and calculate a flame length using CFD.

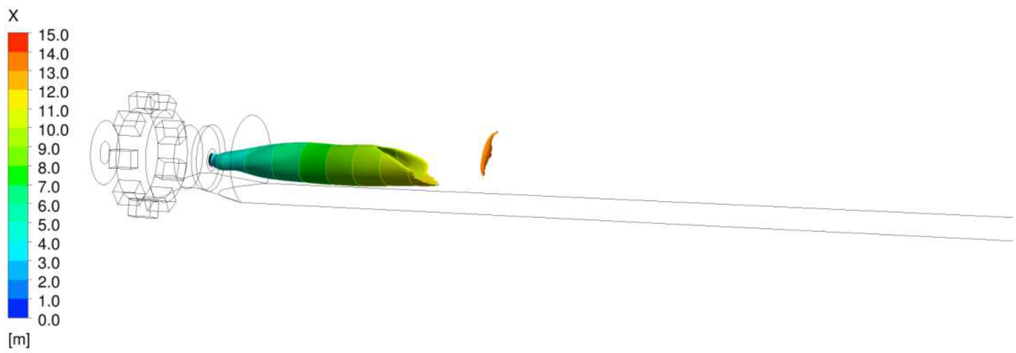

Figure 10 Flame front.

4.2 Gas temperature

The temperature distribution in the lime kiln is important for the lime quality. Figure 11 shows the temperature in the kiln centre plane and Figure 12 shows the temperature in five cross sections along the kiln. It is seen in both figures that the hot gases rise to the upper part of the kiln due to the buoyancy effect, which affects the local temperature at the refractory wall. The high temperature regions are an indication of the flame length and shape since the temperature is highest where the combustion takes place. It provides a prediction of how the flame propagates in the kiln and how it affects the temperature of the kiln walls and lime bed. It is also seen in both figures that the freeboard flow is highly three-dimensional with large temperature gradients and that is the strength of CFD simulations.

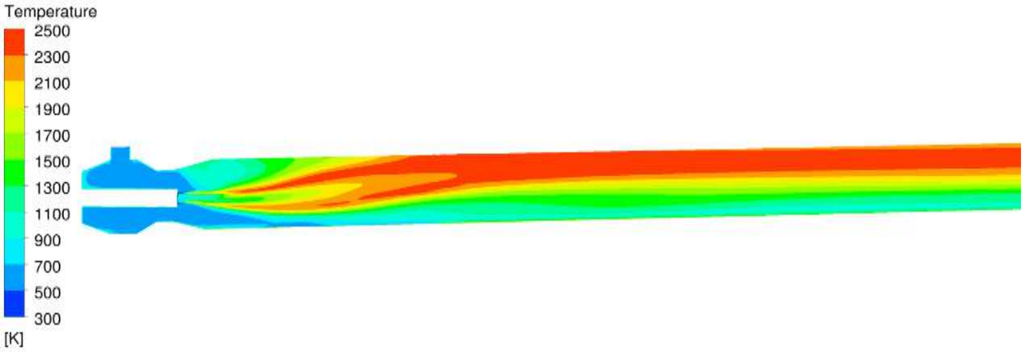

Figure 11 Gas temperature in a cross section along the kiln axis.

