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# Wheat Straw Combustion and Co-firing for Clean Heat Energy Production

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The experimental study and analysis of the effects of wheat straw pellets co-firing with propane flame flow and co-combustion with wood pellets on the processes of thermo-chemical conversion and heat energy production are carried out with the aim to improve the combustion conditions and applicability of wheat straw as an alternative heat energy source. The processes of wheat straw thermal decomposition and combustion of volatiles were studied experimentally using a small-scale pilot device with a heat output up to 2 kW and a test device with a heat output up to 20 kW. To improve combustion conditions, the swirl enhanced mixing of the flame components is used. The analysis of the effect of wheat straw co-firing has shown that additional heat energy supply into the biomass layer provides enhanced biomass thermal decomposition completing the combustion of volatiles and increasing thus the produced heat energy at thermo-chemical conversion of wheat straw pellets. The combustion characteristics for wheat straw pellets can be also improved by providing co-combustion of wheat straw with wood pellets. A very important result is that combustion efficiency, composition of emissions and heat output at wheat straw thermo-chemical conversion can be improved by providing co-firing and co-combustion of wheat straw with wood.

## 1. Introduction

The increasing demand for cleaner energy production with a reduced impact on climate changes results in a growing interest in more intensive utilization of renewable energy sources (wood and agricultural residues) for energy production by partly replacing the fossil fuels with renewable ones (Nussbaumer, 2003). Co-combustion of the fossil fuels (coal) with renewable biomass (Baxter, 2005) or biomass co-firing with gas (Jensen et al, 2008), as well as co-combustion of different biomass types together in one boiler system with the aim to improve combustion characteristics and composition of emission represent an alternative option for reducing greenhouse gas emission during the heat energy production. This can lead to a more intensive use of different local renewable energy resources (wood, straw) with different elemental and chemical composition for energy production (Barmina et al., 2013) or for biohydrogen and biogas production (Drljo et al., 2014) as well as to their advanced applicability as a fuel in combustion devices (Andreasen et al., 1996). Co-combustion and co-firing of biomass with fossil fuels can be advantageous because of higher efficiency of heat energy production with reduced cost and net reduction of greenhouse $CO_2$ emission. In district heating plants the use of wood pellets as a fuel without any operational problems dominates, whereas the use of straw pellets is limited because of lower heating values (LHV, HHV), higher nitrogen and ash content (Ivanova et al., 2015). With account of the limited applicability of straw for clean heat energy production, the main objective of this research is to assess the greater possible use of different types of straw for energy production by co-firing straw pellets with gas (propane flame flow) or providing co-combustion of straw with wood pellets. To improve the mixing of flame components, the swirling secondary air flow is used, which results in the formation of an upstream air flow determining the enhanced mixing of the axial flow of volatiles with the air swirl close to the surface of biomass and in the formation of an axial reaction zone (Abricka et al., 2014). The influence of co-firing and co-combustion of straw on the main combustion characteristics will be evaluated, analysed and compared by measuring the main flame characteristics, combustion efficiency, produced heat energy and composition of the products at different levels of co-firing and by optimizing the composition of the wood and straw mixture by varying the mass fraction of straw pellets in the base fuel (wood pellets).

## 2. Experimental

Thermo-chemical conversion of biomass pellets (wood and wheat straw) was studies experimentally using a pilot device with a heat output up to 2 kW. The constant primary air supply rate in the gasifier (20 l/min) and the secondary swirling air supply at the bottom of the combustor (40 L/min) were used, which provided the fuel-rich conditions in the gasifier ($\alpha \approx 0.5$) and the air excess ($\alpha \approx 2.5$ - 2.7) in the flame reaction zone (Barmina et al., 2013). The pilot device combines a biomass gasifier, which is filled with biomass pellets, and a combustor (D = 60 mm) downstream of which the swirling combustion of volatiles develops. To study the impact of the biomass pellets' co-firing with gas (propane) on thermo-chemical conversion of biomass pellets, a propane flame flow was injected into the upper part of the biomass layer by initiating so the biomass gasification and completing the combustion of volatiles. The heat output from propane flame flow was varied from 0.3 kW up to 0.5 kW. To study the co-combustion of straw with wood pellets, the gasifier was filled with a mixture of straw and wood pellets by varying in this way the proportion between the mass of straw and wood pellets from 0 % up to 100 %. In addition, tests experiments on the effect of the co-combustion of straw with wood pellets on the heat energy production and on the combustion characteristics were performed using a technological device with a heat output up to 20 kW (Figure 1). The device combines a Pelltech burner (1) with continuous supply of biomass pellets, a combustor (2) and a chimney (3). The openings in the sections of the combustor (4) were used to make local measurements of the main combustion characteristics, i.e., the formation of flow velocity, temperature and composition profiles.

