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A computational study of a small-scale biomass burner: The influence of chemistry, turbulence and combustion sub-models

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ABSTRACT

This paper presents a computational study to evaluate the influence of turbulence and combustion models as well as chemistry schemes on the combustion of a 8–11 kW small lab-scale biomass furnace. The analysis is conducted in the zone above the bed (freeboard) where the volatiles are burned. The turbulence models tested are standard $k-\varepsilon$, RNG $k-\varepsilon$ and Realizable $k-\varepsilon$; and the combustion models are SFM (Steady Flamelet Model), UFM (Unsteady Flamelet Model) and EDC (Eddy Dissipation Concept). In addition, several chemical mechanisms with different complexity (reduced and detailed chemical kinetics) are considered. The predictions of the velocity, species, and temperature fields are compared with their counterparts' experimental measurements. The present findings reveal that all tested combustion models (SFM, UFM and EDC) are capable of predicting temperature and major species profiles; whereas only EDC is able to reliably predict slow-chemistry species.

1. Introduction

Global warming concern and limited fossil fuel resources prompted serious interest in developing renewable energy sources such as carbon-neutral fuel (e.g., biomass pellets and woodchips) [1,2]. Grate firing biomass furnace is one of the widespread used technology available in the market owing to its low investment cost and flexibility in terms of feedstock (i.e., wide range of biomass particles size, moisture and ash contents) [3,4]. However, small scale biomass furnaces still suffer from generating high levels of gas emissions. This is caused mainly by the smaller furnace volume and consequently shorter residence combustion time [4]. Therefore, in order to meet future target levels of emissions and increased thermal efficiency, further studies are required to improve this technology [5].

Computational fluid dynamics (CFD) is becoming an increasingly important tool in the development, and optimization of biomass combustion devices due primarily to its noticeably lower cost compared with physical experiments and also to its ability to provide far more details than physical tests [6,7]. CFD simulations of biomass combustion consist of two separate sub-domains; namely the decomposition process of solid fuel in the grate and the gas-phase combustion of the volatile gases in the free room above the bed (known as freeboard) [5]. However, the reliability of the CFD predictions strongly depends on the sub-models used in the simulation of each domain.

To model turbulent biomass gas-phase combustion process, sub-models accounting for turbulence-chemistry interaction are employed. These sub-models employ the characteristics of turbulent field, combustible and oxidizer species, and the chemistry scheme in order to model biomass combustion process. Consequently, the reliability of the predictions (e.g., temperature field and emissions) relies strongly on the degree of simplification and capability of turbulence and combustion models as well as kinetic reaction mechanisms.

Standard (STD) and realizable $k-\varepsilon$ (RKE) turbulence models have been widely used to model turbulence in industrial biomass furnaces. Tabet et al. [8] performed a comprehensive CFD modeling of a domestic biomass stove using STD $k-\varepsilon$ turbulence model along with transport equations of mixture fraction for the gas-phase combustion in the freeboard. Also, in a review study, Chaney et al. [6] examined STD $k-\varepsilon$ model on the role of CFD modeling of small-scale grate firing biomass furnaces for optimizing the combustion performance and NO_x emissions. These studies showed that STD $k-\varepsilon$ turbulence model was able to reasonably predict velocity, species and temperature fields at different inlet airflow conditions. Collazo et al. [9] used RKE turbulence model for simulating a domestic pellet boiler and focusing on the influence of boiler parameters (e.g., air inlet distributions) on the emissions level.

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Nomenclature

C_γ	EDC Model constant	ϑ	kinematic viscosity
C_τ	EDC Model constant	γ	length fraction of fine scales
k	turbulent kinetic energy	τ_{EDC}	EDC time scale
Re_t	turbulent Reynolds number	τ_η	Kolmogorov time scale
$R_{i,EDC}$	EDC mean reaction rate	τ_{mix}	mixing time scale
T_t	turbulent time scale	ε	turbulent dissipation rate

Their model satisfactorily predicted temperature and species profiles when compared with experimental measurements. Buchmaye et al. [5] performed a three-dimensional (3D) CFD simulation of a small-scale biomass furnace where RKE turbulence model was used for the gas-phase combustion. They reported acceptable predictions of temperature and gas emissions in comparison with experimental measurements. Fletcher et al. [10,11] tested both STD $k-\varepsilon$ and Reynolds stress model (RSM) for predicting flow entrainment in a biomass gasifier under isothermal (cold) and flame conditions. They reported that, compared with the predictions of the cold flow case, the predictions (i.e., temperature, gas concentrations and velocity field) of the reacting flow field are less sensitive to the adopted turbulence model [11]. They attributed these differences to changes in the density and hence velocity within the gasifier due to combustion, which dominates the flowfield and makes it less sensitive to the turbulence modeling. In another study, Knaus et al. [12] performed gas-phase simulation in the freeboard of a small-scale 15 kW wood heater in order to examine the application of different turbulence models, where low-Reynolds and STD $k-\varepsilon$ models as well as RSM turbulence model under cold flow and combustion conditions were tested. They reported different flowfield predictions of the cold flow using different turbulence models, whereas combustion characteristics (e.g., temperature and gas concentration) were predicted reasonably well by all models.