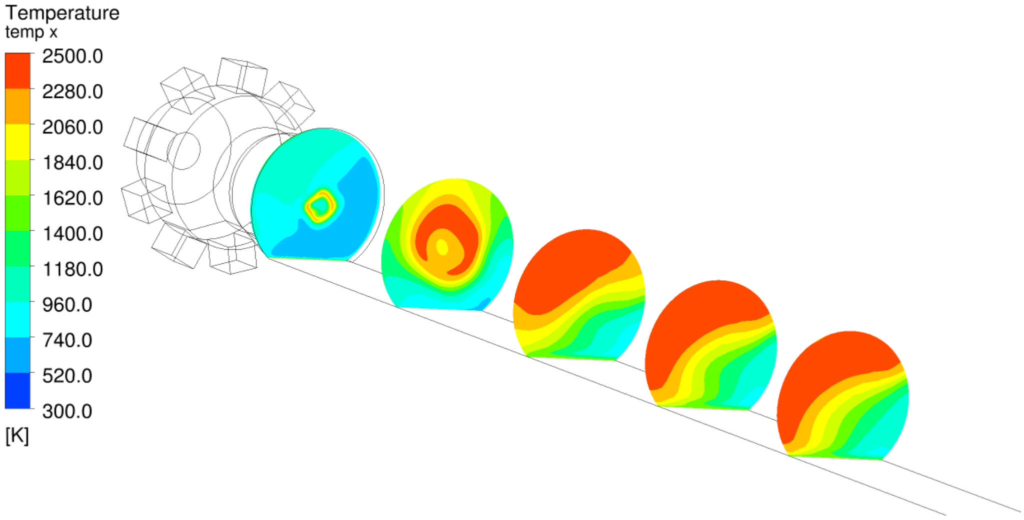

Figure 12 Gas temperature in five cross sections of the kiln (x=5, 10, 15, 20, 25m).

In MesaSim the gas temperature is calculated as a one-dimensional profile in the kiln. In order to compare the three-dimensional results from the CFD simulations with the results from MesaSim the results are transformed by calculating the average gas temperature in a number of cross sections in the kiln. The temperature profiles are shown in Figure 13.

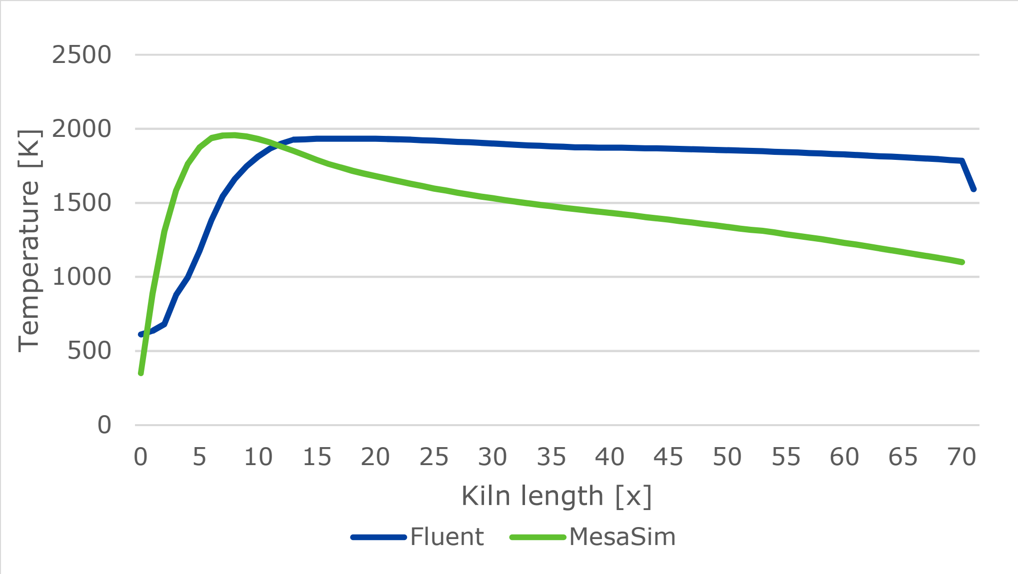

Figure 13 Averaged gas temperature from the CFD simulation compared to the calculated gas temperature from MesaSim.

The temperature levels in the first part of the kiln correspond well between the simulations. The combustion and flame are modelled in different ways by the two models, and this may explain the different slopes. The cooling of the gas is under predicted in the later part of the kiln in the CFD simulation. This is because cooling of the lime when it is lifted up from the bed and falls down again is not taken into account. The surface roughness of the inside of the kiln walls is also not modelled. Both of these factors affect the heat transfer from the gas to the walls.

