



ENVIRONMENTAL EFFECT OF CO-FIRING AND MAGNETIC FIELD ON WOOD PELLETS COMBUSTION

Vera Suzdalenko, Martins Gedrovics

Institute of Energy System and Environment, Riga Technical University, Riga, Latvia

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Abstract. The aim of the recent research is to provide stable, controllable and effective wood pellets combustion with minimum emissions. Two possibilities were chosen, investigated and analysed: wood pellets co-firing with propane-butane mixture and the use of a permanent magnet. The special pilot device was constructed in the laboratory of Heat and Mass Transfer in Institute of Physics. Two types of experiments were conducted: combustion with propane-butane supply (0.9 kW up to 1.27 kW) of wood pellets with different moisture content ($W = 8\%$, 15% , 20% and 25%); combustion of wood pellets with applied magnetic field by using the permanent magnet, an propane-butane supply also was used. The main conclusion of the research is that co-firing and magnetic field can be used as an instrument to provide more effective burnout of volatiles and cleaner heat production.

Keywords: air pollution, wood pellets, propane-butane mixture, co-firing, magnetic field, clean and effective heat energy production.

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Introduction

Biomass is renewable energy resource that is used for environmentally friendly energy production due to carbon dioxide (CO_2) neutrality and relatively low nitrogen oxide (NO_x) emissions (Balat 2008). The biomass combustion involves a number of complicated physical and chemical processes:

- biomass drying: $T > 373 \text{ K}$;
- pyrolysis and gasification: $T = 500\text{--}1373 \text{ K}$;
- oxidation: $T > 1373 \text{ K}$, $\alpha > 1$ (Shen *et al.* 2009; Balat 2009; Nussbaumer 2003; Obernberger, Thek 2004; Van Loo, Koppejan 2008).

The use of wood fuel (firewood, wood chips, pellets, briquettes and wastes) is gradually increasing in the Baltic States (Table 1). The biggest part of wood fuel is used in households; at the same time the use of wood fuel in transformation sector (heat and electricity production) is not high. There are many reasons for that: wood fuel has different moisture content and heating value, combustion efficiency is not as high if comparing with natural gas (Arena *et al.* 2010; Demirbas 2004; Vassilev *et al.* 2010).

Table 1. The use of wood fuel (PJ) in the Baltic States

Country	Year	Gross consumption	Consumption in energy sector	Final consumption in households
Latvia (1)*		39.7	5.1	28.2
Lithuania (2)*	2000	23.7	0.0	19.3
Estonia (3)*		20.7	6.9	13.9
Latvia		49.4	7.1	32.1
Lithuania	2005	30.5	0.0	20.4
Estonia		22.9	9.9	12.3
Latvia		46.9	6.9	26.1
Lithuania	2011	33.3	0.0	20.5
Estonia		51.5	32.9	18.1
	2000	84.1	12.0	61.4
Baltic States	2005	102.8	17.0	64.8
	2011	131.7	39.8	64.7

* (1) Source: Statistical database of the Republic of Latvia;

* (2) Source: Statistics of Lithuania;

* (3) Source: Statistics of Estonia.

Corresponding author: Vera Suzdalenko
E-mail: vera.suzdalenko@rtu.lv

The aim of recent research is to study wood pellets combustion improvement possibilities by using different regulation possibilities:

- wood pellets co-firing with gaseous fossil fuel;
- applying of magnetic field during wood pellets combustion and co-firing.

Co-firing is a combustion process when two or more fuel types are combusted in the same furnace. There is a growing interest in biomass and fossil fuel co-firing (Van Loo, Koppejan 2008; Williams *et al.* 2012). By replacing fossil fuel with renewable resource (RES) it is possible to reach the main goal of the European Union climate and energy package: to reduce greenhouse gas emissions, to increase RES share in energy balance (European Commission ...). There are over 150 installations worldwide in which are co-fired different types of fuel (Al-Mansour, Zuwala 2010). Prevalent coal is co-fired with different types of biomass thus reducing CO₂, SO₂ and NO_x emissions. The biomass share in this co-firing process ranges from 1% to 20% depending on combustion applications.

Natural gas is the friendliest fossil fuel (no SO₂ emissions, PM), however there are not many examples of natural gas substituting with biomass. There is CHP plant in Denmark, where wood chips are co-fired with natural gas. The moisture content of wood chips is varied from 20% to 60% (max) (DongEnergy ...). From previous researches (Barmina *et al.* 2009; Zake *et al.* 2009) it was concluded that gas and wood fuel co-firing promotes the enhanced wood fuel gasification at the primary stage of the swirling flame formation, while the additional heat injection into

the flame reaction zone results with an enhanced burnout of the volatiles.

Another possibility for more effective volatiles combustion and heat production is to apply a magnetic field. The magnetic field gradient influences the flame behaviour (shapes, sizes), rate of heat production and combustion efficiency (Nagaraju 2005; Swaminathan 2005). It is explained that magnetic field provides the field-induced mass transfer of paramagnetic flame components (O₂ and NO_x) in the field direction but diamagnetic flame species (CO, H₂, CO₂, etc.) indicates a weak repulsion by the magnetic field with direct impact on combustion conditions (Arima *et al.* 1999; Gilard *et al.* 2008). This behaviour of flame species that depends on the volume of magnetic susceptibility of paramagnetic and diamagnetic flame species (χ_v), magnetic induction (B) and magnetic gradient (dB/dL) can be used as a tool to control combustion.