The experimental study of the effects of biomass co-firing with gas and of co-combustion of straw with wood pellets was carried out with complex measurements of the flame temperature, composition and heat output. Local measurements of the flame temperature were made using Pt/Pt-Rh thermocouples with data online registration by a Pito logger. Spectral analysis of the products ($CO$, $CH_4$, $C_2H_2$, $C_2H_4$) composition at biomass thermal decomposition was made using a FTIR spectrometer. Local measurements of the flame composition – mass fraction of volatiles ($CO$, $H_2$), volume fraction of the main product ($CO_2$) and combustion efficiency were made using a gas sampling probe and a gas analyzer Testo 350 XL. Calorimetric measurements of the cooling water flow temperature were made by thermo sensors AD 560 with online data registration by a Quick DAQ data plate. The impact of biomass co-firing with gas and the impact of co-combustion of straw pellets with wood pellets on the kinetics of heat energy production and average values of the produced heat energy at different stages of biomass thermo-chemical conversion were estimated.

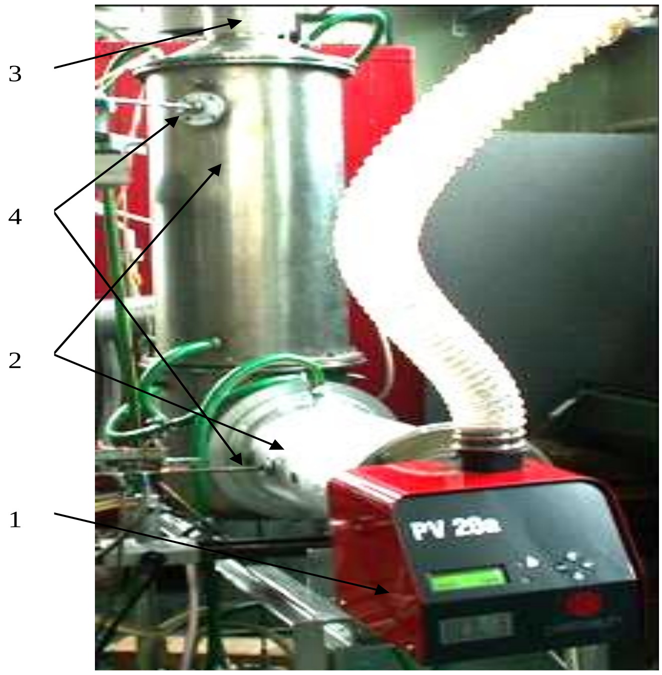


*Figure 1: The technological device for experimental study of thermo-chemical conversion of biomass pellets; 1 - Pelltech burner, 2 - water-cooled sections of the combustor; 3 - chimney; 4 - openings for diagnostic tools.*

## 3. Results and discussion

### 3.1 Wheat straw co-firing with gas

The results of the experimental study shown that the co-firing of wheat straw with gas (propane) first of all results in an enhanced thermal decomposition of wheat straw pellets increasing the biomass weight loss rate at the primary stage of the flame formation (t < 500 s) (Figure 2(a)). This leads to a more intensive release of the combustible gases (CO, $H_2$) entering the combustor (Figure 2(b)). With the constant primary and secondary air supply rates in the pilot device, the enhanced release of the combustible gases results in a decrease of the air excess ratio in the flame reaction zone during the primary stage of the flame formation (Figure 2(c)), improving thus the combustion conditions and determining a faster ignition of the combustibles with a faster increase of the flame temperature up to the peak value (Figure 2(d)).

