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Integrated analysis of biomass co-firing with gaseous fossil fuel. Environmental criteria analysis

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Abstract. The goal of the research described in the paper is to study co-firing of wood pellets and gaseous fossil fuel, evaluating the influence of co-firing on efficiency, produced energy volumes, and emission production. In order to achieve the set aim and objectives a special pilot device for wood pellets and propane/butane co-firing was constructed in an accredited laboratory. The results of the experimental research allow running a complete analysis of co-firing and evaluating the influence of magnetic field on efficiency, produced heat energy volumes, and emission production. The research has a high practical significance and is aimed to increase the level of wood biomass use for energy production as well as to ensure its effective application.

Key words: combined combustion, emissions, propane/butane, wood pellets.

INTRODUCTION

There is a great interest in biomass and fossil fuel co-firing among energy producers (Van Loo & Koppejan, 2007). Co-firing or combined combustion process is a process, where two or more fuels are combusted simultaneously. Usually a renewable energy source, for example biomass, is combusted together with a fossil fuel, for example, coal or natural gas. An essential advantage of wood and fossil fuel co-firing process is reduction of greenhouse gas emissions during combustion process (Al-Mansour & Zuwala, 2010; Berndes et al., 2010). Global warming could be limited by replacing greenhouse fossil fuels (up to 70%) with CO_2–neutral renewable energy sources. Another important factor is a possibility to provide a stable and controllable heat energy production by combusting wood fuel with different composition, structure, and moisture content. Fossil fuel co-firing with wet wood fuel (moisture content – 60%) provides faster heating and thermal decomposition (Arena et al., 2010).

Wood and coal co-firing process is the most common type of co-firing. However, this co-firing process has a number of technical problems: grinding and fuel feeding problems and increased amount of slag production. The share of coal in the transformation sector of Latvia is not as significant as the share of natural gas (higher than 80%), so this study is proposed to investigate co-firing of wood biomass and gaseous fossil fuel with an aim to analyze formation of emissions, combustion efficiency, and heat production.

From previous researches (Barmina et al., 2009; Zaķe et al., 2009; Suzdalenko et al., 2012) it was concluded that gas and wood fuel co-firing promotes enhanced wood fuel gasification at the primary stage of swirling flame formation, while the propane/butane injection into the flame reaction zone results in enhanced burnout of the volatiles.

MATERIALS AND METHODS

Co-firing of wood pellets with various moisture content and propane/butane mixture was performed in the framework of the research experiments. All experiments were carried out at the Heat and Mass Transfer laboratory of Institute of Physics of the University of Latvia, where a special pilot device had been constructed for this purpose. The layout of the pilot device is shown in Fig. 1.

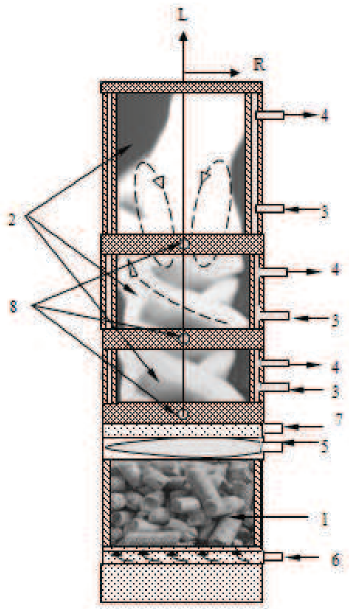


Figure 1. Pilot device: 1 – wood fuel gasifier; 2 – water-cooled combustor; 3 – inlets of cooling water flow; 4 – outlets of cooling water flow; 5 – gas burner; 6 – nozzle of primary air supply; 7 – nozzle of secondary air flow; 8 – diagnostic sections.

The main parts of the device are wood fuel gasifier (1), propane/butane/air burner (5), and cooled channel sections (2), where volatile matters are produced and ignition and combustion occur. In order to ensure gasification and full combustion of volatile matters the air is supplied through two tangential inlets at the bottom of the gasifier (6) and at its upper part (7) above the wood biomass layer. Sections with outlets for diagnostic probes are located between the sections of the water cooling channel. The probes are meant for sampling combustion zone temperature, gas composition, and making axial and tangential velocity measurements. Propane/butane/air flame is formed when radial propane and butane flow and tangential air flow are mixed in the channel.

