CFD simulation results of a full scale oxy-fuel MSW furnace

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Executive Summary

The aim of the CapeWaste/NEWEST-CCUS projects has been to study a potential capture technology based on oxy-fuel combustion where oxygen and CO_2 is used instead of air in the waste incineration process at a potential new Waste-to-Energy (WtE) plant at the Haraldrud site. CO_2/O_2 oxidiser instead of CO_2/N_2 makes carbon capture much more efficient, practical because of much higher CO_2 concentrations to handle. WtE CCS will enable negative CO_2 emissions as MSW is largely biogenic. The present work is based on input and knowledge developed through the work with the CapeWaste/NEWEST-CCUS projects. Numerical full scale CFD simulations have been performed for the Haraldrud WtE furnace under air conditions and under oxy-fuel conditions. The main focus has been on the conversion of the fuel bed. The simulation results indicated that for the conditions of this study the conversion and burn-out of the bed was at least at the same level under oxy conditions as when air is used as oxidiser under similar conditions.

Report

CFD simulation results of a full scale oxy-fuel MSW furnace

MS10 (CapeWaste) / D3.1 (NEWEST-CCUS)

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Report No:

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Report

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SUMMARY
The aim of the CapeWaste/NEWEST-CCUS projects has been to study a potential capture technology based on oxy-fuel combustion where oxygen and CO_2 is used instead of air in the waste incineration process at a potential new Waste-to-Energy (WtE) plant at the Haraldrud site. O_2/CO_2 oxidiser instead of O_2/N_2 makes carbon capture much more efficient, practical because of much higher CO_2 concentrations to handle. WtE CCS will enable negative CO_2 emissions as MSW is largely biogenic. The present work is based on input and knowledge developed through the work with the CapeWaste/NEWEST-CCUS projects. Numerical full scale CFD simulations have been performed for the Haraldrud WtE furnace under air conditions and under oxy-fuel conditions. The main focus has been on the conversion of the fuel bed. The simulation results indicated that for the conditions of this study the conversion and burn-out of the bed was at least at the same level under oxy conditions as when air is used as oxidiser under similar conditions.

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APPENDICES

1 Introduction

The aim of the CapeWaste/NEWEST-CCUS projects has been to study a potential capture technology based on oxy-fuel combustion where oxygen and CO_2 is used instead of air in the waste incineration process at a potential new Waste-to-Energy (WtE) plant at the Haraldrud site in Oslo.

The present work is based on input and knowledge developed through the work with the CapeWaste/NEWEST-CCUS project both in sub-project H3 and in other sub-projects (Becidan et al 2021). Numerical full scale CFD simulations have been performed for the Haraldrud WtE furnace under air conditions and under oxy-fuel conditions. The main focus has been on the conversion of the fuel bed.

2 Modelling methodology

This chapter describes the sub-models, reaction mechanisms and boundary conditions that were used in the CFD (Computational Fluid Dynamics) simulations. ANSYS Fluent 19 [ansys.com] was used for all simulations. Fluent is a commercially available, general-purpose, finite volume based CFD code. In the code, the governing equations and models are discretized and solved iteratively. In all simulations, the coupled, pressure based, transient solver was used together with second order accurate discretization.

Existing sub-models included in CFD tools like ANSYS Fluent are developed for air-fired conditions, and their assumptions might not be valid in the CO_2-rich environment experienced during oxy-fuel conditions. A basis for defining the modelling approach for the CapeWaste/NEWEST-CCUS oxy-fuel CFD simulations, findings and approaches from relevant CFD modelling studies were summarised in a previous CapeWaste deliverable "MS5 Combustion model description", with emphasis on models that are most influenced by the oxidiser/atmosphere. A short description of the selected models for the present study is given in the following sections.

2.1 Physical models

The turbulence-chemistry interaction has been modelled using the combined Finite Rate/Eddy Dissipation Model. The EDM is based on the mixed-is-burnt assumption, and the major advantages are short calculation time and stability. However, the reaction rates are determined by the turbulent mixing rate and multi-step chemical mechanisms cannot be handled accurately. The FR/EDM calculates both Arrhenius and Eddy-Dissipation reaction rates. The net reaction rate is taken as the minimum of these two rates.

The gas phase kinetics can be modelled in several ways, from detailed kinetic mechanisms that are based on elementary steps, and include a large number of elementary reactions, to simplified global mechanisms describing the overall behaviour of the complex chemistry through a limited number of reactions. The latter is most frequently used in CFD simulations due to the computational cost of more detailed models. In this study, the two-step mechanism of Westbrook and Dryer was chosen due to its stability and low computational costs, it has also been widely used previously. As the transient simulations with the implementation of the new fuel bed model are quite computationally expensive, a low-cost gas phase model was chosen.

2.2 Radiation

Radiation heat transfer was modelled using the P1 model. For the case with air as oxidant the gray domain based WSGGM implemented in ANSYS Fluent was used.