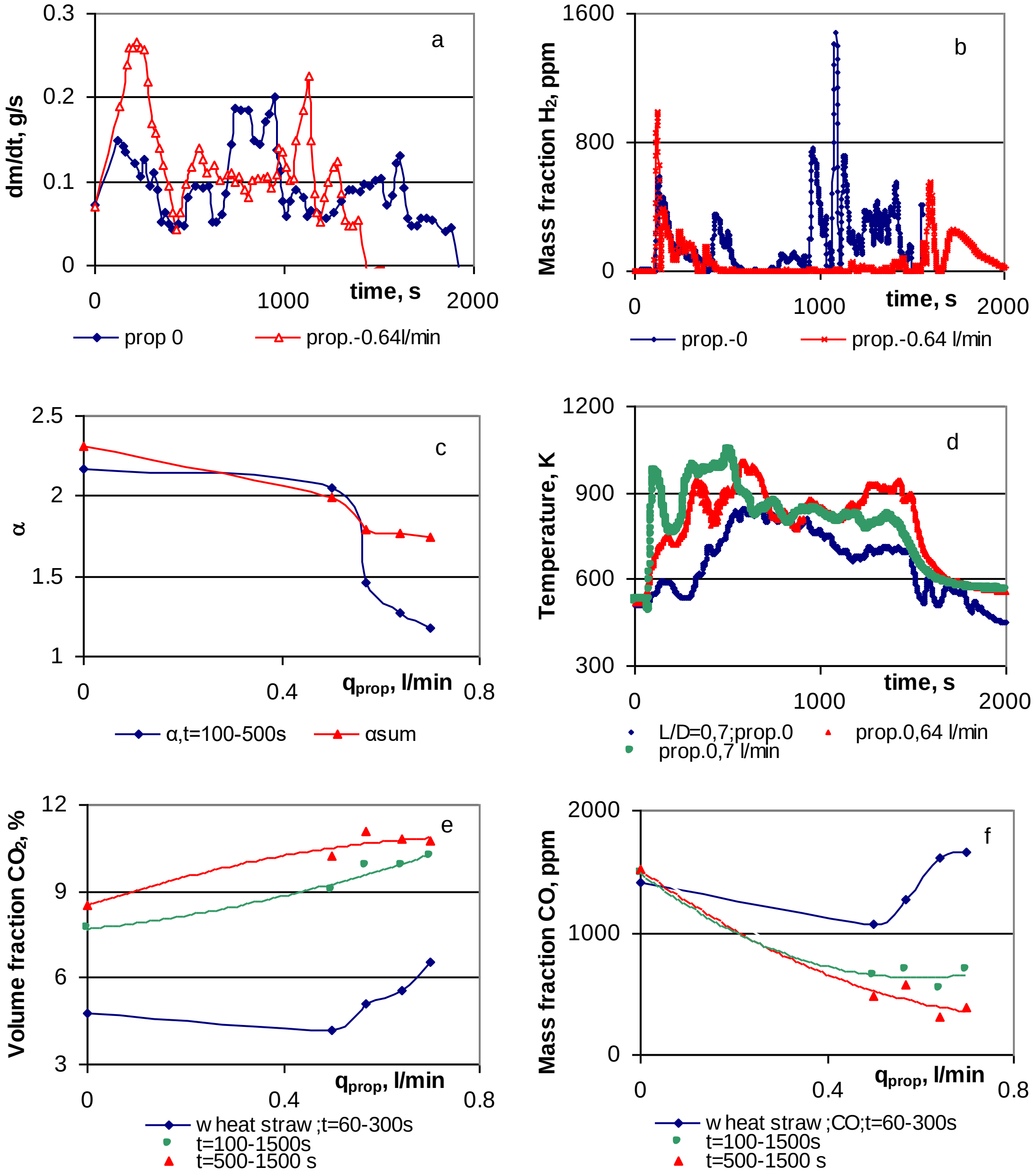


*Figure 2: Effect of wheat straw pellets' co-firing with propane on the kinetics of the biomass weight loss rate (a), mass fraction of released $H_2$ (b), air excess ratio in the reaction zone (c), kinetics of the flame temperature (d) and on the average values of the product composition (e, f).*

