

Experimental pilot device for thermal analysis of biomass co-firing

V. Suzdalenko*, M. Gedrovics and V. Vitolins

Institute of Energy Systems and Environment, Riga Technical University, Kronvalda boulevard 1, LV-1010 Riga, Latvia; *Correspondence: Vera.Suzdalenko@rtu.lv

Abstract. The share of biomass in the transformation sector of Latvia accounts for only 15%, at the same time natural gas share in transformation sector is about 80%. Nonetheless, an ongoing natural gas price growth stimulates its full replacement with biomass. The goal of the research was to construct an experimental pilot device, where could be possible to combust biomass with gaseous fossil fuel. The pilot device was equipped with the following measurement instruments: thermocouples for local temperature measurements and gas analyzer for measurements of flue gas composition, temperature, and combustion efficiency.

Key words: wood product, combustion, gaseous fuel, pilot device.

INTRODUCTION

European Commission and Council Directive 2009/28/EC was approved in year 2009 in order to promote use of renewable energy resources (RES). One of the main aims of the Directive is to achieve 20% of the total European member state energy consumption to be produced from renewable energy sources in 2020. In 2010 this figure accounted for only 10% (EUROSTAT, 2012). Comparing the existing situation with the data from year 1990 it can be concluded that the share of RES in total energy consumption has increased by 143.4%, or in average – by 4.5% per year (EEA, 2012). Despite such a rapid growth additional measures are necessary to be taken in order to provide implementation of the Directive.

Increasing the use of biomass can provide growth of renewable energy share, because it is a cheap and easily available fuel, which requires minimum processing and has a relatively simple combustion technology (Williams et al., 2012).

In comparison to fossil fuels biomass has a number of benefits that could stimulate its use. For example, reduction of greenhouse gas (GHG) emissions and reduction of energy dependence (Beloborodko et al., 2013).

Wood is the most common renewable energy resource in Latvia. Households consume more than 50% of wood fuel (Fig. 1). Wood fuel consumption for heat and electricity production (transformation sector) equals to 15% in average ('LR Central statistical bureau,' 2013).

In the transformation sector natural gas is mainly used for heat and electricity production. The share of natural gas in the transformation sector was 80% in 2011, while the share of wood fuel was 15%. Such a low level of wood fuel use for energy production can be explained by the differences in biomass structure, elemental

composition, moisture content, and calorific value of various types of biomass, which affect the efficiency (Arena et al., 2010).

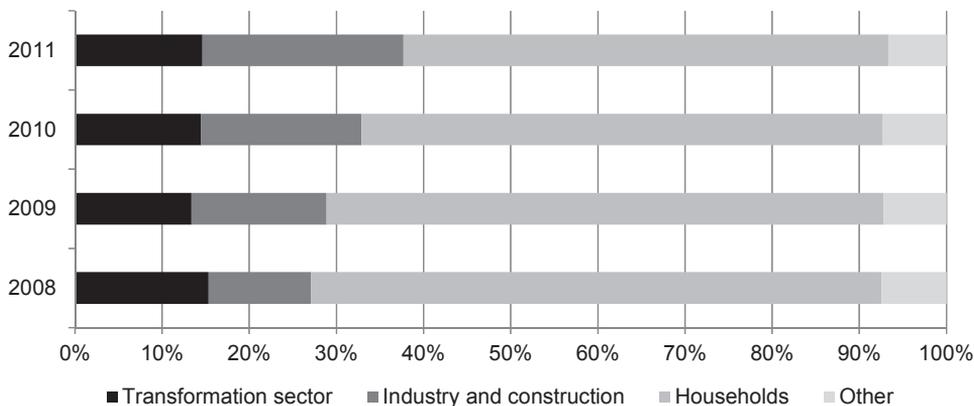


Figure 1. Wood fuel consumption in sectors in Latvia (LR Central statistical bureau).

Determination of biomass composition is an important step to be taken before its combustion, because the composition of the fuel defines combustion characteristics, the quality, potentially used technologies, and emissions that are formed during fuel combustion (Vassilev et al., 2010). The chemical composition and physical properties of biomass depend on several factors, which can be divided into three groups:

1. type of biomass/product;
2. growing conditions, including factors such as day light, geographical location, climate, soil type, and use of fertilizers and pesticides;
3. biomass harvesting and processing (Cuiping et al., 2004; Vassilev et al., 2010; Villeneuve et al., 2012; Williams et al., 2012).