For the oxy-fuel cases, the model of Bordbar et al., which is an extension of the weighted-sum-of-gray-gases (WSGGM) model, was used. The model was developed specifically to handle oxy-fuel atmospheres, where inhomogeneous mixtures of CO_2 and H_2O are present. In the model, the total emissivity weighting coefficients are obtained through the fitting procedure to experimental database of spectral emissivities for a wide range of temperatures, molar fraction ratios (H_2O / CO_2) and path lengths. As opposed to the standard WSGGM model, the absorption coefficients for individual gray gases and the total emissivity weighting factors are formulated as a function of the molar fraction ratio, which makes the model applicable to a wider range of combustion conditions.

2.3 The fuel bed model

Modelling of the fuel bed is the most challenging part of this work. A common simplification has been to define the top of the bed as a boundary with fixed or predefined properties with respect to mass flow rate, gas composition, temperature, and their distribution along the fuel bed. In reality, the instantaneous gas phase reactions and radiation are crucial for the conversion of the fuel bed. It is therefore not appropriate to represent the fuel bed as a boundary with predefined properties.

To handle the interaction between the gas phase reactions and the conversion of the fuel bed properly, a fuel bed model is needed to provide mass flow rate and temperature of the gaseous yield from individual particles, which are to be considered as sources to the gas-phase equations. In this study, the fuel bed model developed and implemented in ANSYS Fluent in the collaborative project KPN GrateCFD was chosen. The model, its implementation and validation against experimental data for a pilot plant firing wood chips under air conditions have recently been published (Haugen et. al). This was also a deliverable in the CapeWaste project (MS8a).

The fuel bed model considers drying, pyrolysis, and char combustion/gasification of the fuel. The fuel bed is made up of representative particles. Every representative particle is individually tracked, with UDFs through Fluent's Discrete Particle Model (DPM) model, and evolved for its entire residence time in the bed.

The main contribution to the UDF is the Single Particle Model (SPM) proposed by Strøm & Thunman, which provides a detailed 1-dimensional description of the evolution of a thermally thick particle that exhibits drying, devolatilization and char conversion. Given the initial particle properties, the inputs to the model are the surrounding gas and radiative temperatures, together with the oxygen mass fraction in the surroundings. Based on this, the SPM yields the mass flow rate, composition, and temperature of the gaseous yield from individual particles, which are to be considered as sources to the gas-phase equations

A fuel bed consists of a large number of particles. Due to CPU restrictions, a simulation cannot handle all these particles individually. Instead, the SPM is solved for representative particles. In Fluent, the concept of parcels can be used for the representative particles. The different representative particles can have different radii and composition. This means that each representative particle will represent a large number of physical particles with the same composition and size. The principle of the fuel bed model is shown in **Error! Reference source not found.**.

Hence, the thermal conversion of individual particles can be described as follows:

$$\text{MSW component} \rightarrow \text{Moisture} + \text{Dried MSW component}$$
$$\text{Dried MSW component} \rightarrow \text{Volatiles} + \text{Char}$$
$$\text{Char} + O_2 \rightarrow CO_2$$

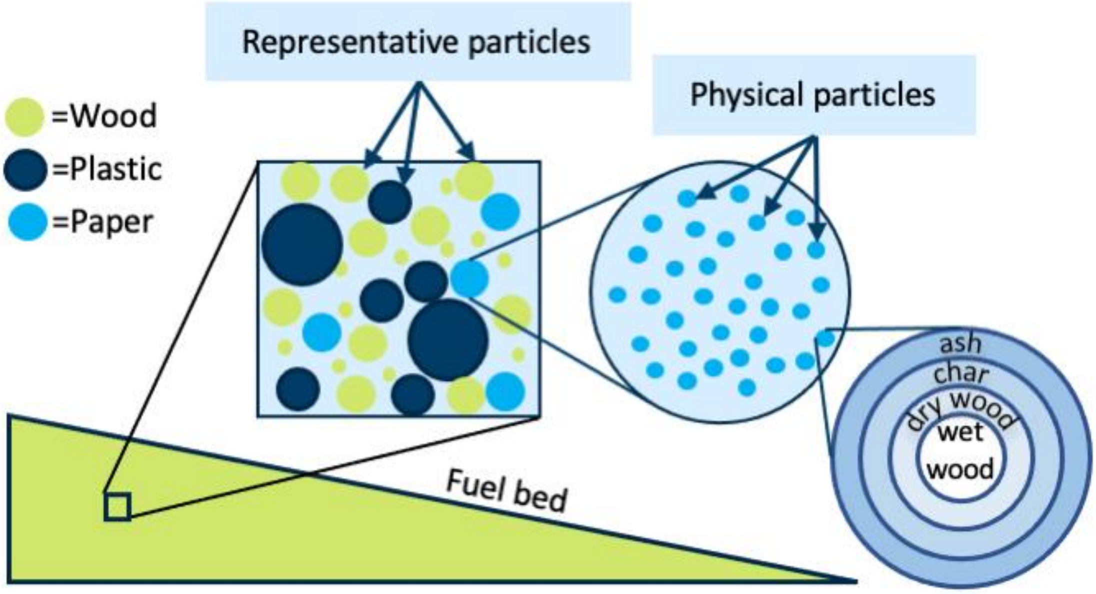

Figure 1 The principle of the Fuel bed model

3 The full scale furnace

3.1 Geometry and mesh

A geometry model for the REG (Renovasjons- og gjenvinningsetaten I Oslo kommune) waste-to-energy furnace at Haraldrud was built in the ANSYS Fluent software. The model was based on the drawing "A0-3372 Hovedarrangement". In the furnace, the air/oxidiser is provided through 4 primary inlets (below the grate) and 14 secondary inlets (above the grate). The secondary inlets are distributed with 7 inlets on the front wall and 7 inlets on the back wall. A schematic view of the furnace model is shown in Figure 2. The narrowing of the geometry prior to the outlet is made to avoid recirculation over the outlet (inlet flow), which could cause unstable simulations.