Considering the variations of the combustion characteristics at co-firing of wheat straw with propane allows to conclude that the heat flux by a propane flame flow assists as a heat source with direct influence on the heat balance by increasing the temperature of the biomass sample. In accordance with global Arrhenius decomposition and mass actions laws, the increase of the biomass surface temperature results in the enhanced biomass decomposition and increased rate of biomass weight loss (Wang et al., 2009):

$$k = k_0 \exp - \frac{E_a}{RT_b} \tag{1}$$

$$-\frac{dm}{dt} = -k\alpha \tag{2}$$

where *k* is the decomposition rate, $k_0$ is the pre-exponential factor ($s^{-1}$), $E_a$ is the activation energy (kJ/mol); $T_b$ is the biomass temperature (K); $R$ = 8.314 $JK^{-1}mol^{-1}$ is the universal gas constant, *α* is the remaining quota of biomass, which can be estimated as a relation between the biomass weight measured as a function of the time $m_t$ and the initial weight $m_0$ of wheat straw pellets: $\alpha \approx \frac{m_t - m_{ash}}{m_0 - m_{ash}}$ .

The improvement of the combustion conditions (Figures 2(a) - (d)) leads to the increase of the average value of the $CO_2$ volume fraction (Figure 2(e)) and to the correlating decrease of the CO mass fraction in the products (Figure 2(f)). Moreover, the enhanced thermo-chemical conversion of wheat straw pellets provides an increase of the heat output up to the peak values by increasing the produced heat energy that strongly depends on the additional heat supply by the propane flame flow. With the maximum additional heat energy supply from the propane flame flow (0.5 kW), the produced heat energy per total mass of wheat straw pellets can be increased by 43 %. In addition, by about 6 - 7 % decreases the mass fraction of polluting $NO_x$ emissions in the products, which indicates cleaner heat energy production.

A similar improvement of the combustion characteristics during the devolatilization period was observed when mixing the wheat straw pellets with wood which have different values of $E_a$ and $k_0$ for the volatilization period (Wang et al., 2009), different elemental composition and heating values (Table 1).

*Table 1: Main characteristics of wood and wheat straw pellets*

| Biomass pellets | Carbon content,% | Hydrogen content,% | Nitrogen content,% | Moisture content,% | Ash content,% | LHV, kJ/mol | $E_a$, kJ/mol | $k_0$ |
|---|---|---|---|---|---|---|---|---|
| Wood | 50.2 | 5.7 | 0.17 | 7 | 0.33 | 19.87 | 91.12 | $2.41 \times 10^4$ |
| Wheat straw | 49.7 | 5.3 | 0.44 | 9.4 | 3.7 | 17.58 | 109.3 | $2.11 \times 10^6$ |

As for wood pellets with the higher heating value and lower activation energy (Table 1), this results in a faster devolatilization and faster ignition of the combustible gases along with an intensive heat energy release during the volatilization of wood pellets at the primary stage of thermal decomposition. The heat energy release from the wood fuel provides the activation and supports the volatilization of wheat straw with an increased release of the combustible gases (CO, $H_2$) from the wheat straw pellets supplied into the combustor. This leads to improvement of the combustion conditions in the flame reaction zone (Figure 3(a)) with a faster heat energy output at thermo-chemical conversion of the mixture (Figure 3(b)) and to a more complete combustion of CO and $H_2$, determining an increase of the temperature in the flame reaction zone and of the $CO_2$ volume fraction in the products approximately by about 3.5 % (Figures 3(c), (d)). Note that a similar increase of the $CO_2$ volume fraction in the products cannot be related to the increase of the carbon content in the mixture, because the carbon content in wood pellets does not exceed 1 % if compared with the carbon content in wheat straw (Table1). Therefore, the observed improvement of the combustion characteristics by mixing wheat straw with wood confirms the activation of wheat straw volatilization. Moreover, it was observed that due to lower nitrogen content in wood pellets (Table 1), increasing the mass load of wood in the mixture resulted in a decrease of $NO_x$ emission in the products from 260 - 280 ppm at thermo-chemical conversion of straw pellets to 65 ppm for wood pellets, indicating thus a gradual improvement of the composition of the products as the mass load of wood pellets in the mixture increases, determining the cleaner heat energy production.

