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Numerical models for thermochemical degradation of thermally thick woody biomass, and their application in domestic wood heating appliances and grate furnaces

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ABSTRACT

This paper reviews the current state-of-the-art of numerical models used for thermochemical degradation and combustion of thermally thick woody biomass particles. The focus is on the theory of drying, devolatilization and char conversion with respect to their implementation in numerical simulation tools. An introduction to wood chemistry, as well as the physical characteristics of wood, is also given in order to facilitate the discussion of simplifying assumptions in current models. Current research on single, densified or non-compressed, wood particle modeling is presented, and modeling approaches are compared. The different modeling approaches are categorized by the dimensionality of the model (1D, 2D or 3D), and the one-dimensional models are separated into mesh-based and interface-based models. Additionally, the applicability of the models for wood stoves is discussed, and an overview of the existing literature on numerical simulations of small-scale wood stoves and domestic boilers is given. Furthermore, current bed modeling approaches in large-scale grate furnaces are presented and compared against single particle models.

Contents

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1. Introduction

Currently, intense research is concentrated on the thermal conversion of biomass, which is due to the more attractive character of biomass compared to traditional fossil fuels for technologies based on thermal conversion, such as combustion [1]. The superiority of biomass-based technologies compared to fossil fuel technologies is related to the environmentally friendly character of botanic biomass, also including lignocellulosic biomass. A plant can only release the carbon dioxide (while burning) that it has stored during growth. The net CO_2 emission is therefore zero, making biomass carbon-neutral [2]. Hence, more research within the field of thermal conversion of biomass can contribute significantly to a sustainable energy mix.

Biomass combustion is one of the main routes of biomass conversion [3]. Different combustion technologies require differently sized lignocellulosic biomass particles [4]. Wood pellets, logs and chips are usually used, and are considered to be thermally thick particles [5]. When modeling thermally thick wood particles, heat and mass transport have to be considered. Overall, there is a large difference between thermally thin and thermally thick particles, which is classified by the Biot (Bi) number. The Biot number is defined as [6]

$$\mathrm{Bi} = \frac{h_{eff} d}{\lambda}, \tag{1}$$

where the thermal conductivity (λ), characteristic length (d) and effective heat transfer coefficient (h_{eff}) are used. The Biot number defines the ratio between heat transfer resistance in the interior of the particle and at the surface of the particle [7]. For low Biot numbers (< 0.1), a thermally thin regime is present, whereas large Biot numbers (> 0.1) indicate the presence of a thermally thick regime [8]. In thermally thick particles, intra-particle gradients of temperature are important [9]. Due to varying temperatures, different conversion stages occur simultaneously within the wood log or particle, and intra-particle transport phenomena also have to be considered. In contrast, thermally thin particles have a uniform temperature distribution. This results in sequential conversion stages [10]. Independent of the applied combustion technology, the conversion steps that occur during combustion are drying, devolatilization and char burnout.

In addition to the fundamental research on thermal conversion of biomass particles, the application of the corresponding models to wood-fired boilers and stoves has recently been intensively studied. The main aim of current research is to improve the combustion process with the aid of modeling tools to help yield an improved design and operation of boilers or stoves. Improvement is required since emissions of carbon monoxide, particulates, organic pollutants such as polycyclic aromatic hydrocarbons (PAH), soot and nitrogen oxides of current small-scale units may be very high [11]. Furthermore, the use of bioenergy will increase in the future, thereby highlighting the importance of optimized stove and boiler designs [12]. In Norway today, domestic heating applications such as wood stoves account for almost 50% of bioenergy use, and the use of wood logs in small-scale units, as well as the utilization of pellets in pellet stoves and boilers, is predicted to increase even further. The Norwegian objective is to increase the rate of energy conversion in wood and pellet stoves by a factor of 2 from 2008 until 2020 [13]. The need for optimization of wood log fired stoves is due to decreasing emission limits and changing market demands [14]. Modern simulation techniques, such as computational fluid dynamics (CFD), are an efficient way to reach these objectives [14]. CFD for the optimization of combustion systems is considered an alternative way of improvement (compared to experiments) that is usually less expensive [15]. Even though numerical simulations are a more time-saving and less expensive optimization route, experiments are needed for the validation of models applied [12].

In order to apply commercial CFD tools, numerical sub-models have to be developed [15]. The sub-models aim to fully describe the thermal conversion of the solid fuel, and eventually link these results