4.3 Lime bed temperature

The temperature at the lime bed surface is calculated in MesaSim and is used as a boundary condition in the CFD simulation, see Figure 14. The one-dimensional characteristics of the MesaSim model are seen in the figure. MesaSim does not calculate the temperature gradient in the lime bed across the kiln axis. The temperature on the lime bed surface affects the freeboard gas flow.

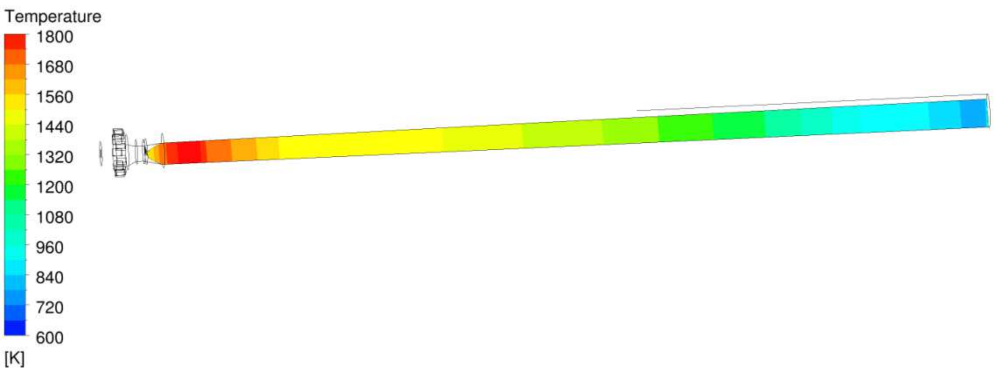

Figure 14 Lime bed temperature calculated in MesaSim and is used as a boundary condition in the CFD model.

4.4 Wall temperatures

The temperature at the refractory walls has a strong impact on the refractory service life. It is important that the temperature does not get too high in any region at the wall. Most of the heat transferred from the fuel to the walls and lime bed is by radiation. The radiation to the walls is highly dependent on the flame temperature, the surface of the flame and the flue gas radiation characteristics, among other things. In essence, these factors determine the temperature distribution in the kiln. Figure 15 shows the temperature profile on the walls inside the kiln

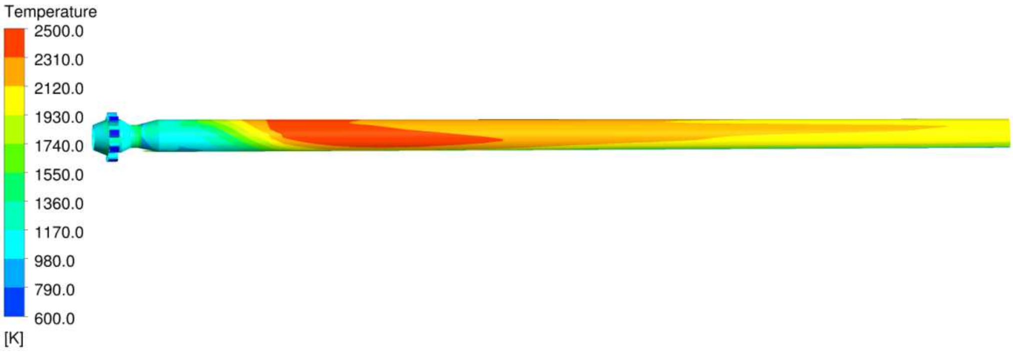

Figure 15 Temperature at the rotating wall on the inside of the kiln.

The average temperature on the inner kiln wall is compared with the temperatures obtained in MesaSim in Figure 16. The temperatures are in good agreement between the two simulations. The temperature calculated by MesaSim is slightly higher than the temperature from the CFD simulations.