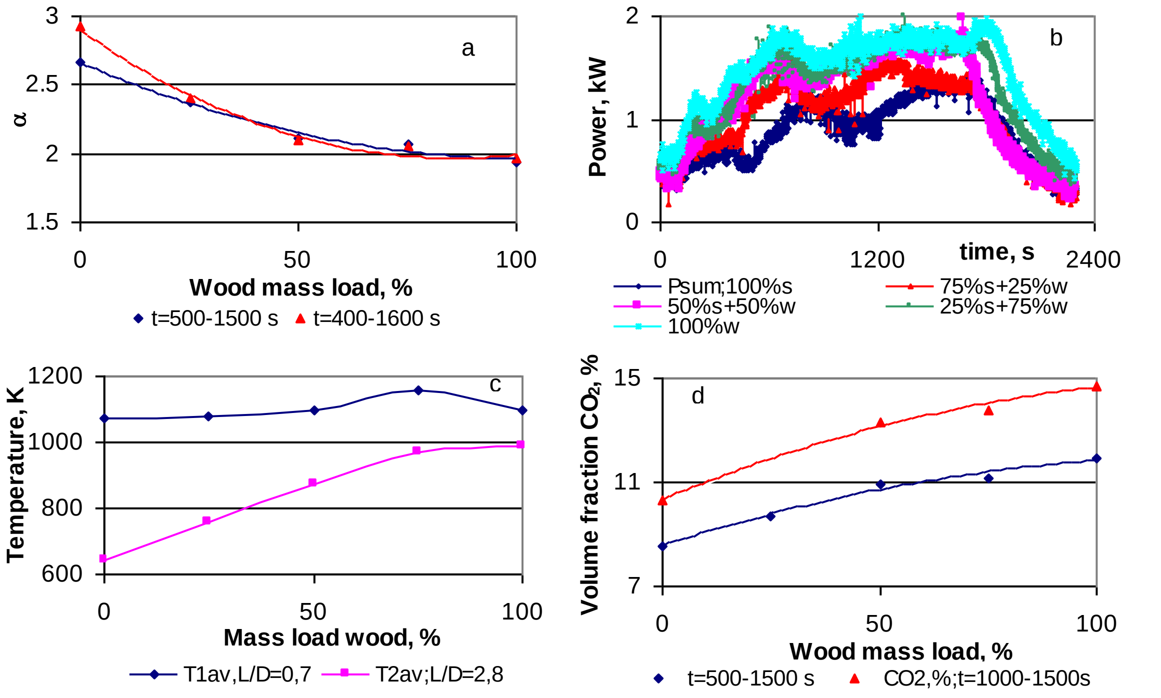


*Figure 3: The wood mass load in the mixture with wheat straw pellets on kinetics of the heat output (a) and combustion characteristics (b-d).*

