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The effects of biomass co-gasification and co-firing on the development of combustion dynamics

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ABSTRACT

Effects of wheat straw co-firing with gas (propane flame) and co-gasification/co-combustion with wood pellets on the development of thermo-chemical conversion of biomass pellets and on heat energy production were experimentally studied and analyzed with the aim to improve the gasification/combustion characteristics and the applicability of wheat straw as an alternative energy source for cleaner heat energy production. The results suggest that the wheat straw co-firing with propane provides an enhanced thermal decomposition of pellets with more complete combustion of volatiles increasing thus the heat output at thermo-chemical conversion of wheat straw and the produced heat energy per mass of burned wheat straw pellets. A similar improvement of the combustion characteristics is observed at co-gasification/co-combustion of wheat straw with wood pellets which have a different elemental composition and different heating values. As a result, adding wood to wheat straw pellets activates the thermal decomposition of the mixture and the combustion of volatiles ensuring the faster release, ignition and combustion of volatiles and improving the combustion characteristics thus providing cleaner heat energy production.

1. Introduction

The increasing demand for cleaner heat energy production with reduced greenhouse gas (GHG) emissions promotes growing interest in a more intensive and efficient use of renewable fuels, i.e. different types of biomass (wood and agriculture residues, etc.), contributing to the GHG emission reduction and meeting the EU targets which require that by 2020 20% and by 2030 40% of energy must be produced from the renewable sources, which will improve energy efficiency by at least 20–27% [1]. At present, although the use of biofuels for energy production is about 15% of the world's total energy consumption and has already provided a significant reduction of greenhouse gas emissions, more efficient use of biofuels, such as straw, has become increasingly topical in EU – UK [2], Denmark [3] and in other countries. Among the countries clearly targeting the 2020 goals that 30% of energy production must come from renewable sources, Denmark should be mentioned, where the straw-fired boilers have gone through rapid development since 1980, their efficiency has doubled, whereas the emission of harmful substances has been reduced significantly. Moreover, the production of straw pellets leads to cost savings for the plants thus proving that the straw-heated district heating plants can be an inexpensive and environmentally friendly alternative to other kinds of heating. It should be noted that along with the utilization of wood and straw pellets as a fuel for cleaner heat production in district heating plants, the conversion of biomass pellets into a fuel gas [4] which is applicable for energy production in internal combustion engines, suggests another way of their utilization by replacing a fossil fuel with a renewable one. The energy content in the biomass depends on a lot of factors, namely, the biomass chemical and elemental composition, the ash content, the bulk density and moisture contents, determining wide variations in energy content and in composition of emissions [5]. An environmentally friendly renewable fuel is wood, whereas the use of straw for heat energy production, which is characterized by the higher content of nitrogen, potassium, chlorine and ash and by the lower calorific value, causes problems for the heat producers due to the increased release of hazardous emissions [6], emissions of NO_x [7], HCl [8] fouling and slagging problems [9]. However, the rapidly growing consumption of wood pellets for residential heating causes the significant shortage of raw material and the need for ever-greater use of alternative renewable energy sources, e.g., straw, through in-depth

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research on the advancing efficiency of its use for heat production. When considering the CO and VOCs concentration in flue gases, wheat straw is a more advantageous fuel if compared with rape straw [10].

In order to resolve the problems caused by the use of straw for heat and energy production and concerned with the emissions of CO, NO, HCl and volatile organic compounds and with the ash formation, combined combustion processes have been developed by co-firing straw with additives of solid or gaseous fuels, i.e. coal [11,12], natural gas [13], woody biomass [14]. Comparative analysis of these processes shows that the biomass co-firing is a promising combustion technology. Typically, combining straw with different types of fuels, such as coal or natural gas, or woody biomass, can provide a better control of emissions, ash chemistry and transformation of the ash chemical composition, structure [15] and deposition on the heating surfaces [16]. Moreover, it is observed that the gasification solutions are also attractive when co-firing straw in the coal-fired boilers, e.g., replacing 15% of the fossil fuel with straw significantly reduces the SO_x, NO_x and GHG CO_2 emissions [17]. However, the analysis of the co-firing of different fuels in different proportions has shown that even relatively small variations in mixture composition can significantly modify the combustion and heat production processes with ash transformation that depends on the thermal, chemical and physical interaction between the components and it is difficult to predict their impact on the process development [18]. Therefore, to achieve a more efficient use of straw as a fuel for cleaner heat energy production with a controllable amount of polluting CO, NO_x and GHG CO_2 emissions, systematic studies are needed to estimate the optimal proportions between the fuel components by co-firing straw with solid fuel or gas, which is the main goal of the current research. The results of previous research allow concluding that the wheat straw co-firing with gas or wood can be used for the control of wheat straw combustion quality and efficiency [19]. The presented research includes comparative experimental investigation and analysis of the main gasification/combustion characteristics by co-firing agriculture residues (straw) with a fossil (propane) or a renewable fuel (wood pellets) in different proportions to assess the optimal conditions for straw co-firing on the reduction of GHG CO_2 and polluting emissions and to support the sustainable development of the regional energy sector by extending the use of the local renewable energy resources (wood and agriculture residues) with a more efficient energy production.