Natural moisture of wood is one of the most important factors that limit use of wood in the transformation sector (Beloborodko et al., 2012). Moisture reduces the combustible substances in the fuel and affects combustion process: hinders fuel ignition, prolongs drying time, reduces fuel combustion heat, and reduces efficiency (Demirbaş, 2001). Wood fuel moisture content affects the wood biomass combustion temperature, increases CO emissions, thus reducing CO₂ emissions (Bhattacharya et al., 2002; Bignal et al., 2008). However, at the same time completely dry wood combustion does not provide maximum efficiency. It has been shown (Yuntenwi et al., 2008) that a small moisture content must be present in biomass in order to reduce emissions and increase combustion efficiency.

Combustion of biomass involves a number of complex physical and chemical processes: heating, moisture evaporation, pyrolysis and gasification with formation of volatile compounds, ignition and combustion of these compounds, and the last stage – formation of charcoal and gas products (Fig. 2) (Nussbaumer, 2003; Obernberger & Thek, 2004; Van Loo & Koppejan, 2007; Shen et al., 2009; Sakalauskas et al., 2011).

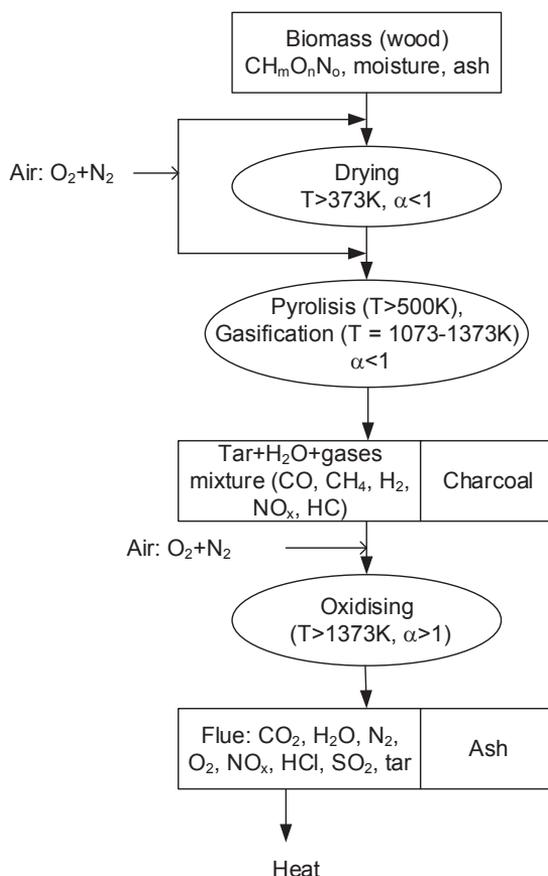


Figure 2. Biomass combustion stages (Oberberger & Thek, 2004).

The main environmental objective of fuel combustion is to ensure efficient fuel combustion with the least greenhouse gas emissions produced. There is a variety of options (Van Loo & Koppejan, 2007) to provide reduction of emissions and more efficient energy production during wood biomass combustion. These options are related to the fuel (wood biomass types, moisture content), combustion equipment (design, fuel and air supply) and combustion conditions (combustion temperature, residence time). Co-firing of biomass with gaseous fossil fuels will be investigated in this research.

Co-firing is a combustion process when two or more fuels are combusted in one technological device. In general, renewable energy sources (biomass) are combusted with fossil fuels (coal or natural gas). There is a great interest in biomass co-firing with fossil fuels worldwide because the share of RES in total energy consumption can be increased and greenhouse gas emissions can be reduced by replacing fossil fuels with RES (Al-Mansour & Zuwala, 2010; Berndes et al., 2010). The amount and type of greenhouse emissions during co-firing depend on co-fired fuel type and percentage of fossil fuel used. Studies in Europe and the United States have established that burning biomass with fossil fuels has a positive impact both on the environment and the economics of power generation. The emissions of SO₂ and NO_x were reduced in most co-firing tests (depending upon the biomass fuel used). The CO₂ net production was

also inherently lower, because biomass is considered CO₂ neutral. In addition, total fuel costs can be reduced in some cases if the biomass processing costs (transportation, grinding, etc.) are lower, on energy basis, than the primary fuel processing costs on an energy basis (Sami et al., 2001).