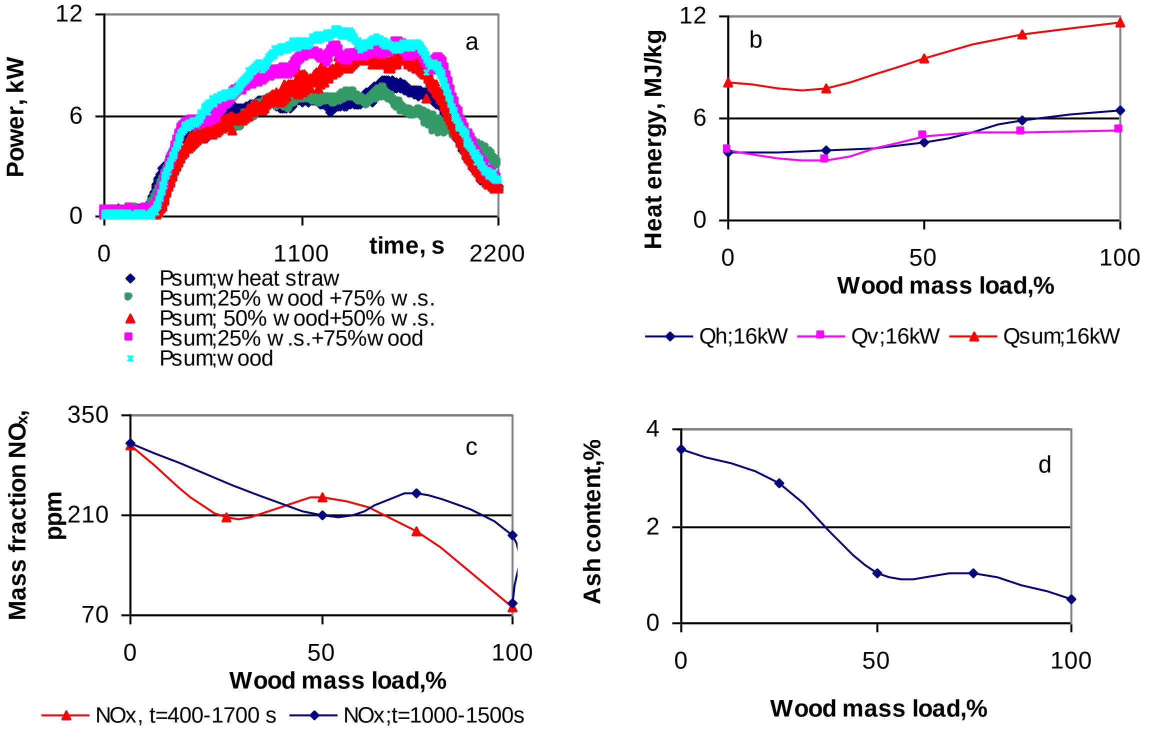


*Figure 4: The wood pellets mass load on kinetics of a heat output (a), produced heat energy per mixture mass (b), mass fraction of $NO_x$ in the products (c) and ash content (d).*

As the data analysis reveals, when wood pellets are added to wheat straw, the modification of the rate of wheat straw thermal decomposition affects the heat release rate, the main characteristics of the flame reaction zone and the composition of the products depending on the mixture composition. This is confirmed by the test experiments with a higher heat power output in the boiler for the continuous supply of the mixture of wood and wheat straw pellets into the burner (Figure 1). By analogy with the effect of the wood mass load on the heat power output at burnout of discrete portions of the mixture in the pilot device (Figure 3(b)), increasing the mass load of wood pellets in the mixture leads to a higher boiler heat output (Figure 4-a) and produced heat energy per mass of the burned mixture (Figure 4(b)). In addition, the volume fraction of $CO_2$ in the products increases by about 4.5 % indicating so that the increase of the wood mass load activates the wheat straw volatilization with the correlating decrease of the air excess ratio from $\alpha \approx 2.3$ to $\alpha \approx 1.6$. Also, an increase of the mass load of wood pellets in the mixture results in a decrease of the mass fraction of $NO_x$ emission in the products (Figure 3(c)) with a correlating decrease of the ash content (Figure 3(d)). As one can see, the most pronounced decrease of the ash content from about 3.6 % to 1 % was observed when increasing the mass load of wood in the mixture up to 50 %, which can be recommended as optimal mass load of wood in the mixture. Actually, the test experiments with the higher heat output have confirmed that the co-combustion of wheat straw with wood pellets allows to control the combustion conditions, heat energy production and the composition of the products.

## 4. Conclusions

A complex experimental study of the effects of wheat straw co-firing with gas (propane) and of co-combustion with wood on the heat output, combustion characteristics and composition of the products was carried out to ascertain suitability of co-firing and co-combustion for the control of wheat straw combustion quality.

The results of the experimental study evidence that the co-firing of wheat straw with gas and the co-combustion with wood result in the enhanced wheat straw volatilization and combustion of volatiles, increasing so the heat output of the device and providing the cleaner heat energy production with the reduced CO and $NO_x$ content in the products.

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