The geometry model is two-dimensional and in full scale, the two-dimensional mesh consists of 6168 control volumes.

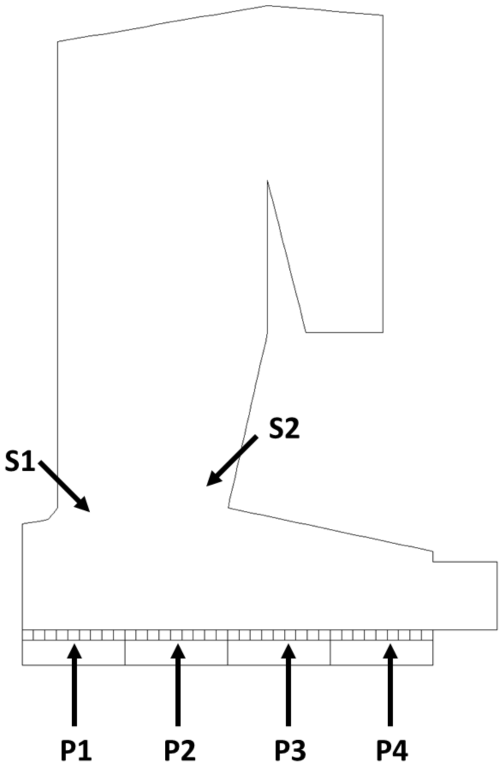

Figure 2 Schematic view of the Haraldrud WtE furnace

3.2 Fuel input

The fuel is Municipal Solid waste (MSW). Fuel characterisation for the MSW used in this study is summarized in Table 1. MSW is a heterogeneous fuel with varying properties over time and locations so an "average, typical" composition is difficult to define. The values chosen are within ranges observed in European MSW (Ref. BAT BREF WI, 2019).

Table 1 Characterisation of the MSW

	Proximate [wt %]
Moisture	30.00
Volatiles (d.b., calc.)	66.23
Ash (d.b., meas.)	22.14
Fixed carbon (d.b., estim.)	11.63

	Elements, major components, [daf wt %]
Carbon	51.0
Oxygen	37.7
Hydrogen	9.4
Nitrogen	1.9
Total	100.0

The specified mass flow rate of MSW is 6.21 ton/hour, which corresponds to approximately 50 000 tons/year (plant yearly availability of ca. 8000 hours). In this study, all the particles will have the same particle size (diameter of 2 cm) at the fuel inlet, even if in reality there will be a large variation in the particle sizes of the MSW.

Naturally, only H_2O is released from the fuel particles due to the drying process. For the devolatilization phase, the gas composition has been optimized towards satisfying available relevant pyrolysis gas compositions while maintaining the elemental balances for the solid fuel. This means that a mean gas composition is used for the devolatilization stage; 60.77% CO, 0.00% CO_2, 22.06% H_2O and 17.16% CH_4, on mass basis. For this study, the composition of the tar is set equal to the composition of light gases, such that they both have this composition.

The grate velocity was set to 0.0025 m/s. The actual grate length is 8.1m, which means that if the particles is transported with constant velocity, the corresponding residence time at the grate is nearly an hour (3240s), a duration seen as typical in many WtE installations. The particles will, however, move more slowly as they are reduced in size due to conversion. This results in a reduction in the velocity of the fuel bed as the bed move further down the grate, and this effect is taken into account in the simulations.

4 Air as oxidiser

The total volume flow rate of air is assumed to be 33 000 Nm3/h, with 64% injected as primary air and the rest as secondary air. The primary air is injected through four inlets, all with the same inlet area, and the distribution is 25/42/20/13 on P1/P2/P3/P4 respectively. The distributions are based on experience from previous work.

The mass flow rate of the secondary air was evenly distributed between all the secondary air inlets, and hence 50% of the secondary air was injected through the inlets at the front wall and 50% through the inlets at the back wall.

Presently, there is no flue gas recirculation at the Haraldrud plant, and there is no preheating of the air. In the simulations, the temperature of the secondary air is set to 373 K.

Modelling of the grate and the primary air inlets is based on the experience from the pilot furnace study (Haugen et al). This work showed that heat is easily transported through the grate elements opposite the flow direction of the bed and that this facilitates ignition of the bed from below. Since the metal grate elements have a significant absorption coefficient, the radiative heat from the bed immediately above the grate will also heat the grate itself, and, through that, the primary air that passes through the grate elements on its way to the bed.