During the experiments wood pellets were combusted with and without propane/butane mixture. Wood pellets moisture content varied from 8% to 25%. A moderate volume of wood pellets was used for combustion in the experiments: in co-firing experiments it was 500 grams of pellets. Propane/butane mixture was supplied with the air. Calorific value of propane/butane mixture was equal to 108.46 MJ m^{-3}. During the experiment supply propane/butane mixture varied from 0 to 1.55 kJ sec^{-1}.

Primary air supply in the experiments was equal to 47 l min^{-1}. This volume was meant for induction of wood pellet gasification. Secondary air supply was equal to 69 l min^{-1}. The secondary air was supplied in order to provide full combustion of volatiles. Primary air supply provided initiation of wood pellet gasification, while secondary air supply provided formation of swirling flow, which significantly affected the volatile matters mixing with air, as well as shape, size, and stability of the flame and combustion (Palies et al., 2010).

A set of flame parameter measurements was performed during the experiments: local flame temperature ($T = f(t)$) measurements, measurements of the temperature and composition (O_2, CO_2, CO, NO_x), combustion efficiency, and local measurements of radial distribution of axial and tangential flame velocity at different stages of the combustion process. Also, measurements of the produced heat were made to analyze the co-firing process.

Thermocouples, gas analyzer probe, and Pitot's tube were used in order to obtain valid data about the processes occuring in the combustion chamber. The first thermocouple was placed at 157 mm above the propane/butane burner, the second – at 187 mm above the propane/butane burner, and gas analyzer was placed at 386 mm above the burner.

Thermocouples were placed in the center of the channel (R = 0), while the gas analyzer probe was placed according to the objective of each experiment: either in the center of the channel (R = 0) in case of making kinetic measurements of the flame composition, or was being moved radially in the channel when making measurements of the flame composition and radial distribution of velocity in the steady combustion process. Measurements of the flame composition and radial distribution of velocity were made moving the probes with an interval of 30 seconds in the direction from the center of the flame to the channel wall and backwards. Diameter of the channel, where combustion process is developed, was 60 mm.

Length of each of the experiment was 2,400 second or 40 minutes, which provided full combustion of the wood pellets. In all of the experiments propane and butane were combusted first, but wood pellets were added at the 60^{th} second of the experiment.

RESULTS AND DISCUSSION

Wood pellets with different moisture content (W = 8%, 15%, 20%, 25%) were co-fired first with propane/butane and then without any gas supply. Moisture content in the fuel has a negative impact on combustion process: it creates difficulties for fuel ignition, prolongs drying, and reduces fuel heating value and combustion efficiency (Demirbaş, 2001; Vassilev et al., 2010).

Fig. 2 shows the influence of moisture content on wood pellet combustion temperature during self-sustaining combustion of wood pellets.

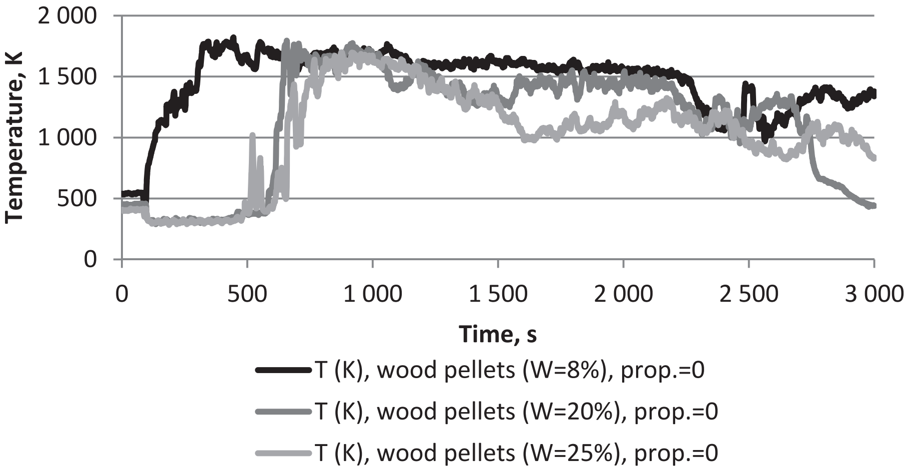


Figure 2. Influence of wood pellets moisture content on the temperature.