1. Experimental set-up

The experimental research was carried out by using a batch size pilot device with a maximum capacity of 2 kW that was specially constructed in the laboratory of Heat and Mass Transfer Institute of Physics (University of Latvia).

The pilot device is composed of wood fuel gasifier (1), sections of water-cooled combustor (2), inlets (3) and outlets (4) of cooling water flow, gas burner (5), and swirling air nozzles with tangential inlets of primary (6) and secondary (7) air supply and diagnostic sections (9). The total length of the pilot device was 700 mm, the diameter – 60 mm.

The air in the pilot device was supplied in two places: primary air was supplied below wood fuel layer initiating wood fuel gasification; the secondary air was supplied above the gas burner and it provided the gradual mixing of the swirling air flow of volatiles and gradual burnout of volatiles.

- The complex measurements for providing the investigation of co-firing and magnetic field influence on wood pellets combustion were done by using diagnostic sections. The following measurements were provided;
- The measurements of the flame temperature by using Pt/Pt-Rh thermocouples;
- The measurements of the axial and tangential velocity of the flame compounds by using the Pitot's tube;
- The measurements of the flame compositions (O₂, CO, CO₂, NO_x) and combustion efficiency were performed by using the gas analyzer TESTO 350 XL.

In order to obtain a valid data about the processes that take place on the combustion chamber, the measurement instruments were inserted at different height values depending on the series of experiment.

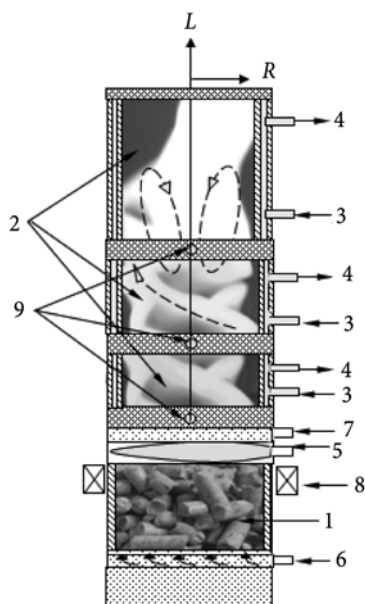


Fig. 1. Pilot scale-up: 1 – wood fuel gasifier; 2 – water-cooled combustor; 3 – inlets of cooling water flow; 4 – outlets of cooling water flow; 5 – gas burner; 6 – nozzle of primary air supply; 7 – nozzle of secondary air flow; 8 – permanent magnets; 9 – diagnostic sections

Table 2. The placement of the measurement instruments above the propane-butane burner

	Co-firing	Magnetic field
First thermocouple	157	55
Second thermocouple	187	380
Gas analyser, Pitot's tube	380	145

Thermocouples were placed in the centre of the channel ($R = 0$), while the gas analyser probe and Pitot's tube were placed according to the aim of the experiment either in the centre of the channel ($R = 0$) in case of making kinetic measurements of the flame composition, or were 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 second in the direction from the centre of the flame to the channel wall and backwards. The data registration was carried out with time interval of 1 second.

As it was mentioned before, two possibilities to provide clean and effective heat energy production were investigated. The characteristics of used fuel and combustion conditions are described below.

2. The co-firing of wood pellets and propane-butane mixture

Wood pellets with different moisture content ($W = 8\%$, 15% , 20% and 25%) was co-fired with propane-butane mixture. The heat combustion of wood pellets was varied from 14.11 MJ/kg for wood with moisture content 25% up to 17.32 MJ/kg for wood with moisture content 8% . The discrete doses (500 g) of wood pellets were combusted during all experiments.

Self-sustaining wood pellets combustion was compared with co-firing process. Non-stationary combustion process was provided during experimental research. Propane-butane supply was varied from 0.9 kW up to 1.27 kW. It was used to initiate gasification of wood pellets and complete the burnout of volatiles.

The primary air was supplied with rate 47 l/min; the secondary air-supplying rate was 69 l/min. The average amount of air that was supplied in the pilot device was 5.4 nm³. The air excess (α) was varied from 2.5 up to 3.07 depending on moisture content of wood pellets.

3. The applying of magnetic field

The permanent magnet (8) with 4 pairs of poles, which height is 50 mm, was attached below the secondary air supply and gas burner in order to produce axial and tangential transfer of paramagnetic oxygen molecules to the pellet layer surface, thus providing more complete mixing

of volatiles and air at the primary stage of combustion process.

Magnetic induction (B) above the magnet poles reached its maximal value of 120 mT at the outer wall of the channel. Axial gradient of the magnetic field gradient (dB/dL) at the wall of the channel, which caused oxygen transfer towards the pellet surface was equal to 1.56 T/m, but it was not higher than 0.8 T/m in the central part of the flame.

Wood pellets were combusted with or without propane-butane supply during the investigation of magnetic field influence. The moisture content of wood pellets was 8% . Discrete doses (320 g) of wood pellets were combusted during the experiments. The propane-butane supply was varied from 1.27 kW up to 1.55 kW. The primary air was supplied with the rate of 47 l/min, but secondary air was supplied with the rate of 71 l/min.

