

EXPERIMENTAL STUDY OF THERMAL DECOMPOSITION AND
COMBUSTION OF LIGNOCELLULOSIC BIOMASS PELLETS

I. Barmina¹, A. Lickrastina¹, M. Zake¹,
A. Arshanitsa², V. Solodovnik², G. Telysheva²

¹Institute of Physics, University of Latvia,
32 Miera Str., Salaspils, LV-2169, LATVIA

²Latvian State Institute of Wood Chemistry,
27 Dzerbenes Str., Riga, LV-1006, LATVIA
e-mail: mzfi@sal.lv

The study is aimed at cleaner and more efficient heat energy production through investigation and analysis of the thermal decomposition of lignocellulosic biomass pellets with different elemental composition, the heating values and contents of hemicellulose, cellulose and lignin. The estimation is provided for the influence of biomass composition on the combustion characteristics for softwood, wheat straw and wheat straw lignin pellets. The kinetics of thermal decomposition was studied experimentally, using a pilot device for two-stage processes of thermochemical conversion including gasification and combustion of biomass pellets under varying conditions. The experimental study includes time-dependent measurements of the biomass pellet weight loss during gasification and the correlating variations of the flame temperature, heat production rates, combustion efficiency and composition of the products at different stages of thermochemical conversion. Estimation is also given for the influence of the biomass composition on the combustion characteristics and heat energy production.

Key words: *biomass pellets, gasification, combustion characteristics, product composition*

1. INTRODUCTION

Utilization of different types of renewable energy resources (wind, solar, biomass) for energy production is of ever increasing importance in meeting the world energy demands and reducing the Earth's atmosphere pollution with greenhouse carbon (CO₂) emissions by minimizing the impact of energy production on the Earth's climate changes [1, 2]. In particular, biomass is now gaining in importance as a renewable resource for cleaner energy production. Bioenergy can be obtained from different biomass types, including agricultural crops and straw, raw material from the forestry and plants, etc. Nowadays, softwoods and wheat straw are the most acceptable lignocellulosic sources for energy production in Europe and worldwide, having no negative influence on the food market. The availability of cheap biomass combined with effective technologies of thermo-

chemical conversion and low levels of polluting emissions makes it an attractive fuel for the energy production [2].

At the same time, utilization of raw biomass for controllable energy production is limited because of considerable variations in physical (moisture content, bulk density, structure) and physically-chemical (heating value, elemental composition, volatile matter and ash content) characteristics of biomass [3, 4]. These variations lead to unstable and unpredictable operation of the energy production systems along with high costs of biomass storage, handling and transportation. Stabilization and prediction of the combustion characteristics at biomass thermo-chemical conversion can be achieved by producing densified biomass as fuel (pellets, briquettes, etc.) with increased bulk density and controllable energy density, elemental composition and moisture content [5, 6]. However, it should be taken into account that biomass is mainly composed of hemicellulose, cellulose and lignin, with significant differences in their mass ratios for different biomass types. Hence, the variations in biomass constituent fractions can result in dissimilar thermal behaviour of densified biofuels thus causing variations in the rate of thermochemical conversion and in gasification and combustion conditions.

With account of the influence exerted by the biomass composition and chemical structure on the processes of thermochemical conversion, this study aims to investigate correlations between the main characteristics of pelletized biomass and the combustion characteristics, in order to predict combustion conditions and efficiency as well as composition of polluting emissions for different biomass types at nearly stoichiometric conditions of combustion ($\alpha \approx 1$).

2. EXPERIMENTAL

The pilot-scale setup for a controllable process of pelletized renewable fuel (softwood, wheat straw, wheat straw lignin) gasification and combustion of volatiles is shown in Fig. 1.

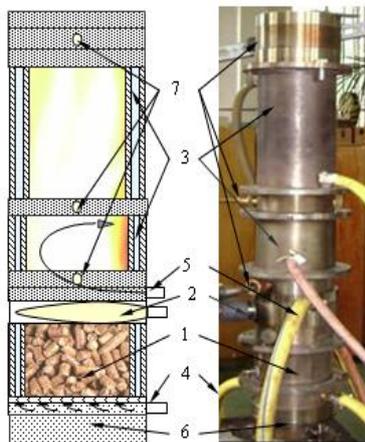


Fig. 1. Schematic and digital images of the experimental setup for gasification and combustion of biomass pellets: 1 – gasifier of biomass pellets; 2 – inlet of propane flame flow; 3 – sections of the water-cooled combustor; 4 – primary air supply nozzle; 5 – secondary air supply nozzle; 6 – ash vessel; 7 – orifices for diagnostic tools.