The process of wood pellet combustion starts with wood pellet endothermic heating, drying, and thermal decomposition processes. As shown in Fig. 2 wood biomass essentially depends on content of moisture in wood at the beginning of thermal decomposition stage. Faster wood pellets drying and inflammation of volatile compounds was noticed during combustion of wood pellets with moisture content W = 8%, which influenced reaching maximum temperature of combustion zone – 1,821 K. Temperature at the beginning of thermal decomposition process decreases (after the 100th second), when wood pellet moisture content is increased, due to domination of endothermic processes of wood heating and drying, thus limiting development of volatile compounds and inflammation. The influence of moisture content at maximum temperature during combustion process is shown in Table 1.

Table 1. Wood pellet moisture content influence on the average temperature

Moisture content of wood pellets	W = 8%	W = 20%	W = 25%
Average temperature	1,463 K	1,125 K	1,029 K
Maximum temperature	1,821 K	1,794 K	1,700 K
Time	445 s	657 s	875 s

The highest average temperature of 1,463 K (Table 1) was detected combusting wood pellets with the smallest moisture content (W = 8%) and maximum temperature was reached at the 445th second. Average temperature for pellets with 25% moisture content was by 30% smaller comparing with the same of dry pellets, and later start of the volatile ignition was observed.

About 25–30 g of charred pellets were left over in the gasifier at the final stage of combustion during moist wood pellet combustion experiment. These charred pellets continued glowing with slight increase of flame temperature at the end of the experiment. Self-sustainable combustion of wood pellets is characterized with unstable combustion process with pronounced temperature fluctuations (Fig. 2) and average temperature about 1,747 K.

It is possible to improve wet wood pellet combustion process using co-firing with propane/butane mixture.

Propane/butane supply in case of moist wood pellet use provided faster development of volatile compounds (Fig. 3): maximum temperature has been reached already at the 175th second after the beginning of wood pellet gasification process. Faster volatile compound combustion was also observed during co-firing process.

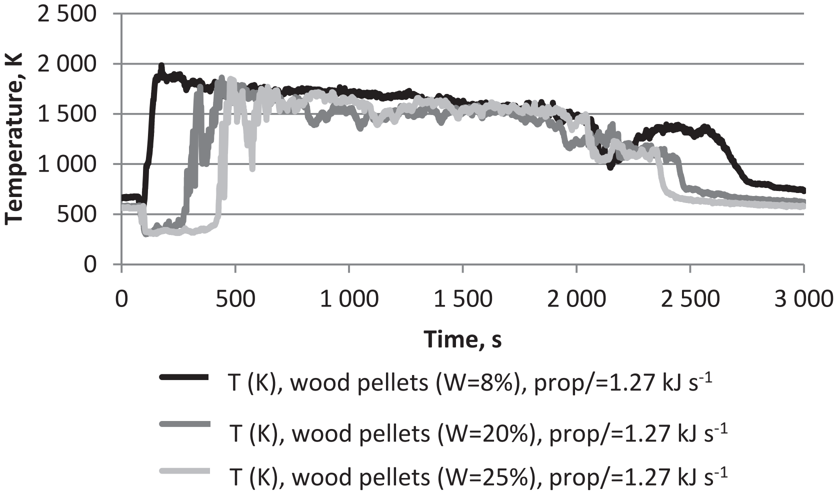


Figure 3. The influence of propane/butane supply on temperature during co-firing process.

