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Performance analysis of a steady flamelet model for the use in small-scale biomass combustion under extreme air-staged conditions

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ABSTRACT

Small-scale biomass boiler development is often based on empirical methods resulting in high efforts for experimental test runs using several prototypes. CFD simulations are able to reduce both, development time and efforts for tests and prototypes, supposing that the models reliability is high and its computational effort is low. Extreme air-staging with an initial gasification stage and a subsequent fuel gas burnout in a downstream gas-burner is a promising new method to reduce NO_X and PM emissions in small-scale biomass boilers. Gasification conditions in the first combustion stage lead to high accumulation of gaseous tars in the fuel gas contributing challenges for combustion simulation because common CFD models use 2 or 3-step global methane reaction schemes to describe combustion chemistry. In this work, the performance of a computationally inexpensive steady flamelet model (SFM) together with a detailed reaction mechanism (18 species, 42 reactions) was scrutinized. In order to evaluate the performance of the SFM, two furnace designs were examined, running under different load shifts and various excess air ratio. Comparative numerical simulations were performed with classical species transport models. The numerical simulations and the experiments for validation were carried out on a wood-chip boiler with a heat output of 40 kW. Results show that flue gas temperature, flame shape, main flue gas concentrations and NO_X can be quantitatively predicted. The SFM shows also reasonable good predictions for CO variation trends. With the present approach, calculation time can be reduced by 90% compared to commonly used models (EDC). The SFM provides sufficiently accurate results within 24 h using a standard processor consisting of six cores (mesh size 1.5 million elements). Thus, the presented model is a perfectly suitable method for applied science and industrial research.

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1. Introduction

1.1. Motivation

Increasing energy costs, the depletion of non-renewable fuels as well as efforts to lower the effects of climate change have all resulted in increased interest in renewable energy. Solid biomass fuels have a great potential to replace fossil fuels and to reduce greenhouse gas emissions. Combustion is the most popular technology for biomass utilization. The reaction heat released is presently the largest source of human energy consumption, accounting for more than 90% of the energy from biomass [1]. However, the use of biomass in boilers for residential heating is often associated with increased gaseous and particulate matter emissions. Thus, environmental directives focus on air pollutants caused by small-scale boilers and reduce the corresponding limits constantly. According this, scientific institutions as well as the biomass boiler industry is invited to develop methods and concepts to meet the progressively stricter emissions standards. Furnace design is often based on empirical methods resulting in high efforts for experimental test runs using several prototypes. CFD simulations are able to reduce both development time and efforts for tests, supposing that the models reliability is high and its calculation time is low. Extreme air-staging with an initial gasification stage and a subsequent fuel gas burnout in a downstream gas-burner is a promising new method to

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Nomenclature

Greek letters

λ_{Prim}	Primary air ratio
λ_{Tot}	Total air ratio

Subscripts

wb	wet base
db	dry base
daf	dry ash free

Abbreviations

CFD	Computational Fluid Dynamics
DO	Discrete Ordinates
EDM	Eddy Dissipation Model
EDC	Eddy Dissipation Concept
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PID	Proportional-integral-derivative
RANS	Reynolds Averaged Navier Stokes
RKE	Realizable $k-\varepsilon$
SFM	Steady Flamelet Model
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
VOC	Volatile organic compound
WSGG	Weighted Sum of Gray Gases

reduce NO_X and PM emissions effectively. The reduced conditions in the fuel bed, as they appear for instance in updraft gasifiers, lead to low bed temperature and consequently high amounts of gaseous tars contained in the fuel gas stream arising from the fuel bed. These tars are a challenge for biomass combustion models because common species transport models use 2 or 3-step global methane reaction schemes to describe combustion chemistry. It is therefore a future task to evaluate the applicability of new and commonly used biomass combustion models under extreme-air-staged conditions.

In a preceding study [2], the authors presented a fast-solving steady flamelet model for small-scale biomass boilers equipped with enhanced air-staging. The current article extends the study aforementioned by the implementation of a NO_X post-processor-model and presents new applicability tests on two furnace designs operating with various load shifts and different excess air ratio.

1.2. Background on combustion simulation

CFD modeling of biomass grate furnaces is especially difficult due to the complexity of the combustion process in the fuel bed on the grate, as well as due to the turbulent, gas-phase combustion in the freeboard [3]. Gas-phase combustion models are well embedded in commercial CFD codes such as ANSYS Fluent. In terms of solid fuel combustion on grates, the capability of commercial software is limited. The thermodynamic state of the fuel gas flow leaving the bed, as a boundary condition for gas-phase combustion modeling, can be either determined by experiments [4,5] or calculated by fuel bed models [6–8]. In the present work, the thermodynamic state variables of the fuel gas flow arising from the fuel bed are approximated by spatially resolved, experimental data which were carried out on a real-scale reactor. 3D steady state approaches are generally used to calculate the turbulent reacting flow in the freeboard. Species transport models, such as EDM [9] or EDC [10] are usually applied for calculating the reactive fluid flow, and thereby 2 or 3-step global methane reaction schemes are mostly used to describe combustion chemistry. Mixture fraction approaches like the SFM [11] are used infrequently [2] in biomass combustion appliances even these models have been used successfully in fossil fuel combustion [12,13]. The advantages of the EDM are the low calculation time and the excellent stability. A weakness of the EDM is that detailed chemistry can not be implemented and, as a result, tars can not be considered accurately. The EDC is most common in biomass combustion simulation, especially in the field of scientific research. This model can handle both, global and detailed chemical reaction schemes [14–18]. If detailed chemical reaction schemes are implemented, the EDC is able to predict species concentrations and flue gas temperature with high precision. However, the instability and the computational effort of this model are high, especially if detailed chemical reaction schemes are used. Thus, the EDC is perfectly suitable for academic research but its not well applicable in applied science in industry. The SFM mixture fraction model combines the benefits of both, EDM and EDC, because it can handle detailed chemistry at very low computational effort. In the SFM, the thermodynamical state of the fluid flow inside the furnace is described by only two variables called the mixture fraction and its variance. The mixture fraction represents the mass fraction of all fuel (C,H, …) and oxidizer elements (O, N, …) in all species. By the introduction of the mixture fraction the chemistry gets reduced to a simple mixing problem and by the mass balance on the atomic level numerically stiff source terms in the transport equations can be avoided [19]. In the SFM approach a turbulent flame is represented by a number of small, one dimensional flamelets [11] which are generated by calculating counter flow diffusion flames. In the 1D flames, species fraction and temperature can be easily calculated and compared with measurements. In the SFM, the flamelet is defined by the mixture fraction and the scalar dissipation rate (strain rate). Chemistry calculation (flamelet calculation) can be pre-processed and stored in tables. As aforementioned, only two additional equations fro

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