4. Results and discussion

4.1. The effect of wood pellets co-firing with gaseous fossil fuel

The process of wood pellets combustion starts with wood pellets endothermic heating, drying and thermal decomposition processes. The thermal decomposition of wood is related to formation of volatiles (CO , H_2 , C_xH_y) and its exothermal ignition and combustion that promotes rapid increase of temperature till it reaches maximum value. The effect of moisture content in wood pellets and propane-butane supply on ignition of fuel is shown in Table 3.

Table 3. The influence of moisture content in wood pellets and propane-butane supply on fuel ignition

Moisture content of wood pellets, %	8	8	25	25
Propane-butane supply, kW	0	1,27	0	1,27
Maximum temperature, K	1821	1984	1699	1923
Time*, s	445	175	875	479

* when maximum temperature was reached.

Investigations with wood pellets of different moisture and different supply of propane-butane in the device (Fig. 2) confirm that in the term of the beginning of thermal decomposition stage essentially depends on content of moisture and supply of propane-butane to wood pellets. While combustion of wood pellets with 8% moisture content with propane-butane supply and without propane-butane supply to wood pellets, inflammation of volatile compounds has been noticed, comparing wood pellets combustion with 25% moist, faster reaching maximal temperature of combustion zone (Table 3). While increasing

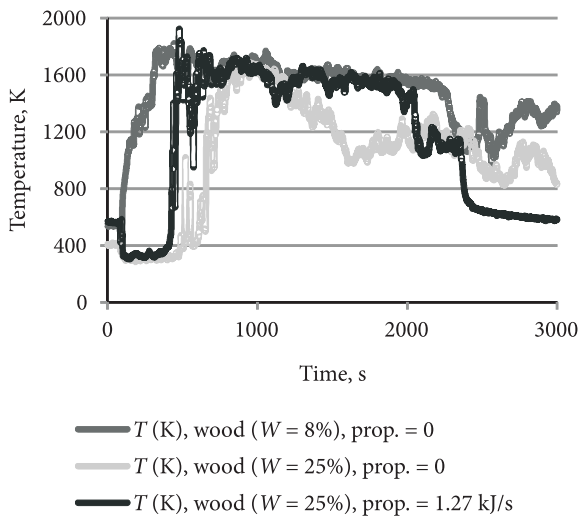


Fig. 2. Temperature changes (K) for wood pellets of different moisture content combustion with and without propane-butane supply

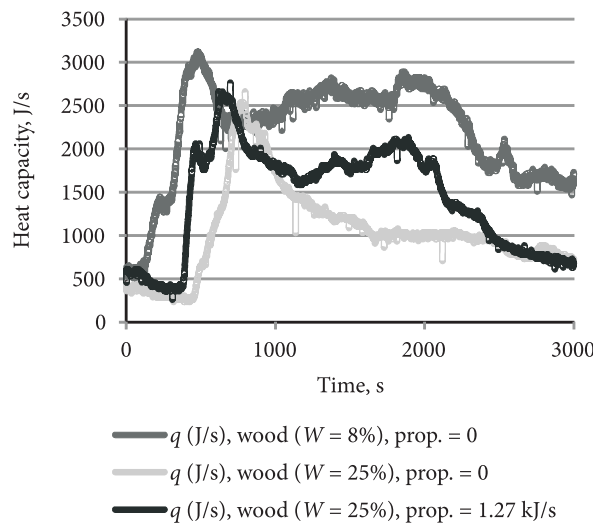


Fig. 3. The effect of wood pellets moisture content and propane-butane supply on heat production rate

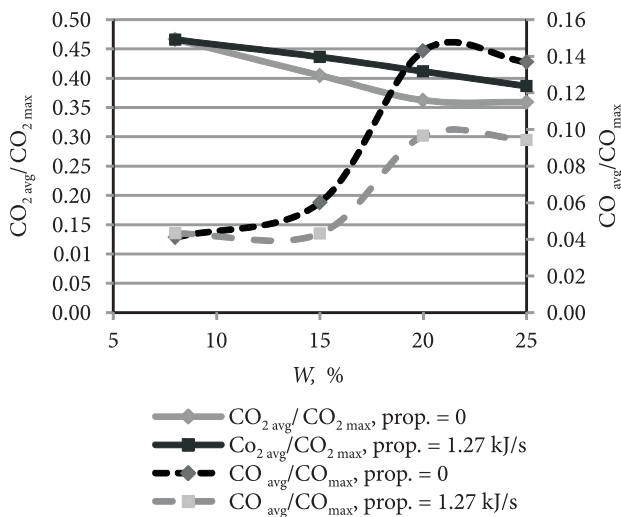


Fig. 4. $CO_{2\text{avg}}/CO_{2\text{max}}$ and $CO_{\text{avg}}/CO_{\text{max}}$ dependence on moisture content in wood pellets for different combustion condition

moisture content in wood pellets, temperature in the beginning of thermal decomposition process decreases (after 100th second), because endometrial processes of wood heating and drying dominate, thus limiting development of volatile compounds and inflammation.

After evaluating results of experimental measuring of the influence of wood pellets moisture content and propane-butane supply on average temperature of combustion zone, the following empirical equation has been obtained:

$$T = 1715.23 - 27.15W + 117.83q, \quad (1)$$

where: W – moisture content in wood pellets (%); q – supply of propane-butane (kW).