2. Experimental

2.1. Batch-size pilot setup

To study the effects of the wheat straw co-firing with gas (propane) and its co-gasification/co-combustion with wood pellets, a batch-size pilot setup with a heat output up to 2 kW was developed and used (Fig. 1). The experimental setup combines a biomass gasifier (1) and a combustor which consists of three water-cooled sections (2) of inner diameter D = 60 mm and of total length up to 600 mm. To begin each experiment in the batch-size device, the gasifier was filled with biomass pellets (wheat straw, a wheat straw mixture with wood, or wood) of a total mass of 170–240 g. The propane flame was used to provide an additional heat supply into the biomass layer and to initiate the thermal decomposition of the biomass pellets and the combustion of volatiles (CO, H_2). The duration of a single batch-size test was determined by the biomass weight loss rate (dm/dt, g/s) and lasted about 2400 s. The primary air was supplied (3) under the layer of biomass pellets at the constant average rate $q_1 = 20$ L/min to sustain the thermal decomposition of the main biomass components (hemicellulose, cellulose and lignin). The thermal decomposition of the biomass pellets developed under the fuel-rich conditions ($\alpha < 0.5$) and resulted in formation of an axial flow of the combustible volatiles (CO, H_2) at the outlet of the gasifier. The secondary swirling air was supplied (4) to the bottom of the combustor at the constant average rate $q_2 = 40$ L/min to provide the enhanced mixing of the axial flow of the combustible volatiles with the air swirl and to sustain the combustion of the volatiles (CO, H_2) downstream the water-cooled combustor (2). The combustion of the volatiles developed at the average air excess ratio $\alpha \approx 1.5$–3 in the flame reaction zone and at the average value of the inlet air flow swirl number $S \approx 0.6$. The air swirl number ($S \approx 2/3{*}w_{av}/u_{av}$) was found from the measurements of the axial (u) and tangential (w) flow velocity profiles close above ($z/D = 0.7$) the tangential air supply nozzles [19] by assessing the average values of the velocity components (u_{av}, w_{av}) over the flow radius.

By co-firing of wheat straw pellets with a gas (propane) continuous heat input by propane flame flow was used (5) which was varied in the range from 0.7 kW up to 1.1 kW. For the co-gasification/co-combustion of wheat straw with wood pellets, the primary processes of mixture thermal decomposition were initiated using the constant heat input into the biomass layer (1 kW) which was switched off upon ignition of the volatiles ($t \approx 350$ s). To assess the effect of the wheat straw mass load on the development of the main gasification/combustion characteristics, the mass load of wheat straw in the mixture was varied from 0% to 100%. To measure the main gasification/combustion characteristics at the thermo-chemical conversion of wheat straw and wood pellets and of their mixtures, the diagnostic sections with openings (6) for the diagnostic tools (Pitot tube, thermocouples, gas sampling probes) were used. The diagnostic sections were placed between the water-cooled sections of the combustor.

2.2. Experimental setup with continuous supply of biomass pellets

In addition to the experiments with the batch-size pilot setup and in order to assess the effect of the wheat straw co-gasification/co-firing with wood pellets on the development of the combustion dynamics, test experiments were carried out using a test setup [20] with the continuous supply of pellets into the combustor (Fig. 2).

The experimental setup combines an industrial Pelltech burner with the heat output up to 20 kW (1) and a combustor consisting of two water-cooled sections (2). The Pelltech burner provides precise dosing of pellets supply into the combustor by internal feeder from a tank, which is filled with biomass pellets. The average supply rate of pellets into the combustor was $dm/dt \approx 1.13 \pm 0.04$ g/s. The burner provides fast electrical ignition of pellets and automated primary and secondary air supply at all power levels. The openings in the water-cooled walls of the combustor are designed to introduce the diagnostic tools (thermocouples, and gas sampling probes) into the flame reaction zone and to make the local online measurements of the flame temperature and composition.

2.3. Diagnostic tools to measure main characteristics

The experimental study of the effects of wheat straw co-gasification and co-firing on the development of the main combustion characteristics includes complex time-dependent measurements of flow velocity component (u,w), flame temperature (T), composition (volume fractions of O_2, CO_2, mass fractions of CO, H_2, NO_x) and biomass weight loss rate (dm/dt, g/s).

The local measurements of the flame characteristics were made online using a special holder for the diagnostic tools equipped with a precise micro manipulator which allows moving the diagnostics tools in the radial direction across the flame flow.

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