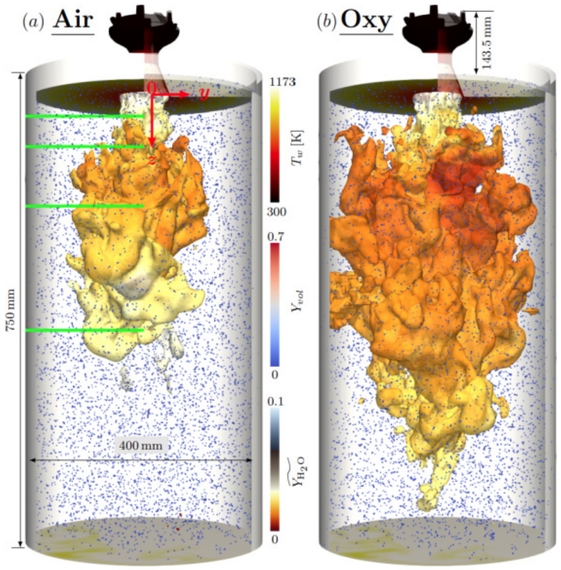
Large-Eddy Simulation of Torrefied Biomass Combustion in Oxy-Fuel Atmosphere



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Clusters
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Software
OpenFOAM

Institute
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Introduction

The safe supply of energy and electrical power will require operation of conventional power plants in the next decades until technical development enables the supply mainly by regenerative sources at minimum emissions of climate gases. Until then, new power plants with nearly no emissions of climate gases and high efficiency are necessary. This affords the development, design and construction of new, especially solid fuel fired power plants. Therefore, numerous time consuming scaling and demonstration steps are necessary. The worldwide increasing climate gas concentrations, however urgently require these new power plants. The vision of the Oxy ame project is to develop methods and models to achieve "predictive engineering" as a design tool for the engineering of burners and boilers to decrease the development time. Research at the institute for Simulation reaktiver Thermo-Fluid Systeme (STFS), TU Darmstadt, aims to develop models and methods for a reliable simulation of combustion phenomena in order to obtain a deeper understanding of the processes on the one hand and to improve the predictive capabilities of combustion CFD (Computational Fluid Dynamics) tools on the other hand. The proposed project is part of the final phase of the SFB/TRR 129 Oxy ame project funded by Deutsche Forschungsgemeinschaft. In the first two phases, the aim of the sub-project is to develop numerical models for simulating pulverized coal combustion. In the third phase, the purpose of the sub-project is to extend these numerical models to simulate biomass combustion. In particular, the pollutant formation, including the soot emissions, in the biomass combustion systems will be numerically investigated.

Methods

The accurate simulation of the combustion of solids is challenging due to various difficulties. The combustion of solids involves various complex chemical processes, both at the solid particle itself and in the surrounding gas phase. To include all chemical species as well as their chemical reactions into the simulations hundreds of transport equations needs to be solved for the species together with thousands of equations for the chemical reaction. For this reason, detailed simulations of the chemical process can be done only in generic testcases. These simulations can then be used to develop and validate reduced models. One reduced model used in this work is the flamelet model. This model is based on the so-called flamelet assumption, which means that turbulent flames can be represented as an ensemble of one-dimensional flames. Based on this assumption, it is possible to calculate flamelets in a pre-processing step and then store them in a flamelet library. This library can be accessed during simulation using the trajectory variables. The implementation of such a method within the framework of biomass combustion under oxy-fuel and air conditions is the subject of current research. In this project, a high-fidelity numerical model was developed to simulate the target burners, and a quadrature-based moment method was proposed to simulate the soot formation in solid fuel flames.

Results

The structure of the pulverized torrefied biomass flames in the air and oxy-fuel atmospheres is first investigated. The instantaneous 3D flame structure for both atmospheres is shown in Figs. 1a and 1b. The iso-surface corresponds to $T=1280K$ to represent the preheating zone, and is colored with Y_{H_2O} . 10000 sample parcels colored with the fraction of volatile matter Y_{vol} are superimposed, and the wall temperature of the furnace is shown as the background color. One of the notable differences in the flame structure is that the flame in the oxy-fuel atmosphere is longer and broader compared to the air atmosphere. In fact, the velocity of the secondary swirling flow in the air atmosphere is higher than that in the oxy-fuel atmosphere, which pushes the flow to the quarl side walls and generates a strong internal recirculation zone in the main flow region. The predicted average major species mass fractions are compared to the measurements next for different oxidizer atmospheres, as shown in Fig. 2. The sample point is located at $r=0$ and $H=8D$ from the burner port, as indicated by the red star in Fig. 1a. It is seen that the mass fractions of major species, particularly for CO_2 in the oxy-fuel atmosphere, can be reasonably predicted with the flamelet/LES method, although discrepancies remain, particularly for H_2O and CO_2 in an air atmosphere. The underprediction of Y_{H_2O} results from either the neglect of moisture in the proximate analysis or the inaccurate modeling of species compositions in volatile matter. To better predict the H_2O mass fraction in torrefied biomass combustion, further work has to be done to tackle the modeling of species compositions in volatile matter.

