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Research paper

Experimental investigation of the primary combustion zone during staged combustion of wood-chips in a commercial small-scale boiler

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ABSTRACT

In this work the primary combustion zone of a modified, commercial, small-scale boiler was investigated during staged combustion of wood-chips. Experimental research on thermal conversion of biomass in fixed beds is necessary to supply reliable data for gas phase combustion model validation and optimization. Furthermore, scruting of pollutant emission formation and combustion efficiency enhancement can be conducted. Two different fuel moistures were used while the primary combustion zone of a small-scale boiler was investigated as a function of the primary air ratio. The combustible products leaving the fuel layer were analyzed under continuous operation by an extractive method. This approach is new in the field of small-scale biomass combustion research and considers the strong coupling between the products leaving the fuel bed and the heat fluxes emitted by the flame of the secondary combustion zone. Additionally, fine particulate matter emissions were quantified to study the effect of varying primary air ratio and different fuel moisture on particulate formation. Results show that the primary air ratio and the fuel moisture have a significant influence on the primary combustion products composition, on the fuel bed behavior and on fine particulate matter emissions. At low primary air ratios, tars constitute a significant part of the heating value of primary combustion products. The smallest amount of particulate emissions was found at low primary air ratio and low fuel moisture. Experimental data was validated with an elemental balance, which showed perfect accordance.

1. Introduction

Due to high carbon dioxide emissions, thermal energy conversion of fossil fuels is one major reason for the greenhouse effect. Since biomass is the only carbon based renewable fuel, serious efforts should be made to establish woody biomass for heating domestic and commercial buildings. To achieve further establishment of small-scale biomass furnaces, improvements with respect to efficiency, emissions and costs are needed. Most of the studies, done in the past on domestic small-scale boilers, have been carried out on secondary combustion, to analyze the complete burnout of primary combustion products. Studies on the composition of products from primary combustion in commercial, small-scale biomass boilers are not available in the literature.

In this research work the thermal conversion of wood-chips in the primary combustion zone of a commercial, slightly-modified, small-scale boiler was investigated. The nominal thermal output of the wood-chip boiler was 50 *kW*. The objective of the study was to evaluate the influence of primary air ratio as well as fuel moisture on the fuel bed characteristics, on the composition of the primary combustion products and on particulate matter emission. This approach is new in the field of small-scale biomass combustion research. The work is relevant since such data are needed for characterization of thermal conversion of biomass in fixed-beds on grates, the development of new furnaces as well as the development and validation of new CFD (Computational Fluid Dynamics) models.

2. Literature review

2.1. Combustion optimization

Numerous studies have been done on the optimization of secondary combustion as well as on emission formation and reduction in biomass heating appliances in the past. Nussbaumer [1] and Williams et al. [2] gave an excellent overview about fundamentals,

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Nomenclature

λ_{prim}	primary air ratio
λ_{tot}	total air ratio
d.b.	dry base
w.b.	wet base
a.f.	ash free
LHV	lower heating value

technologies and primary measures for emission reduction during biomass combustion. The various steps in the combustion mechanisms are given together with a compilation of kinetic data. Chemical formation mechanisms for different pollutants as well as modeling methods are outlined. Tullin et al. [3], Dias et al. [4], Serrano et al. [5] and Liu et al. [6] did experimental research regarding carbon monoxide and nitrogen oxide emissions during wood-pellet and wood-chip combustion in small-scale boilers. They collectively concluded that air-staging can be a very effective method for emission reduction. Ghafghazi et al. [7] explained various factors in their work leading to formation of particulate matter emissions from combustion of solid wood biomass fuel used in district heating appliances. Special attention was paid on particle measurement and the effect of fuel characteristics and operating parameters on the formation of particulate matters. Wiinikka et al. [8,9], and Morrin et al. [10] performed investigations on particle formation mechanisms from combustion of wood-pellets under fixed-bed conditions. They found that fine particulate matter emissions can be minimized by reducing the temperature in the fuel bed and maximizing the efficiency of secondary combustion.