MATERIALS AND METHODS

The general objective of this study was to develop a stable, effective and controllable process of co-firing a fossil fuel (propane, natural gas) with renewable fuel (wood biomass, straw pellets, lignin), providing control of a burnout of the biomass char and volatiles, as well as control of the flame dynamics, processes of the heat/mass transfer and the formation of polluting emissions by co-firing a fossil fuel with renewable one.

In the framework of the research a specially constructed pilot device with a capacity up to 3 kW was created to co-fire wood biomass with gaseous fossil fuel. The layout of the pilot device is shown in Fig. 3.

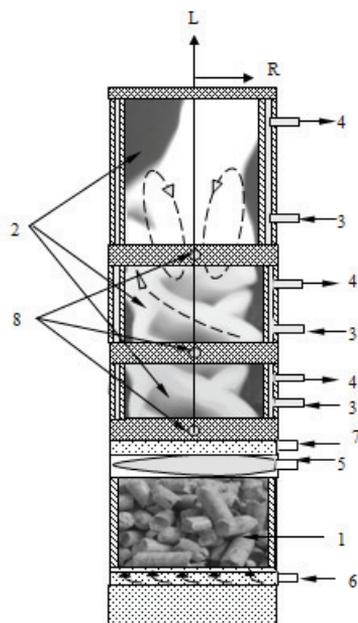


Figure 3. Pilot device: 1 – wood fuel gasifier; 2 – water-cooled combustor; 3 – inlets of cooling water flow; 4 – outlets of cooling water flow; 5 – gas burner; 6 – nozzle of primary air supply; 7 – nozzle of secondary air flow; 8 – diagnostic sections.

The pilot device includes a biomass gasifier (1), water-cooled channel (2) and a premixed propane/air burner (5). Combustion conditions in the system are varied by varying the mass flow rate of the primary air (6) into the bottom part of the combustor and the mass flow rate of secondary tangential air flow (7), introduced from the two tangential air nozzles of inner diameter $D = 5$ mm. The primary airflow ignites the volatiles and initiates combustion, while the secondary airflow completes the fuel combustion. It is possible to combust only wood biomass without gaseous fuel supply

to compare co-firing process with wood fuel self-sustaining combustion. The residual ash is removed from the bottom part of the combustor.

The total length of the experimental pilot device (L) is 1,600 mm. The height of the gasifier is 240 mm and the diameter is 60 mm. The length of the three cooled channel sections is 500 mm (100 mm, 75 mm and 325 mm).

Sections (8) with outlets for diagnostic probes are located between the sections of the water cooling channel. The diagnostic sections were formed to insert measurement instruments. The following measurements should be done in order to study co-firing of wood biomass with gaseous fossil fuel:

- local flame temperature measurements using a Pt/Pt-Rh (10%) thermocouples that are used for temperature measurements up to 1,600–1,700 K.
- temperature and composition of combustion products and combustion efficiency using a gas analyzer TESTO 350–XL. A computer program TESTO 350–M/XL was used for data processing. O₂ %, CO₂ %, CO ppm, NO ppm, NO₂ ppm, NO_x ppm, air excess α % and combustion process efficiency % were measured to control combustion processes;
- velocity measurements (axial and tangential) using Pitot's tube.

Thermocouples, gas analyzer and Pitot's tube placement can be changed depending on the object and purpose of the experiment.

The duration of each experiment should be about 2,400 second or 40 minutes, thus ensuring full combustion of the wood biomass. The data should be registered each second. The on-line calorimetric measurements of the cooling water flow were recorded by using data plate PC-20.

The main characteristics of the pilot device are:

- the mass flow rates of primary and secondary airflows could be varied in a range of 20–90 l min⁻¹;
- the rate of stoichiometric propane supply – could be varied in a range from 0.5 to 0.85 l min⁻¹;
- the heat rate released from the propane combustion - from 770 to 1,400 J s⁻¹;
- the additional energy supply from the propane combustion could be varied from 10% up to 25% of the net amount of the total heat released during the burnout of wood pellets and volatiles;
- the total heat output during the burnout of wood pellets with propane is estimated to be in a range from 4 up to 5 kWh.