Using regressions analysis derives this equation and all equations below.

As a result of experimental investigations it is stated that supply of propane-butane to wood pellets layer provides not only higher temperatures, but also increases heat production rate (Q), which can be seen on Figure 3.

Greater heat production rate was observed when combustion of wood pellets with lower moisture content ($W = 8\%$) took place and vice versa – the lowest values of heat production rate were notified when were used wood pellets with the highest moisture content ($W = 25\%$) (Fig. 3). Similarly to temperature changes (Fig. 2), heat production rate is depended on moisture content in wood pellets and propane-butane supply at the beginning.

The evaluation of produced heat (Q) in the device depending on moisture content of wood pellets and supply of propane-butane to the device revealed mutual interconnectedness of the parameters in the empiric equation:

$$Q = 2.42 - 0.08W + 0.35q, \quad (2)$$

where: W – moisture content in wood pellets (%); q – supply of propane-butane (kW).

The influence of propane-butane and moisture content of wood pellets on CO_2 and CO emissions has been evaluated during the experiment by attributing average CO_2 and CO emissions to the maximal value. In case of CO it was maximal value, which was reached during the experiment, but maximal quantity of CO_2 was calculated depending on supply of propane-butane (kW).

Wood pellets moisture content influences development of CO_2 emission during combustion, as well as its concentration in products. If the wood pellets moisture content is increased, CO_2 emissions decrease, but quantity of CO emissions increases. Supply of propane-butane to combustion camera intensifies wood pellets combustion process, increasing CO_2 concentration, but decreasing CO concentration in products (Fig. 4).

The effect of moisture content on CO emissions is described in Bignal K. L. research (Bignal *et al.* 2008). There was found that moisture content in wood biomass and boiler operation conditions affect concentration of

pollutant. The increasing of moisture content in biomass fuel affects the increase of CO emissions. It was found the relationship of CO and PAH emissions: high CO concentrations correlated with an increase of PAH.

The results of experimental investigations confirm that current correlations can be described with empirical equations:

$$\frac{CO_{2avg}}{CO_{2max}} = 0.49 - 0.01W + 0.03q, \quad (3)$$

$$\frac{CO_{avg}}{CO_{max}} = -0.001 - 0.006W - 0.0391q, \quad (4)$$

where: W – moisture content in wood pellets (%); q – supply of propane-butane (kW).

For total combustion of wood pellets and gas mixture, sufficient air supply should be provided ($\alpha \geq 1$). With wood pellet moisture content increase, theoretically sufficient air volume for fuel combustion decreases, whereas during the experiments the same air volume has been supplied not depending on the wood pellets moisture content. Due to that reason coefficient of air excess increases from 2.5 to 3.07 with wood pellets moisture content increase from 8% to 25% and the process of wood pellets combustion develops at expressed odd air supply in the device.

When the moisture content in wood pellets increases, O_{2avg}/O_{2max} ($O_{2max} = 21\%$) increases and average O_2 concentration in products increases, which confirms that in case of moisture increase in pellets, less air should be supplied for total burn-off of the fuel. At the same time combusting wood pellets with supply of propane-butane to the device, 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 (Fig. 2), providing complete combustion of volatile compounds (Fig. 4).

Analysis of experimental results confirms that influence of wood pellets moisture content and supply of propane-butane on changes in relative O_{2avg}/O_{2max} volume concentration can be approximately characterized using empirical equation:

$$\frac{O_{2avg}}{O_{2max}} = 0.52 + 0.01W - 0.06q, \quad (5)$$

where: W – moisture content in wood pellets (%); q – supply of propane-butane (kW).

NO_x emission during combustion process is essentially influenced by the temperature at combustion zone, air supply in the device, as well as nitrogen content in the biomass (Stubenberger *et al.* 2008; Williams *et al.* 2012). The experimental results (Fig. 2) and regression Equation (1) confirmed that average temperature decreased by increasing moisture content in wood pellets, but increased if propane-butane was supplied. At the same time the

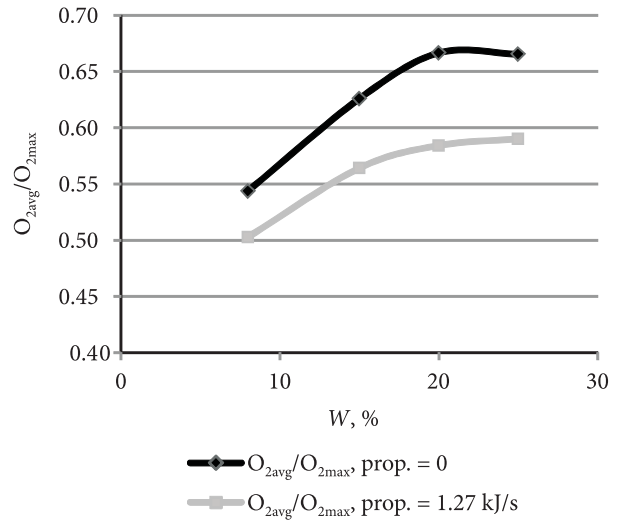


Fig. 5. The O_{2avg}/O_{2max} changes in products depending on moisture content in wood pellets and supply of propane-butane in combustion zone