2.2. Biomass gasification

Fixed bed gasification with air as gasification agent has been studied extensively in the past. Although the processes during primary combustion of biomass in small-scale boilers and those during biomass fixed-bed gasification are quite similar, the composition of wood-volatiles is significantly different. The reason for this are interferences (radiative and convective heat fluxes) between the fuel bed and the secondary combustion zone when dealing with combustion technology. Nevertheless, the results from gasification research help to understand the very complex conversion processes of biomass in fixed-beds on grates. Li et al. [11], Perez et al. [12], Porteiro et al. [13], Simone et al. [14] and Rao et al. [15] performed gasification experiments of different biomass fuels with air as gasification agent. They studied the effect of different air/fuel ratios on temperature profiles, gas composition and heating value of producer gas. Di Blasi et al. [16] designed a lab-scale gasifier to generate data for process modeling and to compare the gasification characteristics of different forms of biomasses. Several authors [17–23] performed experiments to study the effect of different operation modes on tar content in fuel gas. Tar is without doubt the greatest barrier to make the gas usable in thermal engines. Sheth et al. [24] and Plis et al. [25] investigated the variation of producer gas characteristics as a function of the key operation parameters: air/fuel ratio, air temperature and fuel moisture. Plis et al. [25] compared their results with findings of other researchers. Yang et al. [26] did pyrolysis experiments with the main components of biomass: hemicellulose, cellulose and lignin.

2.3. Comparable measurements

As mentioned in the introduction, studies on primary combustion of biomass in commercial, small-scale heating appliances are rare or non-existing, respectively. The small quantity of experimental data available is based on lab-scale reactors and on large-scale biomass boilers. Mandl et al. [27] performed experiments with a lab-scale, fixed-bed updraft gasifier coupled to a combustion chamber. They investigated temperature profiles, composition of producer gas and fuel bound nitrogen release. The extracted producer gas composition was measured by gas chromatography equipped with a thermal conductivity analyzer. The producer gas tar content was quantified using a gravimetric method. Thunman et al. [28] and Leckner et al. [29] did experimental research on a 31 MW grate-fired boiler. Wet forest waste was used for the experiments while temperatures and the fractions of the combustion and pyrolysis gases evolving from the fuel layer were measured at different positions in the large-scale boiler. The extracted gas samples were quantified by NDIR, FID and FTIR method. Mura et al. [30] did biomass pyrolysis experiments in a semi-industrial-scale reactor and studied fuel-nitrogen oxidation during combustion of wood-volatiles. They found that the temperature of pyrolysis does not affect the production of fuel nitrogen oxides. The gases produced during combustion were analyzed by FTIR method. Fleckl et al. [31] applied an in-situ FTIR measurement appliance in a 350 kW biomass traveling-grate furnace to investigate the gaseous compounds leaving the fuel bed. They showed that quantitative and qualitative detection of gaseous compounds in reducing and oxidizing zones of furnaces is possible. Stubenberger et al. [32] found in their work that the extractive method delivers more accurate results than those obtained by in-situ FTIR method. The investigations were carried out on a lab-scale reactor with different woody biomass fuels. Samuelsson et al. [33] performed experiments on a batch-fired experimental rig using wood pellets as fuel. For the extractive gas analysis they used NDIR, FID, FTIR and GC. Ryu et al. [34] investigated the combustion of different biomass fuels in a lab-scale, batch-type reactor. Temperature, gas composition and mass losses curves were identified. A gas analyzer was used for the detection of primary combustion product composition.

3. Combustion theory

The whole combustion process of solid biomass can be divided into several overlapping sub processes [1,2]. The mechanisms during primary combustion are evaporation of moisture, volatile release/char formation and gasification/oxidation of char. Volatile oxidation occurs, subsequently, in the secondary combustion zone.

Two staged combustion systems are increasingly common in small-scale biomass boiler design since this technique can be very effective for pollutant emission reduction. In the first stage the solid biomass is converted to char, volatile compounds and ash. Wood volatiles are composed of different gaseous species, water and tar. The gaseous components consist mainly of H_2, CO, CO_2, CH_4, N_2, H_2O and other light hydrocarbons. In case of lateral fuel insertion, primary combustion occurs in different sections, stratified along the grate length. At the fuel inlet, the solid biomass is heated and dried. The energy required is provided mainly by partial oxidation of wood volatiles and char oxidation. At increased temperatures (>500 K) decomposition of the woody fuel takes place and solid char and wood volatiles are formed [26]. The char particles move to the opposite side of the fuel inlet, driven by the inflowing fresh fuel. Char is partially converted into gaseous components by reduction mechanisms. The remaining char particles are burnt on the grate, mainly at the opposing side of the fuel inlet, by the supplied primary air.

Biomass combustion leads to relatively high emissions of particulates. The majority of the particulates are smaller than 10 μm. If,