Propane/butane/air flame was formed when radial propane and butane flow and tangential air flow are mixed in the channel. The diameter of the channel was 20 mm (Fig. 4). The mixture of propane/butane was supplied to the burner through six radial openings (\varnothing 0.3 mm) that were placed in the channel wall. Tangential air flow was formed by air supplied through eight tangential openings (\varnothing 3 mm) at the base of the burner.

The supply of propane/butane and air in the pilot device was controlled by using differential pressure meter calibrated before the beginning of experiments. The

differential pressure meters to control air and propane/butane supply in the burner and rotameters to control primary and secondary air supply in the gasifier.

The following formulas were used for the calculation of propane and air consumption using differential pressure meters data in mm (ΔH). The formulas were derived during calibration process of differential pressure meters.

$$\begin{aligned} Q_{prop} &= 0.064\sqrt{\Delta H(mm)} \\ Q_{gaiss_prop} &= 0.54\sqrt{\Delta H(mm)} \end{aligned}, \text{ l min}^{-1} \quad (1)$$

where: ΔH – water column height (mm) in the corresponding differential pressure meters.

The experiment steps are following. The discrete doses of the wood fuel (up to 320 g) are inserted into the gasificator up to the inlet port of the propane flame flow that is used to initiate the wood fuel gasification and complete the burnout of the volatiles. A height of the wood fuel in the gasificator at the initial stage of the flame formation is about 150 mm. Both the primary and secondary airflows were supplied by a compressor and were injected by tangential inlets. The primary air at a rate 38 l min⁻¹ is supplied below the wood fuel layer with the aim to initiate the wood fuel gasification, while the secondary air swirl at a flow rate up to 70 l min⁻¹ is supplied above the inlet port of the propane flame flow, providing the gradual mixing of the swirling air flow with the flow of volatiles and gradual burnout of the volatiles. The intensity of swirling flow is described by a dimensionless parameter *S*. *S* is a swirling number. It is estimated by using the following formula (Palies et al., 2010):

$$S = \frac{2}{3} \frac{v_{ax}}{v_{tg}} \quad (2)$$

where: v_{ax} – axial velocity; v_{tg} – tangential velocity.

To provide the detailed research of the swirl effect on the flow field formation and flame structure, the complex measurements of the flame parameters include the local measurements of the axial and tangential flame velocity compound by using the Pitot tube. The local measurements of the flame temperature at different distances from the outlet of the gasifier were carried out by using the Pt/Pt-Rh (10 %) thermocouples, while the local measurements of the flame composition (O_2 , CO, CO_2 , NO, NO_x and NO_2) and combustion efficiency were performed using the gas analyzer Testo 350XL.

To control the correctness of O_2 , CO_2 and CO measurements the diagram developed by Russian scientist Karjakin was used as the second tool for flue gas analyzing. Karjakin diagram is used to analyze incomplete combustion containing CO. The diagram is a simple right triangle – one leg represents specific for every fuel maximal CO_{max} content, the second leg in the same scale is 21 – maximal O_2 content.

The diagram links O_2 content (line segment AH = MG) with CO_2 content (line segment AM = HG) and CO content in dry flue gases (line segment DE) (Fig. 4).

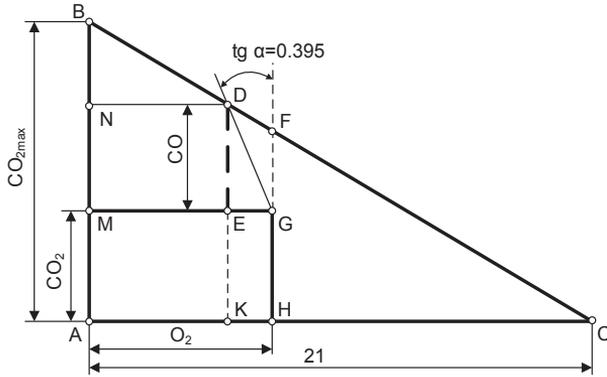


Figure 4. Karjakin diagram.