In the simulations, however, the grate is emulated as a porous zone, which do not interact with radiation. On top of this, in order to reduce thermal inertia, and hence to reduce the required run-time to reach stationary state, the porosity of the grate is chosen to be very high, which yields too low thermal conductivity. In order to compensate for this shortcoming, the temperature of the primary air is set to 900K for the four primary air wind boxes.

4.1 Simulation results

Simulation results showing the development of the fuel bed is presented in Figure 3. After entering the bed, the fuel particles are first dried, before they devolatilise to form char. For the present conditions, this occurs above the first primary air zone. It can be seen that the char conversion extends for significantly longer but that all the particles are nevertheless fully converted before reaching the end of the grate. The bed extension is approximately to the middle of PA-zone 4. In the last part the particles are just ash.

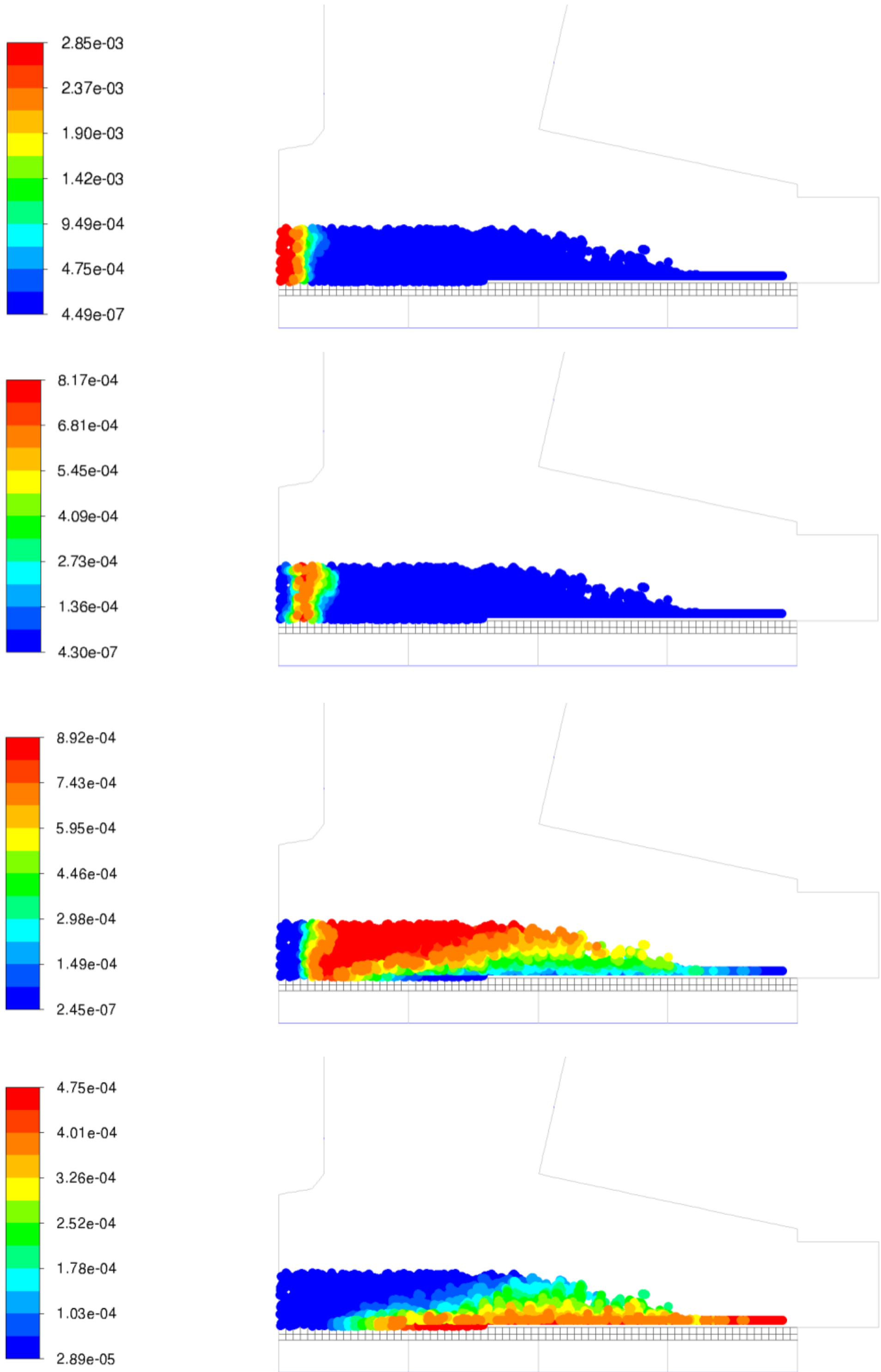

Figure 3 The development of the fuel bed for the air case. The particles in the bed, color coded by mass of wet mass (upper), dry mass (no 2 from top), char (no 3 from top) and ash (lower). The color coding corresponds to the following fraction of the maximum mass of the respective fraction: Dark blue: <10%, green: ~ 50% and dark red: >90%.