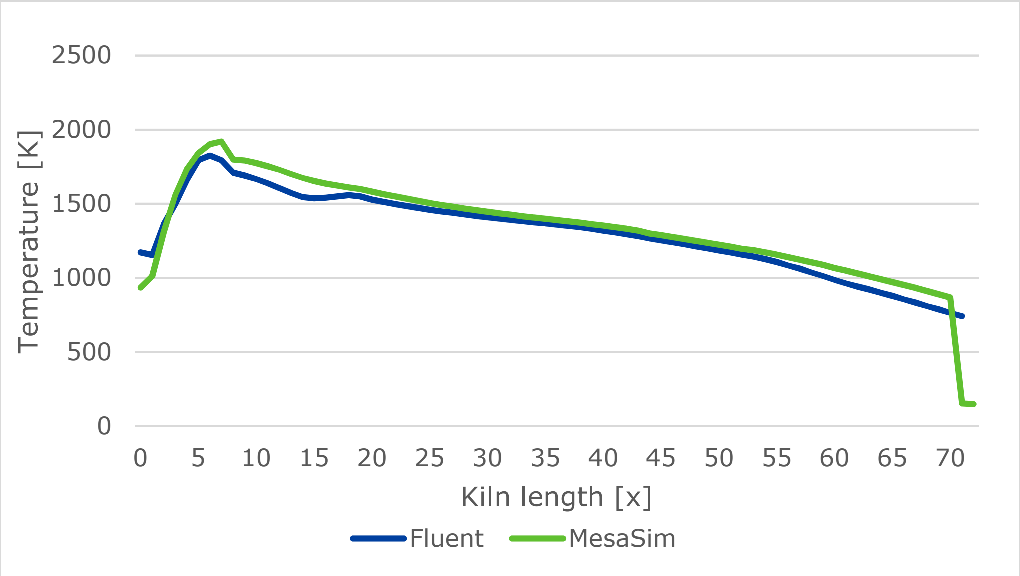

Figure 16 Averaged inner wall temperature from CFD simulation and MesaSim.

Figure 17 shows the outer wall temperature from the two simulations are compared.

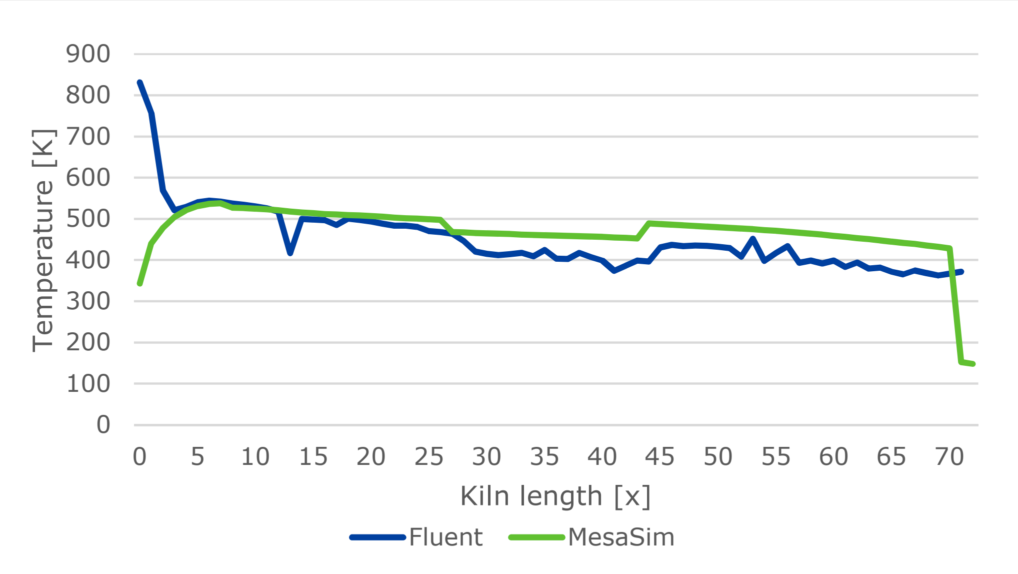

Figure 17 Averaged outer wall temperature from CFD simulation and MesaSim.