The diagram allows defining one of three parameters CO_2 , O_2 and CO , if two of them are given.

If CO_2 (AM) and O_2 (AH) are given values, then line segment DE is representing CO . The angle DGF must be such to get $tg \alpha = 0.395$.

From triangles NBD and ABC we can obtain:

$$\frac{NB}{CO_{2max}} = \frac{ND}{21} \text{ or } NB = \frac{ND \cdot CO_{2max}}{21}$$

Line segment $ND = AH - EG = O_2 - DE \cdot tg \alpha = O_2 - CO \cdot tg \alpha$. Then

$$NB = \frac{ND \cdot CO_{2max}}{21} = \frac{(O_2 - CO \cdot tg \alpha) CO_{2max}}{21}$$

On the other hand

$$AB = AM + MN + NB \text{ or } CO_{2max} = CO_2 + CO + \frac{(O_2 - CO \cdot tg \alpha) CO_{2max}}{21}$$

From this equation CO content in dry flue gases

$$CO = \frac{CO_{2max} (21 - O_2) - 21 CO_2}{21 - CO_{2max} \cdot tg \alpha}$$

If the given values are O_2 (AH) and CO (DE) then CO_2 (KE) content can be expressed as

$$KE = CO_2 = \frac{CO_{2max} (CO \cdot tg \alpha + 21 - O_2) - CO}{21}$$

If the given values are CO_2 (HG) and CO (DE) then O_2 (AH) value can be expressed as

$$AH = O_2 = 21 - \left(\frac{21(CO_2 + CO)}{CO_{2max}} - CO \cdot tg \alpha \right)$$

RESULTS AND DISCUSSION

The amount of produced heat energy during wood biomass and gaseous fuel co-firing depends on wood fuel amount (grams) and gaseous fuel supply (kJ s^{-1}). For example, when in initial experiments 320 grams of wood pellets were co-fired with propane/butane mixture and supply of propane/butane mixture was in range from 0.7 up to 1.16 kJ s^{-1} , heat energy volume produced from gaseous fuel varied between 22% and 35% of the total heat production.

The flue gas composition was tested using gas analyzer Testo 350XL. The measured CO_2 , O_2 and CO were checked with Karjakina diagram (Fig. 5). Such comparison allowed to exclude in further statistical calculations some measurements not corresponding to the mathematical basis of diagram.

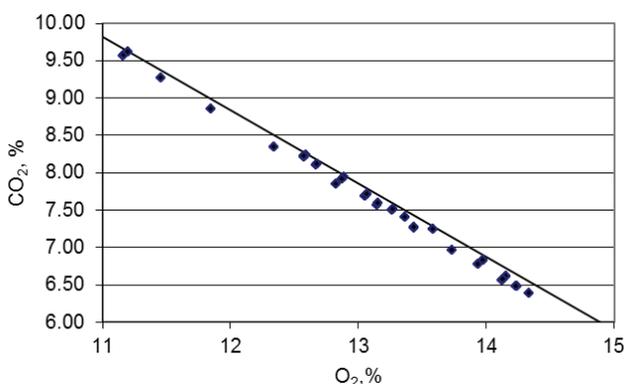


Figure 5. The part of Karjakin diagram. The line is a line segment of the chart hypotenuse.

First experiments of co-firing the wood granules with propane have shown that it can provide more effective burnout of wood granules, increasing a rate of wood pyrolysis, thermal breakdown of volatiles, as well their ignition and burnout, depending on rate of propane/air supply into the swirl burner and air excess ratio inside the gasifier.

The flame dynamic has an important role in gaseous and solid fuel stable combustion process. The correct flame dynamics creation promotes an effective fuel mixing with air flow and complete combustion of volatiles. The air flow in the pilot device was divided into three streams:

- air supply in propane/butane burner;
- primary air supply in the base of the gasifier;
- secondary air supply above the wood biomass layer.

Primary air was supplied below the wood biomass layer to provide initiation of wood biomass gasification. Secondary air was supplied above the wood biomass layer and propane/butane burner to ensure complete combustion of volatiles. The secondary air was supplied tangentially through the two openings with a diameter of 5 mm, thereby ensuring the formation of a swirling flow. Swirling flow is widely used in

combustion chambers as a possibility to control the flame size and shape, stability and intensity of combustion.