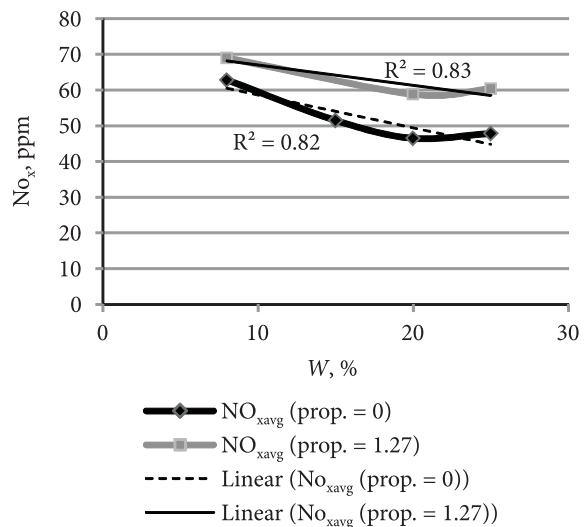


Fig. 6. The NO_{xavg}/NO_{xmax} changes in products depending on moisture content in wood pellets and supply of propane-butane in combustion zone

average concentration of oxygen increased by increasing moisture content in wood pellets (Fig. 5). It should be noticed that increasing moisture content also changes elementary composition of wood pellets. All these factors impact the formation of NO_x emissions in combustion zone. The impact of moisture content in wood fuel and propane-butane supply on NO_x formation is illustrated in Figure 6.

The amount of NO_x emissions decreased for self-sustaining wood fuel combustion and for combustion with propane-butane supply by increasing moisture content in wood fuel (Fig. 6). The same results was founded in (Bhattacharya *et al.* 2002) during wood fuel combustion.

Results of the experimental measuring show that influence of wood pellets moisture content and supply of propane-butane on relative changes of NO_{xavg}/NO_{xmax} can

be described using Equation (6). $NO_{x,avg}$ is an average value during the experiment, but $NO_{x,max}$ – maximal value during the experiment.

$$\frac{NO_{x,avg}}{NO_{x,max}} = 0.65 - 0.01W + 0.12q, \quad (6)$$

where: W – moisture content in wood pellets (%); q – supply of propane-butane (kW).

While combusting the biomass it is important to arrange combustion process not only with limited exhaust of hazardous emission into atmosphere, but also higher heat production and efficiency of combustion process should be provided. While proceeding experimental data on efficiency of combustion, it is stated that supply of propane-butane and changes in wood pellets moisture content influence efficiency of the combustion process (η), which increases with higher supply of propane-butane to the combustion zone and decreases with higher moisture content in wood pellets (Fig. 7).

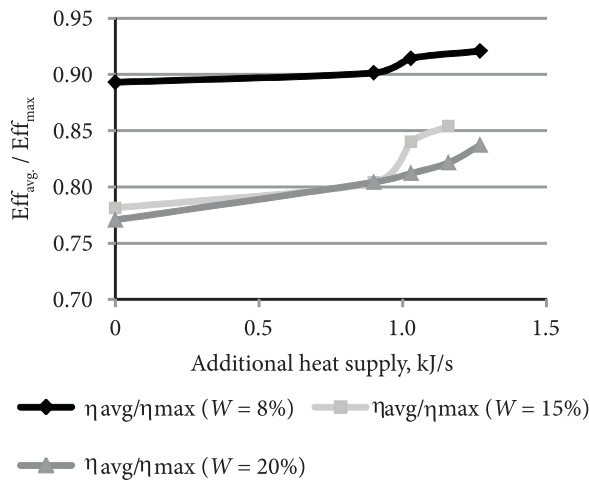


Fig. 7. η_{avg}/η_{max} at different velocity of propane-butane supply and at different moisture content in wood pellets

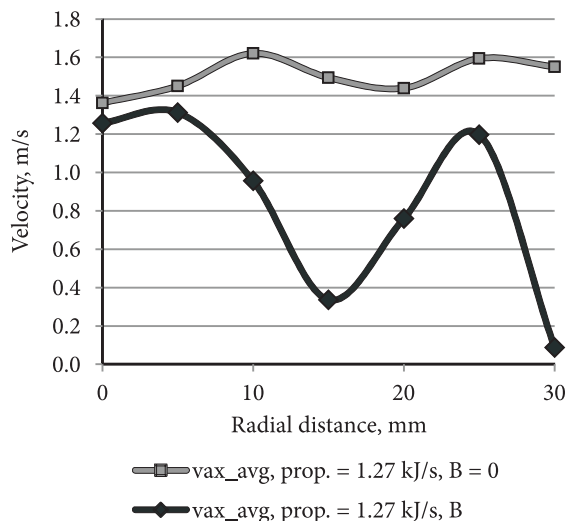


Fig. 8. Effect of magnetic field on formation of flame axial (a) and tangential (b) velocity distribution in the process of co-firing

The influence of moisture content in wood pellets and propane-butane supply on efficiency can be described with equation:

$$\frac{\eta_{avg}}{\eta_{max}} = 0.93 - 0.008W + 0.04q, \quad (7)$$

where: W – moisture content in wood pellets (%); q – supply of propane-butane (kW).