After evaluating the results of the experimental measuring the following empirical equation has been obtained. The equation shows influence of wood pellet moisture content and propane/butane supply on average temperature in the combustion zone:

$$T_{avg.} = 1715.23 - 27.15W + 117.83q \qquad (1)$$

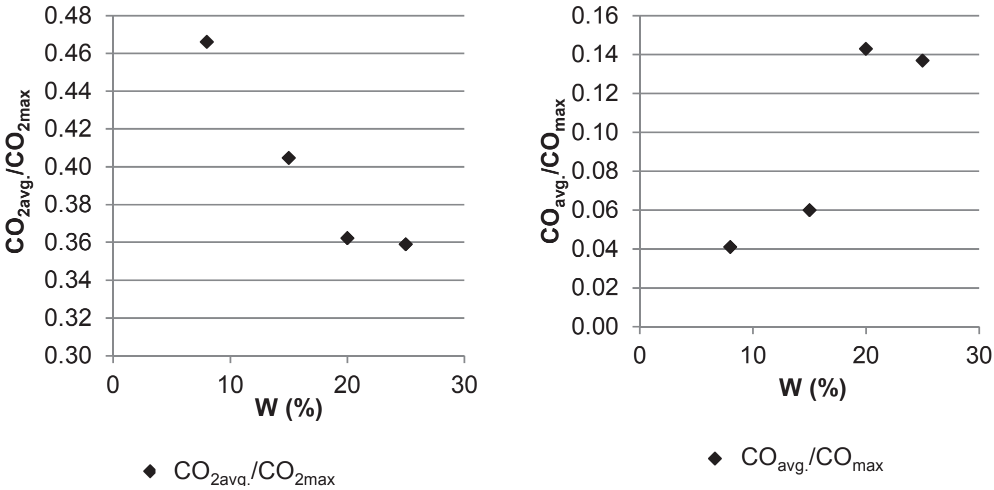
where: W – moisture content of wood pellets, %; q – supply of propane/butane, kJ s^{-1}.

The moisture content of wood pellets influences produced heat energy, which decreases by increasing moisture content of wood pellets. If propane/butane was supplied to the base of combustion zone, the total produced heat increased. The influence of moisture content of wood pellets and propane/butane supply is described with the following equation:

$$Q_{avg.} = 2.42 - 0.08W + 0.35q \qquad (2)$$

where: W – moisture content of wood pellets, %; q – supply of propane/butane, kJ s^{-1}.

The analyses of combustion process products confirm that the main factor, which influences the formation of emissions and their concentration levels during wood fuel combustion, is moisture content in the wood.



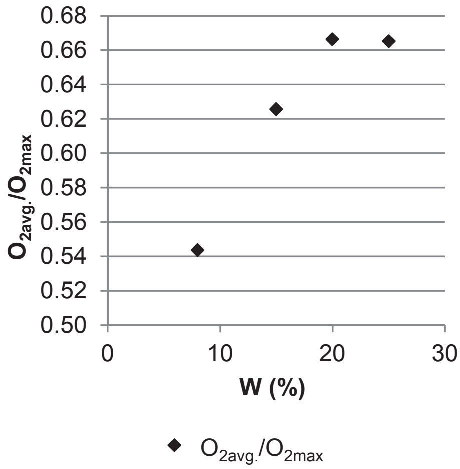
a) b)

Figure 4. The influence of wood pellets moisture content on relative changes in $CO_{2avg.}/CO_{2max}$ (a) and $CO_{avg.}/CO_{max}$ (b).