The secondary air supply was chosen in such a way that the swirling number S is greater than the value of 0.6 to form a recirculation zone. The recirculation zone is described by changes in the velocity distribution and high flow turbulence level, providing an intense flame mixing components at the molecular level with interrelated chemical reaction speed changes in the combustion zone (Tang et al., 2002; Syred, 2006).

The first experiments showed that for given system configuration and the cold air flow conditions at the initial stage of the wood fuel gasification the air swirl can be characterized by relatively high swirl intensity, determining the variations of air swirl number ($S \approx 2/3v_{tg}/v_{ax}$) in a range of 0.8–1.3. The flow field structure in the primary mixing region indicates the formation of the well pronounced central recirculation zone (Fig. 6). The maximum tangential velocity (v_{tg}) occurs almost at the same radial distance from the axis as the peak of the axial velocity (v_{ax}) – close to the channel walls. The non-zero values of the axial flow velocity recorded near the axis of combustor are determined by the influence of primary air supply at the bottom part of the gasifier and can be increased by increasing the primary air supply, penetrating through the layer of the wood pellets and central recirculation zone. The formation of the flow field structure near the outlet of the secondary air is developing at high level of the turbulence, providing the variations of Reynolds number in a range of 3,000–10,000. The higher turbulence levels, determining mixing of the flame compounds at the initial stage of the flow field formation are fixed in the inner shear layer of the velocity gradients by decreasing the primary air supply into the bottom part of the gasifier below 50 l min^{-1} .

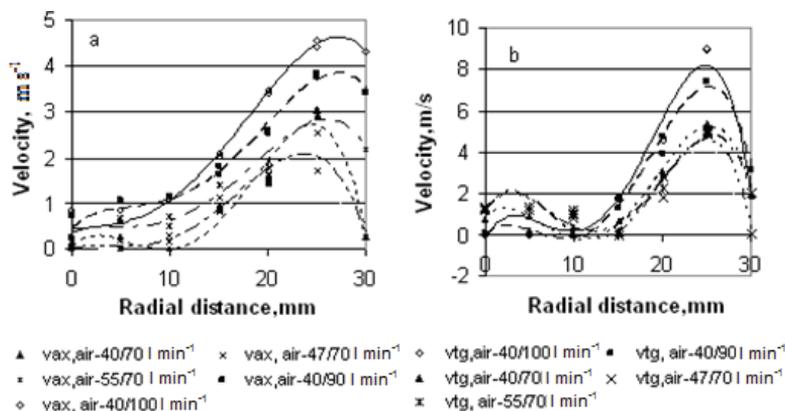


Figure 6. The influence of the rates of primary and secondary air supply on the formation of the flame flow field at the initial stage of the flame formation ($L = 30 \text{ mm}$ above the secondary air inlet).

The time dependent variations of the flame temperature have shown that during the burnout of the wood fuel the axial flame temperature gradually decreases with correlating decrease of a height of the wood layer inside of the gasifier (Fig. 7, a, b), so gradually increasing a distance between the inlet port of a propane flame flow and upper part of the wood layer and promoting transition to the self-sustaining wood fuel

burnout. At this stage of the wood fuel burnout the additional heat supply by the propane flame flow predominately is used to complete the burnout of volatiles, produced during the self-sustaining wood fuel combustion.