4.5 Gas composition

4.5.1 CO_2 Concentration

The gas composition varies along the kiln, see Figure 18 and Figure 19, where the mass fraction of CO_2 is shown.

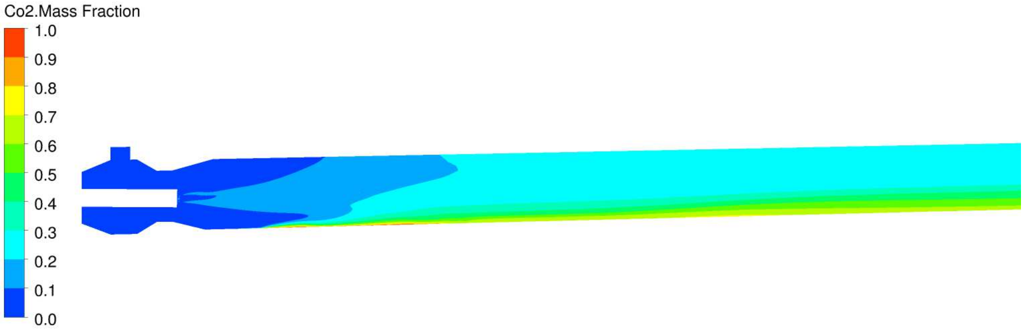

Figure 18 Mass fraction of CO_2 in a cross section along the kiln axis.

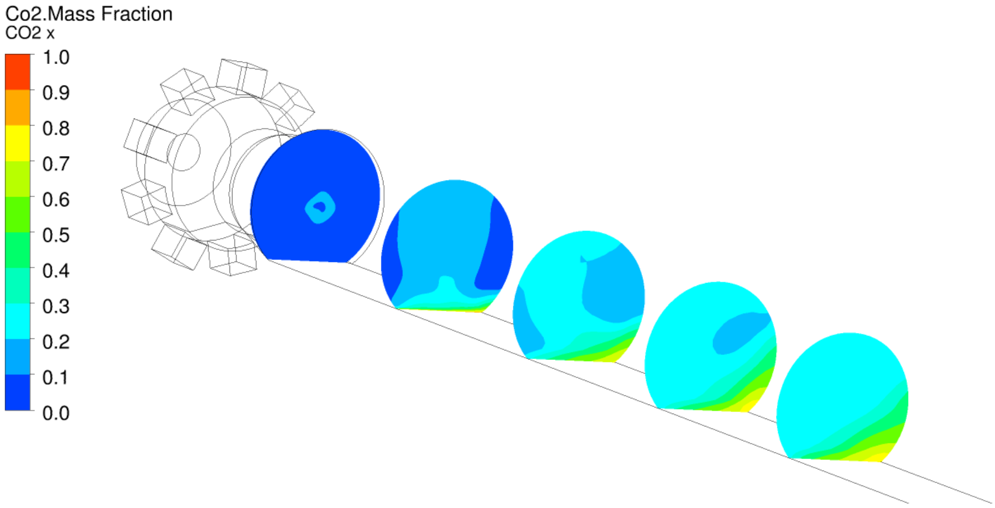

Figure 19 Mass fraction of CO_2 in five cross sections of the kiln (x=5, 10, 15, 20, 25m).

In the same way as for the temperature, there are large concentration gradients in the cross section of the kiln, which may affect the conditions for combustion. The high CO_2 concentration at the lime bed comes from the calcination reaction that is calculated in MesaSim and is applied as a mass source term in the cells at the lime bed surface. Due to the effect of gravity on the gas, the colder carbon dioxide that is released from the lime bed settles as as a thick layer on the bottom of the kiln.

In Figure 20 the averaged mass fraction of CO_2 in the kiln are compared.