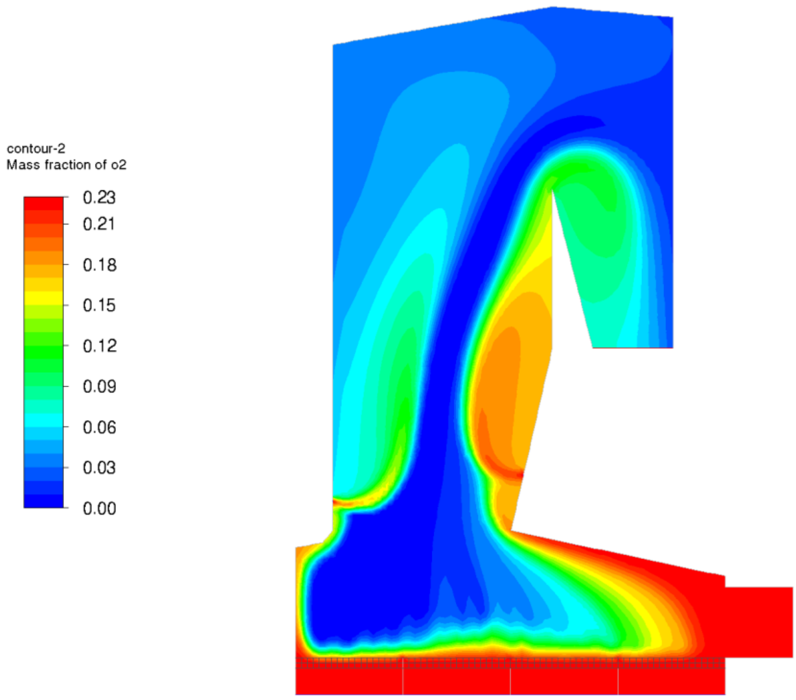

Figure 4 Concentration (kg/kg) of Oxygen for the air case

It can be seen from Figure 4 that nearly all the oxygen is consumed in the primary chamber above the three first grate zones, while there is some excess oxygen in the area above the fourth grate zone where the fuel particles are fully converted. Additional air is added through the secondar inlets, and burn-out of the combustibles occurs in the secondary chamber. The concentrations of CH_4 and CO at the outlet are infinitesimal, and the oxygen concentration at the outlet is approximately 5 vol %. An oxygen concentration of 5 – 11 vol% in exhaust is typical for many WtE-plants.

5 Oxy-fuel simulations

The specifications for the oxy-fuel simulations are based on the results from the CapeWaste H1-activity, which suggests recirculation of flue gas (RFG) for the oxy-fuel case. RFG is included to better control and limit the temperature, as we do not want to have too high temperatures, which is a risk with oxyfuel combustion, as it would require the use of expensive materials. The aim is to apply oxyfuel conditions with as little changes as possible to existing technology.

O_2/CO_2 oxidiser instead of O_2/N_2 makes carbon capture much more efficient, practical because of much higher CO_2 concentrations to handle. WtE CCS will enable negative CO_2 emissions as MSW is largely biogenic.

For the same fuel input as in the air-case, the total mass flow rate of RFG and oxygen that should be injected though the primary and secondary inlets is 28 587.5 kg/h. The composition of this oxidiser gas mixture is given in Table 2, and the temperature is 645.5 K, provided from subproject H1.

Table 2 Oxidiser gas composition for the primary and secondary inlets in the oxy-fuel case

Specie	Composition [Vol. fraction]	Composition [Mass. fraction]
CO_2	0.4753	0.5914
H_2O	0.1358	0.0692
O_2	0.2788	0.2522
N_2	0.1101	0.0872

5.1 Oxy-fuel case no 1

The first oxy-fuel case has the same distribution of oxidiser as the air case, which means a primary/secondary ratio of 0.64/0.36. The secondary oxidiser is distributed evenly between the front and back wall, while the distribution of the primary oxidiser is 25/42/20/13 on P1/P2/P3/P4 respectively.

A snapshot of the fuel bed for this case is shown in Figure 5. It can be seen that the drying and devolatilization of the fuel occurs at the start of the bed, above the first PA-zone, as for the air case. However, the char conversion zone is extended, and the particles are not fully converted when reaching the end of the grate. The reason for the lower conversion ratio could be that the amount of oxygen added through the primary inlets is lower than for the air case. It can be seen from Figure 6 that the oxygen added from the primary zones are consumed and the amount of oxygen available above the fuel bed is minimal, also above the fourth zone.

5.2 Oxy-fuel case no 2

The mass flow rate of oxidiser is lower in the oxy-fuel case 1 than in the air case, and the mass flow rate of oxygen is also lower. Based on what we learned from Oxy-fuel case no1, we now define a second case (case no 2) where the distribution between primary and secondary oxidiser is changed such that the amount of oxygen that enters in the primary zone is the same as in the air case. The distribution between the primary zones is unchanged, which means that for each of the primary zones the amount of oxygen is the same as in the air case. This gives a quite low mass flow rate of secondary oxidiser, and hence the two oxy-cases represent two "extreme points" of operation modes.

Figure 7 shows the simulated development of the fuel bed for this case. It can be seen that the extent of the char conversion zone is significantly reduced compared to Oxy-fuel case no 1 and the particles are fully converted when reaching the end on PA zone three. This means that the fuel bed is even shorter than for the air case. From Figure 8 it can be seen that there is excess of oxygen above the last part of the grate.