The effect of moisture content on efficiency was investigated by Bhattacharya S. C. (Bhattacharya *et al.* 2002). There was concluded that the efficiency decreased with increase of moisture content in biomass fuel. At the same time it was concluded (Yuntenwi *et al.* 2008) that extremely dry biomass fuel inhibited combustion efficiency.

4.2. The influence of magnetic field on wood pellets combustion and co-firing with propane-butane

The results of previous investigations (Zake *et al.* 2010; Suzdalenko *et al.* 2011) confirm that effects of interaction between flame and inhomogeneous magnetic field can be used in order to achieve additional impact on the combustion process. The effect is based on transfer of paramagnetic oxygen towards the gradient caused by the magnetic field gradient. It provides fluctuations of local oxygen concentrations in the air and in volatile mixtures with the following changes in combustion of volatiles.

Influence of the magnetic field gradient (dB/dL) on the flow dynamics is mainly defined by the magnetic force (F_{mag}), which depends on the magnetic susceptibility of the oxygen (χ_v) and magnetic permeability (μ_0). Force generated by the magnetic field gradient defines fluctuations of the swirling flow dynamics, followed by fluctuations in volatile matter combustion process.

As the result of the interaction of the magnetic field gradient generated force and the flame fluctuations of swirling flow dynamics are observed with an evident reduction of axial and tangential velocity of the flame (Fig. 8). Considering this a forecast can be made that in the process of magnetic field and flame interaction length of volatile matter containment in the combustion zone will increase, providing more complete combustion of volatile matters.

Supply of propane-butane in the combustion zone and impact of the magnetic field on formation of flame axial and tangential velocity distribution are related to the fluctuations of the swirling flow number (S), which defines the formation of recirculation zone and intensity of swirling flow (Fig. 9). The results of the experimental measurements prove that increase of propane-butane supply to the combustion chamber gradually reduces the swirling flow of the flame. Accordingly, axial increase of velocity caused by the supply of propane-butane limits formation of the recirculation flow.

Influence of the magnetic field on combustion process emissions, temperature, and produced heat energy was investigated and evaluated also in the process of wood pellet combustion with supply of propane-butane at the bottom of the combustion zone, while changing supply of propane-butane from 1.27 kW till 1.55 kW. These experimental data were compared with the process of wood pellet and gaseous mixture co-firing process, where magnetic field was not applied ($B = 0$). Average parameter values were calculated for the data analysis. These average values obtained from the experiments with magnetic field (B) were divided by the average values obtained from the experiments without magnetic field ($B = 0$) (in the Figures it is marked as $B/(B = 0)$).

Figure 10 shows how $O_2(B)/O_2(B = 0)$ ratio depends on supply of propane-butane during the experiments.

When wood pellets are combusted without supply of propane-butane (prop.-but. = 0 kW) in the bottom of the combustion zone, $O_2(B)/O_2(B = 0)$ ratio is greater than 1. It means that average amount of oxygen at the bottom of the combustion zone increases if paramagnetic oxygen transfer is intensified along the magnetic field. At the same time if wood pellets are combusted with supply of propane-butane in the bottom of the combustion zone, $O_2(B)/O_2(B = 0)$ ratio reduces, which indicates reduction of the average amount of oxygen. Basically this can be explained with the fact that in case if wood pellets are combusted with supply of propane-butane additional heating of paramagnetic oxygen is provided, ensuring transfer of hotter heat flow to the pellet surface. This improves gasification of the wood pellets and provides more intensive formation of volatiles.

In contrast to the changes of oxygen concentration, a higher $CO_2(B)/CO_2(B = 0)$ ratio for wood pellet combustion process is observed when supply of propane-butane to the bottom of the combustion zone is increased (Fig. 11). More complete volatile combustion can be achieved by combining supply of propane-butane at the bottom of combustion zone with magnetic force produced paramagnetic oxygen transfer.

The effect of propane-butane supply on $CO_2(B)/CO_2(B = 0)$ ratio can be described with linear equation:

$$\frac{CO_2(B)}{CO_2(B = 0)} = 0.25q + 0.77, \quad (8)$$

where: q – supply of propane-butane (kW).

After influence of magnetic field and supply of propane-butane on concentration of CO emissions is stated that supply of propane-butane ensures reduction of $CO(B)/CO(B = 0)$ ratio (Fig. 11). The highest $CO(B)/CO(B = 0)$ ratio is observed if wood pellets are combusted without supply of propane-butane at the bottom of combustion zone, when paramagnetic oxygen transfer stimulates formation of air excess and temperature reduction. When supply of propane-butane is provided, this ratio decreases

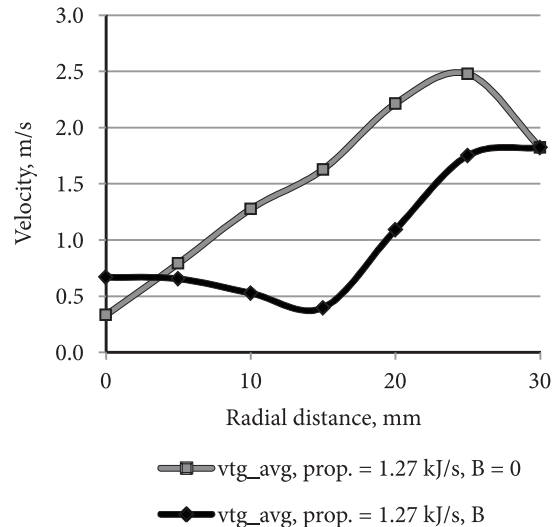


Fig. 9. Influence of propane-butane supply and magnetic field on swirling flow number