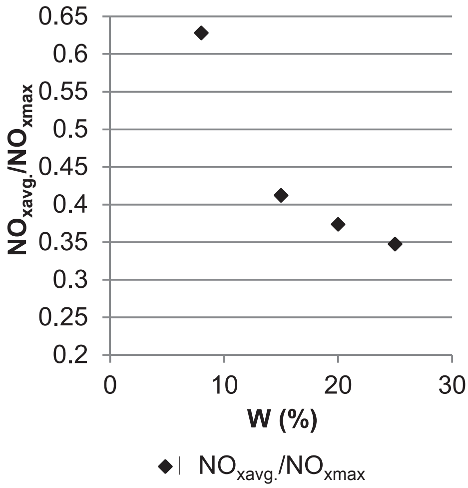
Fig. 4 shows the influence of wood pellet moisture content on formation of CO_2 and CO emissions during wood pellet combustion without gaseous fuel supply. The influence of moisture content on CO_2 and CO emissions has been evaluated during the experiment by relating average CO_2 and CO emissions to the maximum value. In case of CO it was the maximum value, which was reached during the experiment, but maximum quantity of CO_2 was calculated depending on the speed of propane/butane supply (kJ sec^{-1}). If the wood pellet moisture content is increased, CO_2 emissions decrease, but CO emission volume increases. These results can be described with the linear correlation.

Fig. 5a shows fluctuations of $O_{2avg.}/O_{2max}$ volume depending on moisture content of wood pellets. In this case the average value of O_2 during the experiment was attributed to 21 (O_{2max}). When the moisture content in wood pellets increases, $O_{2avg.}/O_{2max}$ increases and average O_2 concentration in products increases, too, which confirms that in case of pellet moisture increase, less air should be supplied for total burn-off of the fuel.

NO_x emissions during combustion process develop in accordance to Zeldovich's mechanism, which development is mainly influenced by the temperature at the combustion zone, air supply in the device, and nitrogen content in the biomass (Williams et al., 2012). Increase of moisture content in wood pellets provides changes of wood pellet elementary composition – nitrogen content decreases and oxygen content increases. These factors significantly influenced formation of NO_x emissions in combustion zone: if moisture content of wood biomass was increased, then decrease of NO_x concentration was observed (Fig. 5b).



a)



b)

Figure 5. The influence of wood pellet moisture content on relative changes in $O_{2avg.}/O_{2max}$ (a) un $NO_{xavg.}/NO_{xmax}$ (b).

It is important to arrange biomass combustion process not only ensuring limited exhaust of hazardous emissions into the atmosphere, but also providing higher heat production and effectiveness of combustion process. Moisture content of wood pellets influences efficiency of combustion process – during the experiment efficiency decreased when moisture content in wood was increasing (Fig. 6).

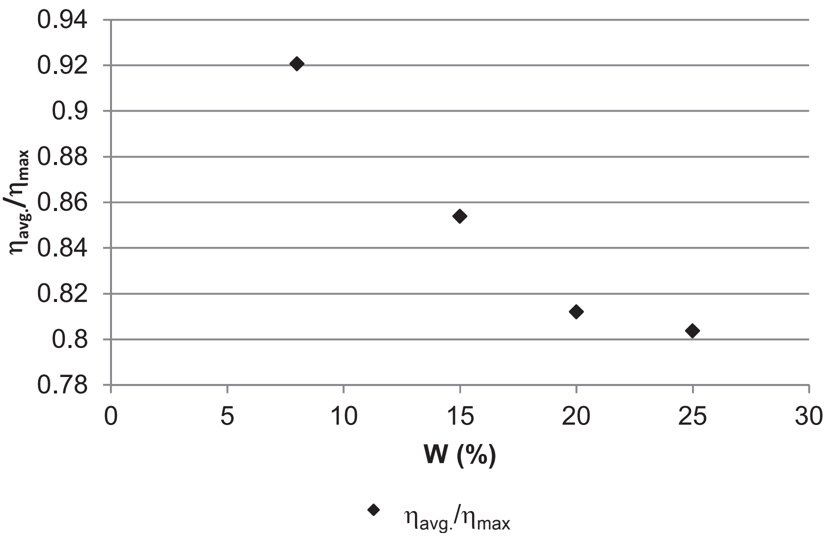


Figure 6. Influence of wood pellet moisture content on relative changes in $\eta_{avg.}/\eta_{max}$.

It is possible to improve combustion process of moist wood pellets by supplying more propane/butane mixture into the wood pellet gasifier. Table 2 compares experimental results for wood pellet self-sustainable combustion and for co-firing process. Propane/butane mixture supply was changed from 0.9 kJ s^{-1} to 1.16 kJ s^{-1}. Wood pellet moisture contents was equal to 20%.