Comparing oxy-fuel cases 1 and 2 emphasize one of the important benefits of the current bed-model compared to traditional pre-defined bed-models, namely that the evolution of the fuel-bed depends in a consistent manner on the surrounding conditions. In order to have any predictive abilities, it is crucial that the fuel-bed evolves in close relation with the rest of the furnace – including primary air inlets, incident radiation, fuel properties (size, humidity, composition etc.) and flow parameters. This is indeed what this bed-model does, which puts the user in a position where he can vary a large range of parameters, even in a transient manner, and obtain physical correct results. The current study is performed just to give the reader a flavour of what the tool can do, but the real power of this tool will become apparent when one starts to test the effect of various furnace designs, fuel properties and operational conditions.

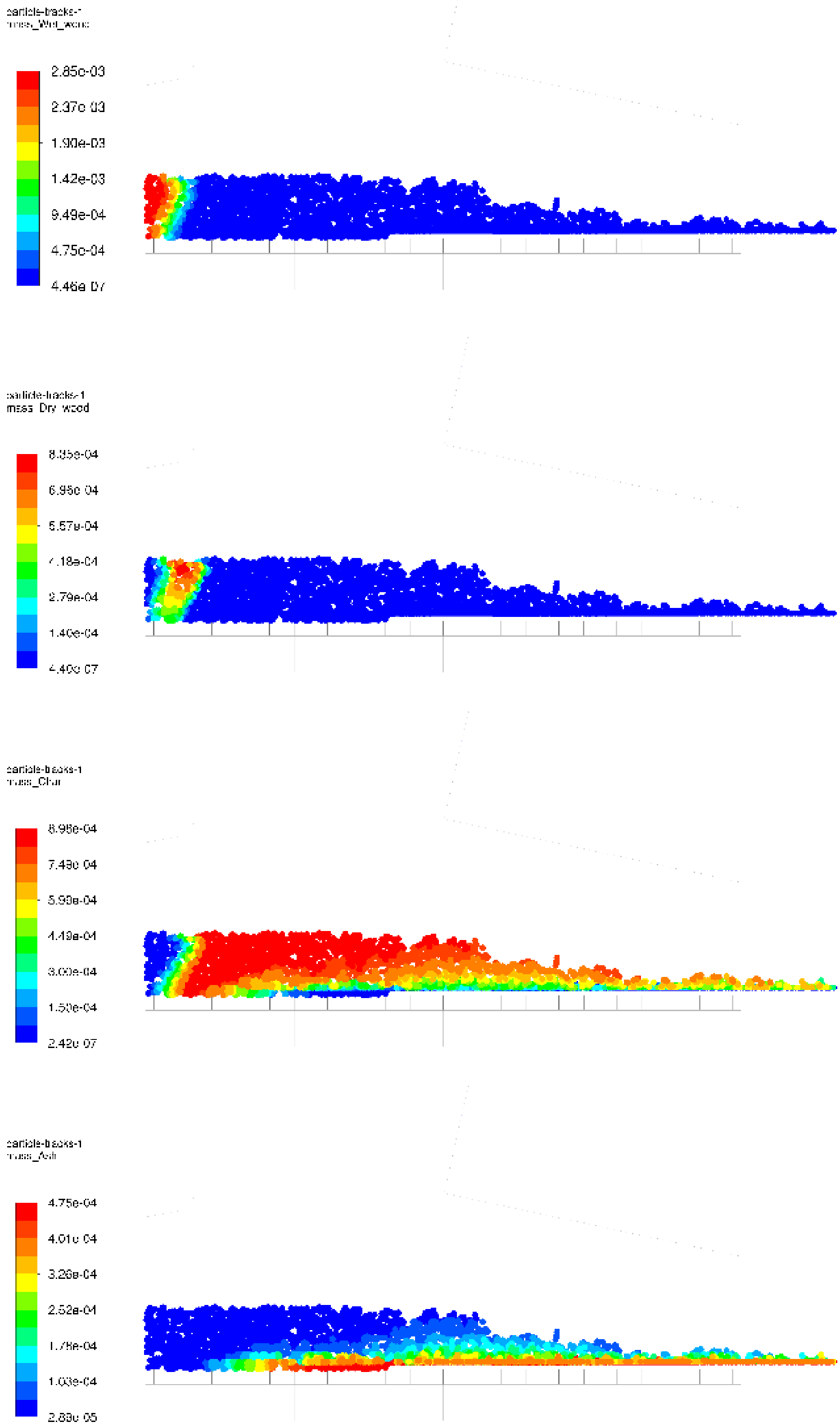

Figure 5 The development of the fuel bed for det first oxy-fuel case. The particles in the bed, color coded by mass of wet mass (upper), dry mass (no 2 from top), char (no 3 from top) and ash (lower). The color coding corresponds to the following fraction of the maximum mass of the respective fraction: Dark blue: <10%, green: ~ 50% and dark red: >90%.