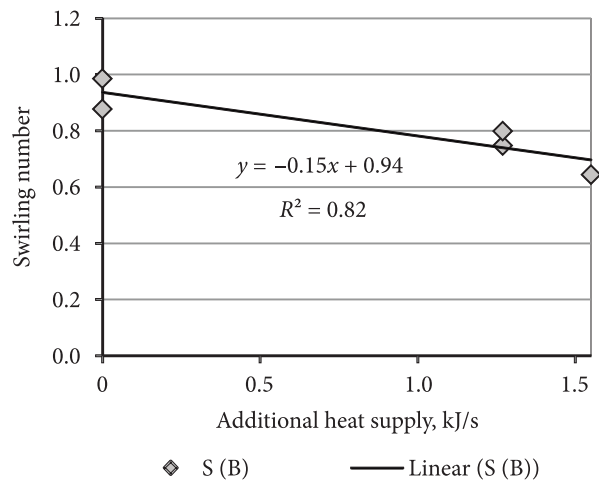


Fig. 10. Influence of propane-butane supply on $O_2(B)/O_2(B = 0)$ ratio

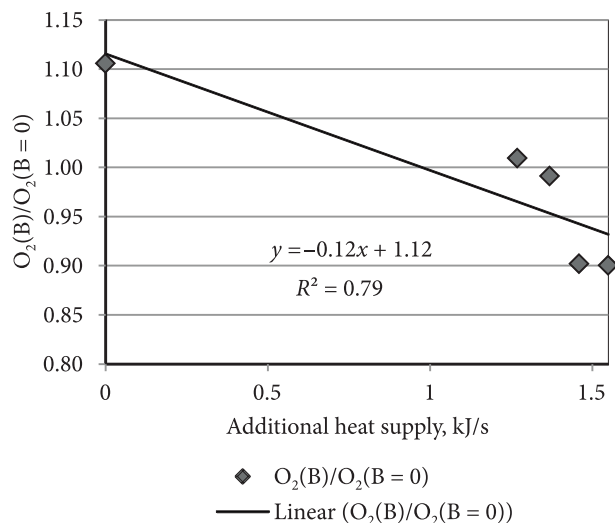


Fig. 11. Influence of propane-butane supply on $CO_2(B)/CO_2(B = 0)$ and $CO(B)/CO(B = 0)$ ratio

and provides more complete combustion process as well as decreases release of harmful CO emissions into the environment. Influence of propane-butane supply on $CO(B)/CO(B=0)$ is described with the following linear equation:

$$\frac{CO(B)}{CO(B=0)} = -0.28q + 1.28, \quad (29)$$

where: q – supply of propane-butane (kW).

Paramagnetic oxygen transfer caused by the magnetic field and supply of propane-butane at the bottom of combustion zone influence also formation of NO_x . The results of the experimental research on influence of this factor on fluctuation of $NO_x(B)/NO_x(B=0)$ are summarized in Figure 12.

As it is seen from Figure 12 in the process of wood pellet combustion $NO_x(B)/NO_x(B=0)$ ratio increases,

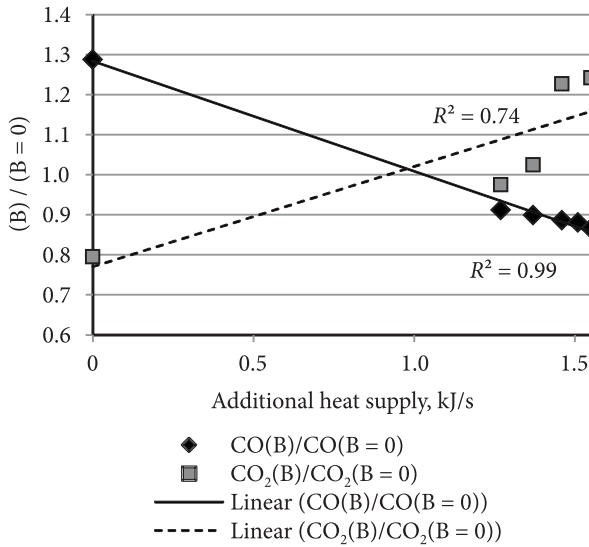


Fig. 12. Influence of propane-butane supply on $T(B)/T(B=0)$ and $NO_x(B)/NO_x(B=0)$ ratio