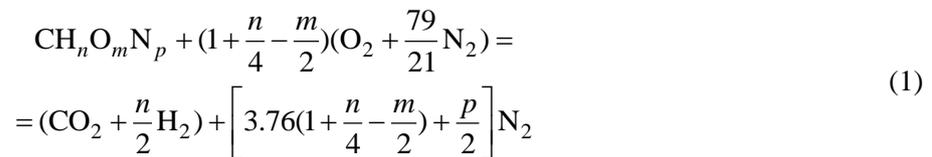
The experimental setup is composed of two main parts: a gasifier and two water-cooled sections of the combustor (60 mm in diameter and 600 mm in length, $L/D = 10$). The diagnostic sections with orifices are located between the water-

cooled sections to provide arrangement of the diagnostic tools (Pt/Pt–Rh thermocouples, a gas sampling probe) in the flame reaction zone for local measurements of the flame temperature and composition. In the upstream gasifier, discrete doses of biomass pellets (230–270 g) are put on a steel grate located at the bottom (see Fig. 1). The propane burner is used as an external heat energy source for additional heat energy supply (1.2 kJ/s) into the upper part of the biomass layer in order to initiate thermal decomposition of biomass. The primary air is supplied to the bottom part of the biomass layer to support the biomass gasification, while the secondary swirling air – above the biomass layer – through two tangential air nozzles to provide good mixing of the air with combustible gases released during the biomass gasification and complete combustion of the volatiles downstream the combustor. The primary and secondary air supply rates are in the range 0.6–1.6 g/s, which allows for variations of the air excess in the gasifier from $\alpha \approx 0.3$ up to $\alpha \approx 0.5$, and in the flame reaction zone – from $\alpha \approx 0.8$ up to $\alpha \approx 1.8$.

In order to estimate the biomass consumption rate (dm/dt) during the thermal degradation of biomass and combustion of volatiles, the time-dependent variations of the biomass layer height (dL/dt) in the gasifier at the pelletized biomass gasification are measured using a test tool (a moving rod with a pointer [7]).

The temperature variations inside the flame reaction zone during thermal conversion of biomass pellets are controlled using a Pt/Pt–Rh thermocouple inserted in the central part of the swirling flame flow ($R = 0$) at a distance $L = 150$ mm above the secondary air nozzle. The variations in the product composition during the burnout of volatiles are monitored using a gas sampling probe inserted through the gas sampling orifice at $L = 400$ mm ($L/D \approx 7$) above the secondary air nozzle and examined by a Testo 350 XL gas analyzer. The variations in the flame composition at the primary stage of swirl flame formation are controlled at $L = 20$ mm ($L/D = 0.3$) above the secondary air nozzle using a FTIR spectrometer. To estimate the influence of the variations in biomass characteristics and combustion conditions on the heat production rates at the combustion of volatiles, calorimetric measurements of the cooling water flow in the water-cooled combustor sections were made using thermo-sensors. The measurements of the temperature and heat production rates at different stages of the biomass burnout are recorded using a PC-20 TR data plate.

In this study, the combustion characteristics were explored and analyzed for softwood, wheat straw and wheat straw lignin pellets with different elemental composition and content of hemicellulose, cellulose and lignin in biomass. The main characteristics of the pellets and stoichiometric air-to-fuel ratio (A/F) for their thermo-chemical conversion are presented in Table 1 [8]. The stoichiometric A/F ratio is estimated with account for the data of proximate and ultimate analysis of the biomass pellets ($\text{CH}_n\text{O}_m\text{N}_p$) assuming that the biomass combustion can be described by the following reaction [9]:



Wheat straw lignin was produced by enzymatic hydrolysis (separated hydrolysis and fermentation – SHF) at the SAFISIS pilot plant (France) in the framework of the European Integrated Project (FP-6-2004) NILE.

A laboratory flat die pellet mill KAHL (14-175) with a 3 kW engine, the 24 mm thick die and 6 mm bore diameter, was used to pelletize the wheat straw lignin.

The water content and the ash content in the plant biofuel pellets were defined with reference to CEN/TS 14774-3 and CEN/TS 14775, correspondingly. The C, N, and H contents were found using the Analysis System Vario Macro CHNS [10].

Lower and higher heating values (LHV and HHV) were estimated in accordance with ISO1928, and the sulphur contents – according to CEN/TS 15289.

Table 1.

Main characteristics of biomass pellets

Main characteristics of pelletized biomass $CH_nO_mN_p$	Wood	Wheat straw	Wheat straw lignin
<i>Proximate analysis</i>			
Moisture content, %	7.9	9.4	6.4
Ash content, %	2.1	3.7	6.0
Lower heating value (LHV), kWh/kg	4.6	4.2	4.7
<i>Ultimate analysis</i>			
Carbon content on DM, %	50.2	49.7	49.7
Hydrogen on DM, %	5.7	5.3	5.54
Nitrogen on DM, %	0.18	0.44	1.04
Sulphur on DM, %	0.01	0.132	0.086
Stoichiometric air-to-fuel ratio (A/F)	6.06	6.02	6.36
<i>n</i>	1.36	1.28	1.34
<i>m</i>	0.62	0.61	0.57
<i>p</i>	0.003	0.007	0.018