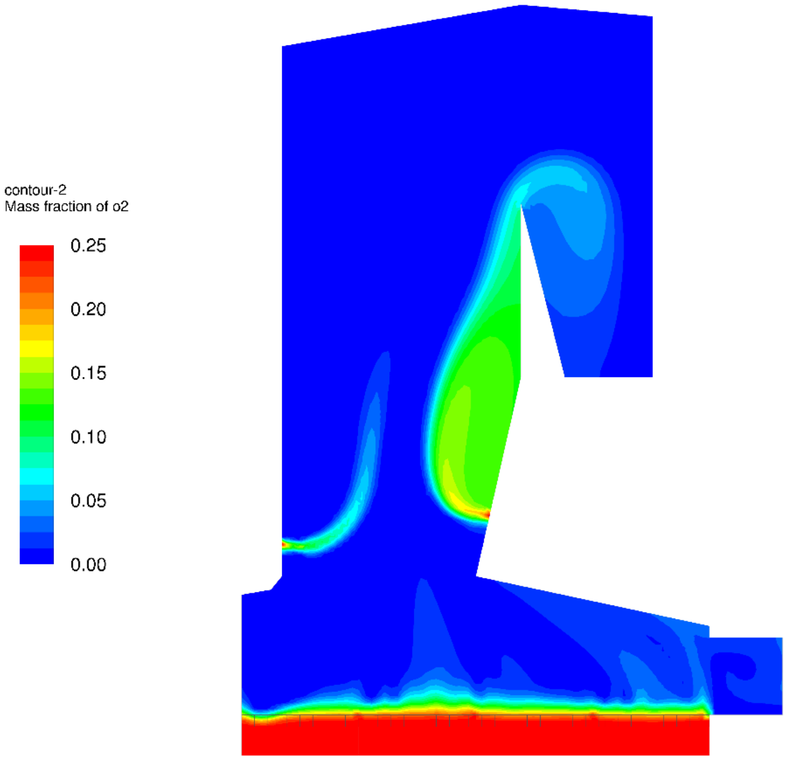

Figure 6 Concentration (kg/kg) of Oxygen for the first Oxy-fuel case

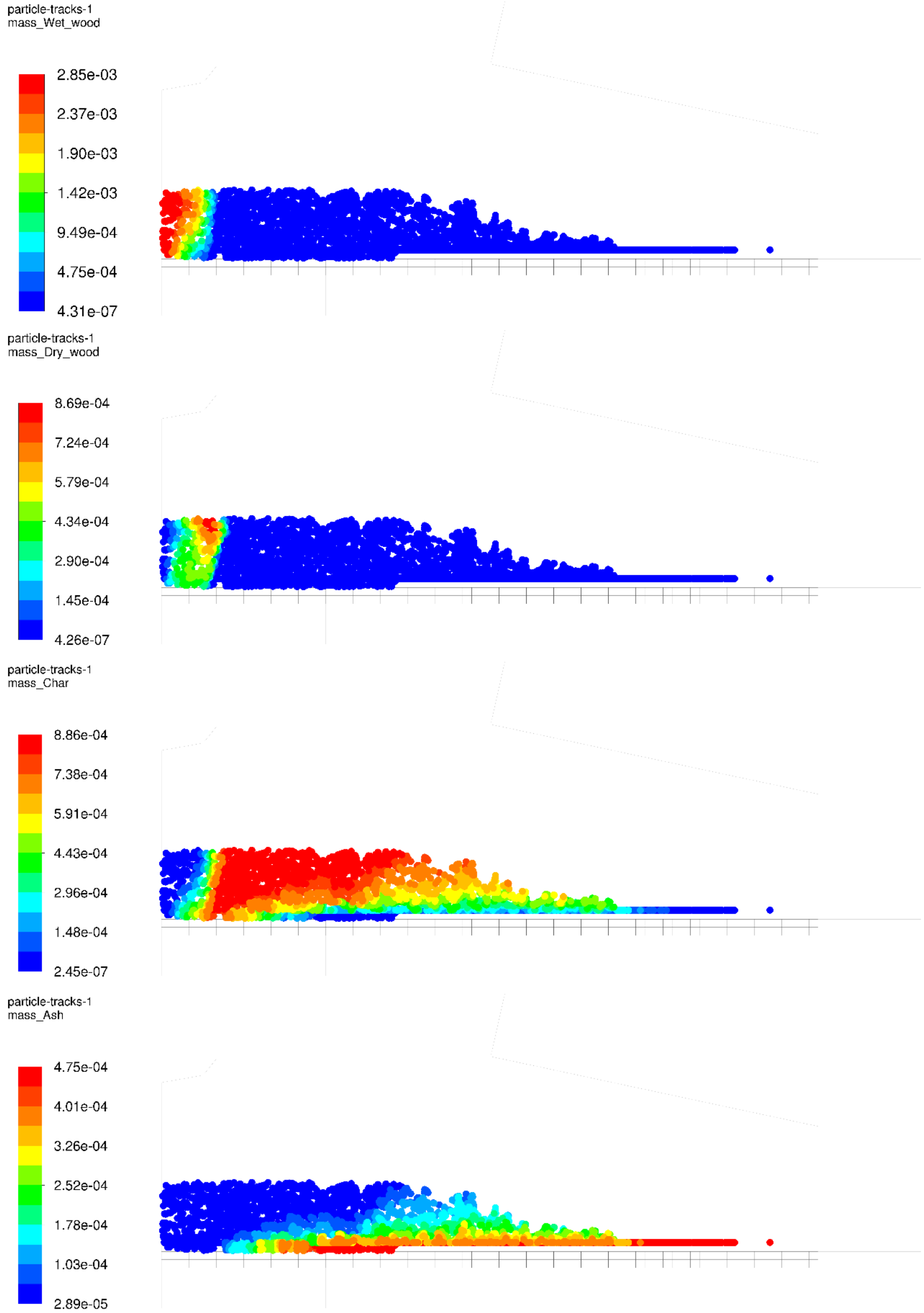

Figure 7 The development of the fuel bed for det 2nd oxy-fuel case. The particles in the bed, color coded by mass of wet mass (upper), dry mass (no 2 from top), char (no 3 from top) and ash (lower). The color coding corresponds to the following fraction of the maximum mass of the respective fraction: Dark blue: <10%, green: ~ 50% and dark red: >90%.

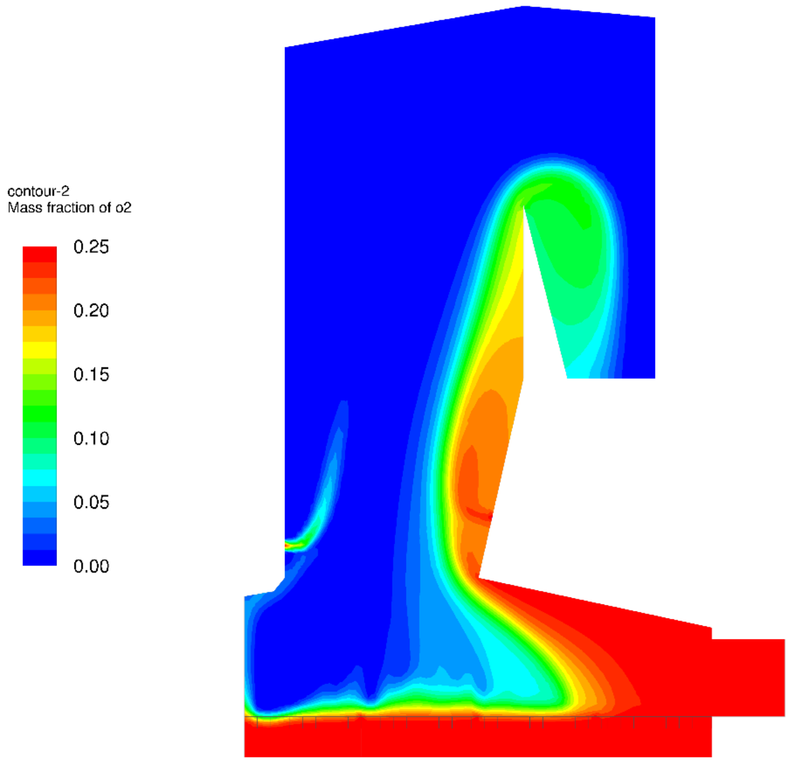

Figure 8 Concentration (kg/kg) of Oxygen for the second Oxy-fuel case

6 Summary

Two-dimensional CFD simulations have been performed for the Haraldrud furnace firing MSW under both air and oxy-fuel conditions. Instead of using the common simplification for the fuel bed, where the top of the bed is defined as a boundary with fixed or predefined properties with respect to mass flow rate, gas composition, temperature, and their distribution along the fuel bed, a newly developed fuel bed model was used in this study. The fuel bed model used considers drying, pyrolysis, and char combustion/gasification of the fuel, and representative particles are individually tracked and evolved for their entire residence time in the bed.

The simulation results indicated that for the conditions of this study the conversion and burn-out of the bed was at least at the same level under oxy conditions as when air is used as oxidiser under similar conditions adding the same amount of oxygen through the primary inlets. This was also the results in the study by Mack et al (2021) using wood chips in the Stuttgart pilot facility under air and oxy-fuel conditions.

A lower conversion was indicated for the oxy-fuel case when using the same ratio between primary/secondary oxidiser as in the air case, probably because this gave a lower amount of oxygen added through the primary inlets.

There is uncertainty associated with some parameters, and a more comprehensive study should be performed to study the effect of these. This applies to the bed velocity and the particle size. Larger particles will probably extend the drying and the devolatilization phase – in addition to the char conversion phase. In the present study, the devolatilization was occurring and finalised quite early on the grate.

Other parameters that will influence the combustion in the furnace and the conversion of the fuel bed, are moisture content of the MSW, MSW composition and oxygen distribution. In this study, the same gas composition was used in all oxidiser inlets, also for the oxy-fuel cases. An interesting option could be to reduce the oxygen content in the first primary zone which is usually dedicated to drying in air-fired WtE plants.

The simulations performed illustrate the important benefits of the current bed-model compared to traditional pre-defined bed-models, namely that the evolution of the fuel-bed depends in a consistent manner on the surrounding conditions. The current study gives the reader a flavour of what the tool can do, but the real power of this tool will become apparent when one starts to test the effect of various furnace designs, fuel qualities and operational conditions.

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