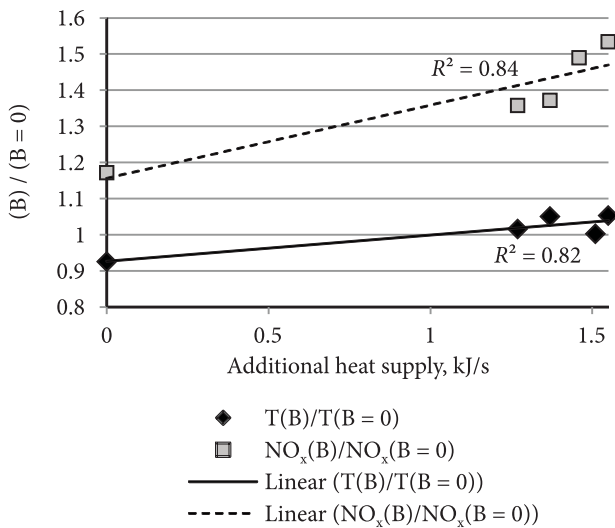


Fig. 13. Influence of propane-butane supply on $Q(B)/Q(B=0)$ and $\eta(B)/\eta(B=0)$ ratio

thus increasing supply of propane-butane at the bottom of combustion zone. The figure shows that in all cases $NO_x(B)/NO_x(B=0)$ ratio is greater than 1, which means that application of magnetic field intensifies formation of NO_x with higher NO_x emission release into the atmosphere. This should be evaluated as a negative result of the interaction between the field and the flame.

The effect of propane-butane supply on $NO_x(B)/NO_x(B=0)$ is described with linear equation:

$$\frac{NO_x(B)}{NO_x(B=0)} = 0.20q + 1.16, \quad (10)$$

where: q – supply of propane-butane (kW).

One of the most significant factors that influence formation of NO_x emissions is fluctuations of combustion zone temperature. Figure 12 shows that fluctuations of $T(B)/T(B=0)$ ratio depends on supply of propane-butane at the bottom of combustion zone. Temperature increases when supply of propane-butane is provided. Considering that oxygen transfer provided by the magnetic field simultaneously increases concentration of oxygen, combustion of the volatiles gets intensified. Influence of propane-butane supply on the temperature is described by the following linear equation:

$$\frac{T(B)}{T(B=0)} = 0.07q + 0.93, \quad (11)$$

where: q – supply of propane-butane (kW).

The results of magnetic field and propane-butane supply effect on efficiency and heat production are shown in Figure 13.

In the result of interaction between the flame and magnetic field average efficiency of combustion process is higher than its efficiency in those cases, when magnetic field has not been applied and paramagnetic oxygen transfer towards gradient of the field has not been intensified.

The effect of propane-butane supply on $\eta(B)/\eta(B=0)$ is described with following linear equation:

$$\frac{\eta(B)}{\eta(B=0)} = 0.07q + 0.90, \quad (12)$$

where: q – supply of propane-butane (kW).

Figure 13 shows influence of propane-butane supply on $Q(B)/Q(B=0)$ ratio, comparing produced heat energy (kWh) in the experiments with and without application of magnetic field. Influence of propane-butane supply on the ratio $Q(B)/Q(B=0)$ is described with the following linear equation:

$$\frac{Q(B)}{Q(B=0)} = 0.08q + 0.98, \quad (13)$$

where: q – supply of propane-butane (kW).

In the result of interaction between the flame and magnetic field increase of produced heat energy is observed. It increases when supply of propane-butane to the device is increasing.

Conclusions

Two possibilities were investigated in order to obtain complete wood pellets combustion for clean and effective heat energy production: wood pellets co-firing with propane-butane supply and magnetic field effect on combustion process.

The following conclusions were made in the result of co-firing of wood pellets with different moisture content ($W = 8\%$, 15% , 20% and 25%) with supply of propane-butane:

Duration of thermal decomposition of wood pellets substantially depends on moisture content and supply of propane-butane. Moisture in the wood biomass delays formation and ignition of volatiles, as well as its combustion, in the process of which the highest temperature in the combustion zone is reached. Moist wood pellets ($W = 25\%$) combustion is unstable, temperature fluctuations are observed, the formation and ignition of volatiles is observed after 875th second only, the average temperature is for 30% lower comparing with dry wood pellets ($W = 8\%$) combustion. The propane-butane supply provides more stable moist wood combustion, faster formation and ignition of volatiles (479th second) and increase of the average temperature.

The analysis showed that formation of CO_2 emissions in the process of wood pellets 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. But during co-firing process formation, ignition, and combustion of volatiles is intensified, as well as formation of CO_2 emissions in combustion products is increased, but concentration of CO emission is reduced.

The increase of temperature when wood pellets were combusted with propane-butane provided the increasing of NO_x emissions comparing with wood pellets self-sustaining combustion.

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;

The following conclusions are drawn by analysing the influence of magnetic field during wood pellets self-sustaining combustion and for co-firing with gaseous fossil fuel:

Applying of magnetic field provides the changes of velocity profiles – decreasing of axial and tangential velocity. It means that a longer residence time of volatiles in combustion zone is obtained.

Complete combustion of volatiles was provided with increased efficiency and heat energy production.

Applying of magnetic field and propane-butane supply during wood pellets combustion provides

intensive combustion processes with an increase of temperature, in the result amount of NO_x emissions also is increased.

The main conclusion of the recent research is that co-firing and magnetic field can be used to provide more effective heat energy production with more complete combustion of volatiles.

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Vera SUZDALENKO. Dr Sc.ing., Riga Technical University, Institute of Energy System and Environment. She is a co-author of 12 scientific papers. The main research area is the investigation of renewable and fossil fuel co-firing and magnetic field effect on swirling combustion.

Martins GEDROVICS. Dr Sc.ing., Professor, Riga Technical University, Institute of Energy System and Environment. He is an author of about 80 publications. The main research area is combustion of biofuels.