Table 2. The influence of propane/butane supply on combustion products and efficiency

	W = 20%				
	$CO_{2avg.}/CO_{2max}$	$CO_{avg.}/CO_{max}$	$O_{2avg.}/O_{2max}$	$NO_{xvg.}/NO_{xmax}$	$\eta_{avg.}/\eta_{max}$
Prop. = 0 kJ s^{-1}	0.36	0.14	0.67	0.38	0.77
Prop. = 0.9 kJ s^{-1}	0.38	0.10	0.64	0.41	0.80
Prop. = 1.03 kJ s^{-1}	0.39	0.08	0.63	0.42	0.81
Prop. = 1.16 kJ s^{-1}	0.43	0.07	0.60	0.43	0.82

Supply of propane/butane into the combustion camera intensifies wood fuel combustion process, increasing CO_2 concentration, but decreasing CO concentration.

If combusting of wood pellets is performed with supply of propane/butane to the device, the increase of relative $O_{2avg.}/O_{2max}$ volume concentration in products is slightly lower, because supply of propane/butane increases average temperature of combustion zone, providing complete combustion of volatile compounds.

Slight increase of NO_x concentration in products is observed due to supply of propane/butane to the combustion zone. Nevertheless, maximum NO_x concentration in products when propane/butane is supplied to the device does not exceed 70 ppm, which is provided by small nitrogen concentration in wood fuel (0.18%), which, in turn, provides an environmentally cleaner combustion process.

It is possible to increase combustion efficiency for moist wood biomass combustion by supplying propane/butane to the gasifier. During the experiment combustion efficiency was increased with higher supply of propane/butane to the combustion zone.

CONCLUSIONS

The following conclusions were made in the result of co-firing of wood pellets with different moisture content with supply of propane/butane:

- Duration of wood pellet thermal decomposition significantly depends on the moisture content. Moisture in the wood biomass delays formation and ignition of volatiles, as well as their combustion, in the process of which the highest temperature in the combustion zone is reached. Moist wood biomass combustion could be improved by supplying propane/butane, thus intensifying formation and ignition of volatile compounds.
- It was stated as the result of experimental research that supply of propane/butane to the wood pellets layer provides higher amount of produced heat energy. Combustion of wood pellets with 25% moisture content without supply of propane/butane produced 0.87 kWh of heat energy during the experiment. Co-firing this wood with gaseous fuel of 1.27 kJ s^{-1} generated 36% greater amount of heat energy;

- The analysis showed that formation of CO_2 emissions in the process of wood pellet combustion is significantly influenced by the moisture content in the wood pellets: CO_2 emission formation is reduced if moisture content increases, while CO emission volume increases. This proves that using supply of propane/butane to the wood fuel provides intensification of volatile formation, ignition, and combustion, as well as formation of CO_2 emissions, but concentration of CO emission in combustion products is reduced;
- An increase of moisture contents in the wood fuel provides increase of average O_2 concentration in the products, which means that increase of moisture content in the biomass limits combustion of volatiles and air supply has to be reduced in order to provide complete fuel combustion. Combustion of wood pellets with supply of propane/butane to the device provides slightly lower increase of relative $O_{2avg.}/O_{2max}$ volume concentration – by 11% in comparison with wood pellet combustion without supply of propane/butane, since supply of propane/butane increases average temperature in the combustion zone, providing more complete combustion of volatiles;
- An increase of moisture content in wood pellets limited formation of NO_x emissions, which is related to increase of oxygen concentration. At the same time, during wood co-firing with supply of propane/butane a moderate NO_x emission increase which was related to the increase of average temperature;
- Processing the experimental data on combustion efficiency showed that supply of propane/butane and changes of moisture content in the wood pellets influence efficiency of combustion process. It increases when supply of propane/butane in the combustion zone is increased and reduces when wood pellets moisture content is increased.

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