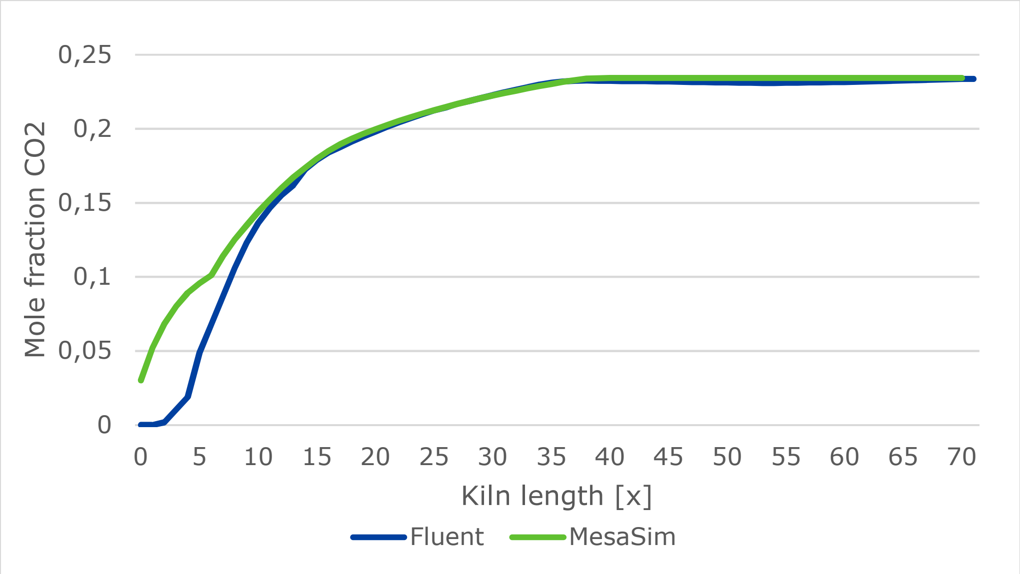

Figure 20 Averaged mass fraction of CO_2 from CFD simulation and MesaSim.

The concentration is higher in the beginning in MesaSim and after 10 m the concentrations are almost the same. MesaSim does not take into account that the air inlets are located before the lime outlet and the oil burner. That is why the concentrations differ in the beginning and are the same after the combustion is complete.

5 Conclusions

In this study, a method to model rotary lime kilns has been developed, where a three-dimensional CFD model is coupled with the one-dimensional model MesaSim. Previously it has been difficult to implement the calcination reaction in a CFD model for the whole kiln. It is now shown that this problem can be solved by coupling a CFD model that models the freeboard hot flow and the rotating wall and uses input from MesaSim as boundary values for the lime bed. MesaSim is an established method for modelling the lime kiln and the results from the CFD simulations are then used as input for MesaSim in order to get a more accurate prediction of the flame length.

The methods complement each other and the advantages of both models are utilized. MesaSim is fast and gives good results. With the results from the CFD simulation the input data to MesaSim is improved. A three-dimensional CFD model also provides an opportunity to study the detailed flame characteristics and the gas flow in the kiln. It is also a very good tool to evaluate the effect of different fuels on the flame characteristics which affect the temperature distribution and composition and thereby the lime quality.

In this study it has been shown that the results from the simulations in MesaSim and Fluent in terms of temperature distribution and gas composition agree well. The results also show that the method works well for oil that has well-known combustion properties. The calculated flame length converges in two simulation loops. For other fuels that do not have that good combustion data it will be very useful to simulate the combustion and calculate a flame length using CFD as input to MesaSim. With better input data for the flame, the model can be used to examine how different operating conditions affect the process properties and lime quality. The flame characteristics also have large impact on the temperature at the refractory wall. The method makes it possible to study the local temperature distribution at the refractory walls and the thermal load on the walls can be evaluated in more detail. The temperature at the refractory wall has a strong impact on the refractory life time.

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