The modified version of the well-known eddy break-up (EBU) approach [13], known as finite-rate kinetic/eddy dissipation model (FRK/EDM) [14], has been widely adopted for simulating a variety of combustion systems due to its low computational cost and high stability [15,9,16,17]. For FRK/EDM, both kinetic and mixing rates of reactions are calculated and the lowest of the two reaction rates determines whether the combustion process is mixing or kinetically limited. In the case of biomass combustion, FRK/EDM with reduced chemical reaction mechanisms (e.g., two-step mechanism) has been widely employed. Yin et al. [18] applied FRK/EDM along with a two-step reaction mechanism with CO as the intermediate species to simulate the combustion of a wheat straw grate-fired boiler. They achieved reasonable predictions of temperature and major species in comparison with their counterpart's experimental data. The study discussed earlier by Collazo et al. [9] adopted FRK/EDM combustion sub-model together with the global two-step kinetic mechanism proposed by Westbrook and Dryer [19]. Yin et al. [20] examined the influence of chemistry scheme and combustion sub-model on the simulation of a co-firing straw with coal in a dual-feed burner. They tested the four-step reaction mechanism proposed by Jones and Lindstedt [21] using EDC model [22] and compared the predictions against those of Westbrook and Dryer [19] reaction mechanism using FRK/EDM. Their results showed improved performance of the former approach (i.e., EDC) with respect to the prediction of flame volume (i.e., the region with high CO and low O_2 concentrations) [20].

The drawback of FRK/EDM is its inability of considering detailed chemistry for mixing limited conditions and consequently its inaccurate predictions of the intermediate species and pollutant emissions such as CO and NO_x [23]. In order to overcome this handicap, eddy dissipation concept (EDC), as an extended version of EBU models, has been proposed by Magnussen [22] to incorporate detailed chemistry in turbulent reacting flows. EDC has been widely used in biomass combustion applications. For instance, Klason and Bai [4] adopted EDC with fast gas-phase combustion assumption to model a small lab-scale grate firing biomass furnace. They reported that air inlets' turbulence intensity has a significant impact on the predictions. Sukumaran and Kong [2] used EDC with a modified version of GRI 3.0 [24] mechanism to model fuel NO_x formation from biomass-derived gas in a large-scale burner. They reported that their model can reasonably capture the level and trend of NO_x emissions. Bugge et al. [25] simulated a biomass grate fired combustor with more emphasis on the prediction of NO_x emissions using EDC along with three different chemistry schemes proposed for gas-phase biomass combustion [26]. Their predictions revealed significant effect of the chosen reaction mechanism on the prediction of NO_x emissions, especially in the primary zone of the burner. It is well-known that despite the ability of EDC to employ detailed chemistry in turbulent flames, its capability to model weakly turbulent reacting flows and slow chemistry poses a real challenge (e.g., [27–29,23]). In fact, there exist only a few studies which examined and addressed its limitations in biomass combustion (e.g., [30,23]). For instance, Shiehnejadhesar et al. [30] proposed a hybrid FRK/EDC model suitable for weakly and highly turbulent flow conditions. Later on, they examined the performance of the standard EDC against their hybrid model for simulating a small-scale biomass boiler, and reported that the standard EDC over predicted CO concentration [7]. Farokhi and Birouk [23] performed a sensitivity analysis on EDC coefficients for both weakly and highly turbulent reactive flow conditions and suggested a method for modifying EDC coefficients based on turbulent flow characteristics (i.e., turbulent Reynolds number and turbulent time scale). They then simulated the gas-phase combustion of a small lab-scale biomass furnace using the modified EDC and reported improved predictions of temperature and species when compared with its standard version [31].

Another disadvantage of EDC is associated with its relatively high computational cost, especially when detailed chemistry is employed for simulating industrial combustion plants. That is why these types of simulations are restricted to reduced chemical schemes (i.e., two-step to four-step mechanisms) [32]. Mixture fraction approaches (i.e., steady flamelet model (SFM) [33] and unsteady flamelet model (UFM) [34]), which are capable of incorporating detailed chemistry at low computational cost, as alternative combustion sub-models are considered in the present study. In most commercial CFD softwares, such as FLUENT [35], the application of SFM and UFM are limited to one type of combustible mixture which can be used with different mixture fraction through different inlet boundaries. In the case of grate-firing biomass furnaces, this can be applied by assuming a uniform mixture of volatile gases throughout the bed, which is an acceptable assumption for most small-scale biomass furnaces. Mixture fraction approaches (e.g., SFM and UFM) have been rarely used in biomass combustion. Albrecht et al. [36] performed a comparison between a mixture fraction-PDF method and EDC for grate-firing biomass