Discussion

Large-eddy simulations are, for the first time, conducted for a 40 kW th torrefied biomass furnace in both air and oxy-fuel atmospheres using an extended flamelet model. The predicted species mass fractions are compared to the experimental data for both atmospheres. The comparisons show that the major species mass fractions can be reasonably predicted by the flamelet/LES method for both atmospheres. To achieve the same oxidizer-to-fuel ratio near the burner, the designed secondary flow velocities are different for different atmospheres, which has significant effects on the overall biomass combustion process. Specifically, the flame is longer and wider in the oxy-fuel atmosphere as the strong internal recirculation zone cannot be generated due to the weaker swirling flow. In addition, in the oxy-fuel atmosphere, the unburnt biomass particles can be transported across the quarl zone by the positive axial velocity, forming an overall jet-like flame, i.e., a circular cone-shaped region with high oxygen concentration is formed in the central region while the burnt products and high temperature are formed annularly.

Figures

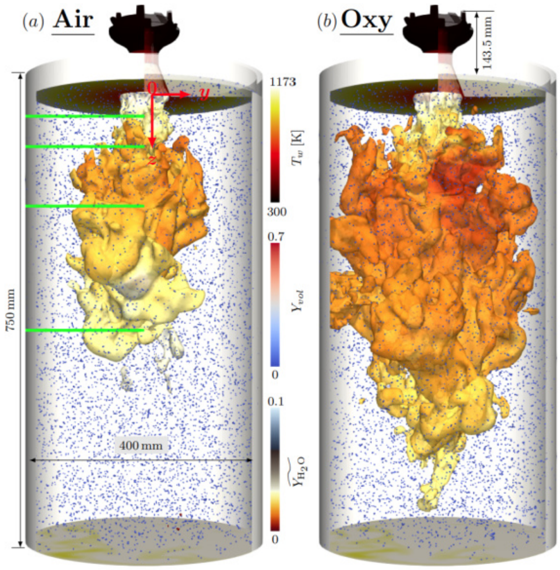

Figure 1: Instantaneous 3D fame structure in (a) air, and (b) oxy-fuel atmospheres. The iso-surface of $\tilde{T}$=1280K is colored with Y_{H_2O}, the particles are colored to indicate Y_{vol} (= 0 in most regions), and the wall is colored to indicate the temperature. The inset shows a magnified ed view of the quarl zone, and the unburnt particles (Y_{vol} >0) crossing the quarl zone are indicated. The green horizontal lines in (a) indicate the sample lines where the velocity components are measured.

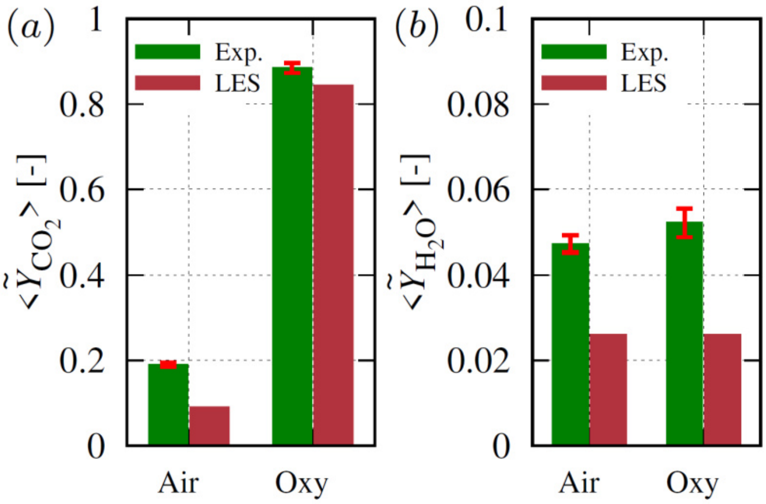

Figure 2: Time-averaged (a) CO_2, and (b) H_2O species mass fractions, comparing the experiment and the simulation for different atmospheres at *r=0* and *H =8D*.

Publications

Wen, X.; Nicolai, H.; Debiagi, P.; Zabrodiec, D.; Mameyer, A.; Kneer, R.; Hasse, C.: "Flamelet LES of a 40 kWth pulverized torrefied biomass furnace in air and oxy-fuel atmospheres", Proceedings of the Combustion Institute, 2023 https://doi.org/10.1016/j.proci.2022.07.135

Wen, X.; Ferraro, F.; Nicolai, H.; Hashimoto, N.; Hayashi, J.; Nakatsuka, N.; Tainaka, K.; Hasse,C.:"Flamelet LES of a turbulent pulverized solid fuel flame using a detailed phenomenological soot model", Proceedings of the Combustion Institute, 2023
https://doi.org/10.1016/j.proci.2022.07.190

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