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The virtual biomass grate furnace - an overall CFD model for biomass combustion plants

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Abstract

This paper presents the virtual biomass grate furnace, which comprises of comprehensive CFD models of all relevant processes for the simulation of biomass grate furnaces. The models consist of a 3D packed bed model, a gas phase combustion model for laminar to highly turbulent flows and a model to account for the influence of the flue gas streaks arising from the fuel bed in the freeboard. The simulation results of a 20 kW underfeed stoker furnace show that the overall CFD model is able to provide valuable insight on the processes occurring in the packed bed and freeboard and their interactions.

Keywords: virtual biomass grate furnace; CFD modelling; packed bed model; hybrid model; streak formation model

1. Introduction and objectives

CFD simulations are an efficient tool for the design and optimization of biomass grate furnaces to complement and reduce the extent of experimental investigations. The existing bed models resolve packed bed combustion separately from the gas phase above it and produce heat and mass release profiles which serve as boundary conditions for gas phase simulation by a CFD code. However, an appropriate packed bed model shall be directly linked with the gas phase combustion models in the freeboard to make a simultaneous simulation of the entire biomass grate furnace possible. In the freeboard, especially in the region above the fuel bed of small-scale biomass

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furnaces, gas phase mixing is highly influenced by laminar and low turbulence zones. Therefore, an accurate gas phase reaction model is needed to provide detailed information concerning predictions of flow, temperature and gaseous emissions (e.g. CO and NO_x). Moreover, the mode of gas combustion in a grate furnace can be classified as partially premixed with a locally different mixing degree of oxidizer and fuel, whereas in this context the combustible gases released from the solid biomass fuel bed are to be understood as (gaseous) fuel. The amount and distribution of combustibles and oxidizer in the gas released from the biomass particles in the fuel bed are locally strongly differing. It leads to streaks arising from the fuel bed which influence gas mixing and combustion and it has to be considered when modelling the biomass grate furnaces.

A comprehensive biomass packed bed combustion model has been developed by BIOENERGY 2020+ [1]. For gas phase, the same group developed a reaction model for laminar to highly turbulent flows [2] and a model [3] to account for the influence of the flue gas streaks arising from the fuel bed on reaction progress. In this work, the authors present the virtual biomass grate furnace, which is the coupling of three aforementioned models. Hence it combines the advantages of individual models. Therefore, the calculations of the freeboard region and the packed bed are combined. The interactions between the gas and solid phases as well as the radiative and conductive heat transfer between the particles are considered. Furthermore, the interaction between them allows to investigate the influence of operating conditions and fuel properties not only on the combustion behavior of the fuel bed but also on gas phase combustion in the freeboard at a highly detailed level. The advantages of the virtual biomass grate furnace are demonstrated by its application for the simulation of a 20 kW underfeed stoker furnace. An additional simulation was also performed with the state-of-the-art Eddy Dissipation Concept (EDC) model to highlight the benefits of the hybrid-streak formation gas phase model over the EDC in terms of flue gas temperature peaks, position and extension of the reaction zones.

2. Models

2.1. Packed bed model

A flexible 3D CFD model for the simulation of solid biomass combustion on the grate has been developed by BIOENERGY 2020+. The model considers the biomass fuel bed as an ensemble of representative particles, where each of these particles undergoes thermal degradation processes. The movement of the particles and their thermal degradation are the main parts of the packed bed model. The Euler-Granular model is employed to simulate the movement of the particles. This model enables to consider the particle-particle interactions, which is important for the granular flow in the packed bed regime. The conversion of the particles is modelled by the layer model (LM), a thermally thick particle model, which is able to describe the most essential characteristics of the thermal degradation of the biomass thermally thick particles, such as the intra-particle temperature gradient, the reaction rates of drying, devolatilization and char oxidation. In the layer model, the particle is divided into four layers: drying layer, pyrolysis layer, char and ash layer, whereas each layer corresponds to a conversion stage (wet fuel, dry fuel, char, ash). The boundaries between the layers are related to the conversion sub-processes: drying, pyrolysis and char burnout fronts in which simultaneous progress of the sub- processes is possible. In the particle model drying is assumed to take place at a constant temperature (the boiling temperature of water). Therefore, the drying rate is limited by the heat transfer. The pyrolysis is described by three independent competitive reactions for cellulose, hemicellulose, and lignin. The kinetic rate of each reaction is calculated by an Arrhenius equation where the empirical constants are obtained from fast heating thermal gravimetric analysis (TGA) experiments. Due to the structure of the layer model, the char conversion reactions are assumed to occur at the interface between the char and the ash layer. Char oxidation with O_2 and gasification with CO_2, H_2O and H_2 are considered as char conversion reactions. There is clear evidence that both CO and CO_2 are primary products of char oxidation and increasing the particle temperature favors CO production [4]. Therefore in the layer model the ratio of CO to CO_2 production changes with temperature [5]. More details about the layer model and its validation can be found in [6] and [7].

In order to combine these two models, Euler-Granular and layer model, in ANSYS FLUENT a simulation with non-reacting flow based on the Euler-Granular model with appropriate granular viscosity (empirically determined) was performed and the simulated velocity field of the granular phase was stored as user defined memories (UDM). Then these data were used to prescribe the particle velocities in the discrete phase model (DPM) simulation by