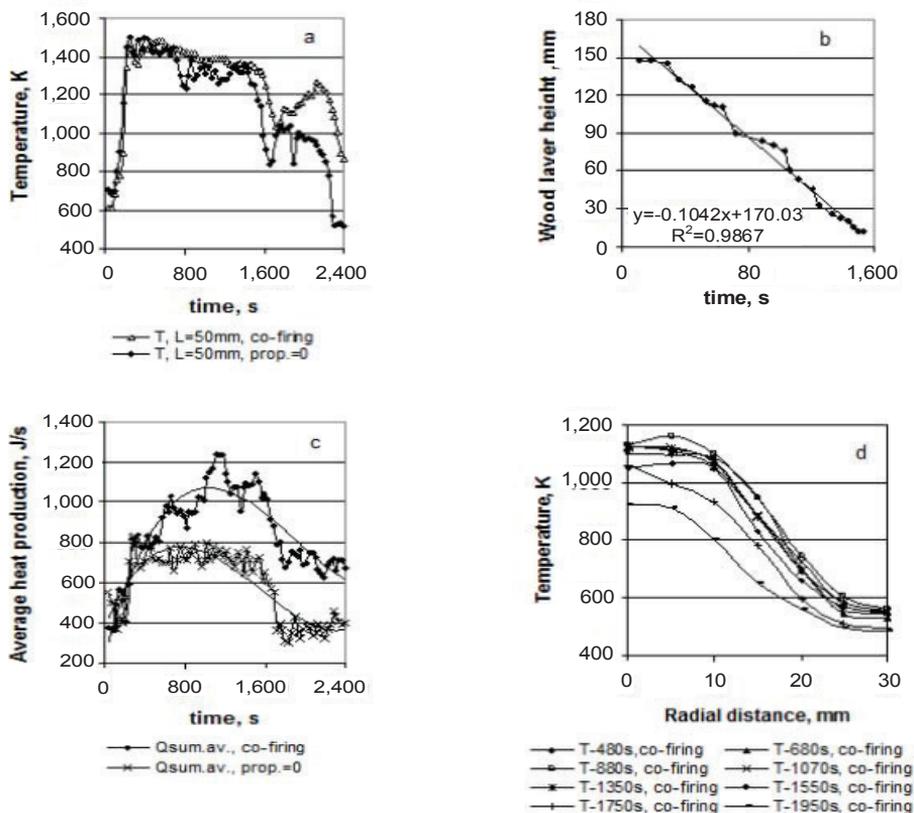


Figure 7. The time dependent variations of the flame temperature (a), height of the wood pellets inside of the gasifier (b), heat production rate (c) and variations of the shape of the flame temperature profiles (d) at different stages of the swirling flame formation and wood fuel burnout, constant rate of propane co-fire (30%) and constant primary and secondary air supply rates (40/70 l min⁻¹) into the combustor.

The swirling flame flow field formation during the burnout of the volatiles with no propane co-fire indicates the formation of the intensive pulsations of the temperature and heat production rate, determined by the turbulent mixing of the flame compounds (Fig. 7, c). As follows from Fig. 7, stabilization of the flame temperature and heat production rates during the burnout of the volatiles can be achieved by co-firing the wood fuel with propane. The time dependent measurements of the heat production rate have shown that the peak value of the heat production rate during the burnout of the volatiles can be achieved at 1,000–1,400 s, when the intensive burnout of the volatiles promotes the radial expansion of the flame reaction zone (Fig. 7, d) with correlating increase of the heat flow to the channel walls. During the end stage of the wood fuel burnout, when the axial flame temperature starts to decrease and flame

reaction zone narrows in width (Fig. 7, d) a correlating decrease of the heat production rate downstream of the flame channel flow has been observed (Fig. 7, c).

CONCLUSIONS

There is a relatively high potential for wood fuel use in Latvia. Amount of woodland has doubled during last 100 years and has reached 50.9%. Despite the high potential, the specific weight of wood use in energy transformation sector is not sufficient and makes only 15%. At the same time share of natural gas in the transformation sector is approximately 80%, but its continuously growing price provides conditions for partial natural gas substitution with wood fuel, simultaneously providing conditions for more efficient combustion of wood.

The process of natural gas being replaced by wood fuel in the transformation sector is a complex process that requires a long-term development strategy. One of the possibilities to increase wood fuel share in heat and electricity production is wood co-firing with gaseous fuel. A special pilot device was constructed with an aim to investigate wood fuel and gaseous fossil fuel co-firing process.

A lot of attention has been paid to the air supply during pilot device construction in order to provide sufficient air supply. The secondary air above the wood biomass layer was supplied tangentially providing formation of swirling flow. By changing the swirling number S in the burner outlet and recirculation of combustion products it is possible to provide targeted fluctuation of temperature in the combustion zone, thus varying the speed of chemical reactions in the combustion zone and the composition of combustion product.

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