3. RESULTS AND DISCUSSION

3.1. Thermal decomposition of biomass pellets

The primary processes of biomass heating, drying and thermal decomposition (gasification) are initiated and develop in the gasifier under the fuel-rich conditions ($\alpha \approx 0.4-0.5$), while the ignition and combustion of the volatiles develop downstream the combustor at the near-stoichiometric combustion conditions in the flame reaction zone ($\alpha \geq 1$). The biomass weight loss curves (Fig. 2a) are of the shape typical for thermal decomposition of lignocellulosic materials, with well demarked regions of biomass heating, drying, devolatilization and char conversion stages. The thermal decomposition of biomass samples starts with the weight loss due to the release of moisture and light volatiles at $T = 300-420$ K, which is lasting up to 350–400 s. The next stage of biomass thermal conversion at $t > 400$ s refers to the thermal decomposition of hemicellulose, cellulose and lignin at temperatures 490–600 K, 580–650 K and 520–800 K, respectively [11] (see local peaks on the curves in Fig. 2b).

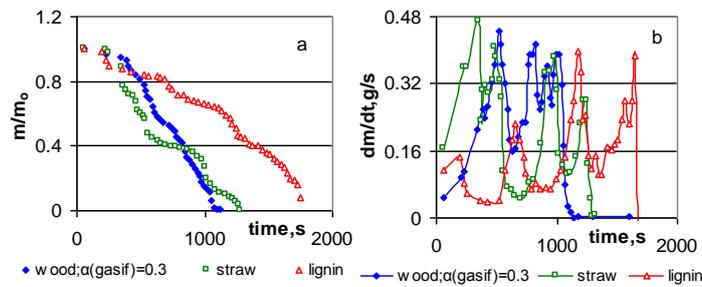


Fig. 2. Time-dependent variations of the weight loss (a) and its rates (b) for different biomass samples.

The comparative analysis has shown a considerable difference in the weight loss (m/m_0) and weight loss rate (dm/dt) curves for softwood, wheat straw and wheat straw lignin samples (Fig. 2a,b), which can be related to the variations of their elemental composition and content of hemicellulose, cellulose and lignin in the samples (Tables 1 and 2).

Table 2

Content of hemicellulose, cellulose and lignin in selected biomass

Biomass type	Biomass composition, %		
	Hemicellulose	Cellulose	Lignin
Wood			
Shen <i>et al.</i> [11]	15.37	52.1	27.45
Demirbas [12]	24.8	42.68	32.5
Sullivan <i>et al.</i> [13]	24	41	28
McKendry [14]	27.5	37.5	28.5
Belderok [15]	20	45	28.5
Olsson [16]	25	41	28
average	22.78	43.21	28.83
Wheat straw			
Demirbas [12]	45.2	33.83	20.96
Sullivan <i>et al.</i> [13]	28	40	17
Bridgeman <i>et al.</i> [17]	30.8	41.3	7.7
McKendry [14]	22.5	36.5	17.5
Greenhalf <i>et al.</i> [18]	24	33.2	15.1
Pasangulapati [19]	24.6	39	17.17
Olsson [16]	21	24	20
average	28.01	35.40	16.49
Lignin*	–	–	49

* Klason lignin content (experimental data)

As follows from Tables 1 and 2, the wheat straw biomass has the highest moisture content (9.4%) and the greatest average weight fraction of hemicellulose (up to 28.01%), while the minimum LHV (4.2 kWh/kg) and lignin content in the biomass (~ 16.5%). The samples of softwood biomass have the highest carbon (50.2%) and hydrogen (5.7%) content and the highest average – for cellulose (up to 43.21%), whereas the samples of wheat straw lignin show the highest LHV (4.7 kWh/kg) and lignin content (49%) in the biomass.

Because of the highest moisture content, the thermal decomposition of wheat straw samples starts with a sharp increase in the weight loss rate (up to 0.5 g/s) at the primary stage of thermal decomposition ($t = 350$ s, Fig. 2*b*). The next peaks of the mass loss rate for the wheat straw samples are at 480 s and 980 s and can be related to the thermal decomposition of hemicellulose and cellulose with the minimum value of weight loss rate (0.28 g/s) at the char conversion stage ($t \approx 1200$ s). Thermal decomposition analysis of the wheat straw shows [12–14] that its devolatilization occurs in a temperature range of 450–825 K, with the peak rate at 610–650 K (when hemicellulose and cellulose decompose). The char conversion of wheat straw occurs in the range of 710–825 K with the peak of mass loss at 755–775 K [20] (which associates with the peak rate of mass loss at $t \approx 1200$ s, Fig. 2*b*).

The time-dependent variations in the weight loss rates during the thermal decomposition of softwood pellets evidence the formation of their peak values at $t = 520$ s, $t = 980$ s and $t = 1245$ s (Fig. 2*b*) that can be due to the thermal decomposition of hemicellulose, cellulose and partial decomposition of lignin, respectively. The TG analysis of wood chips [21, 22] has shown that the thermal decomposition of hemicellulose in the softwood samples occurs in the 490 to 580 K range with the peak rate of weight loss at ~ 540 K, while the decomposition of cellulose – within 580–860 K with the peak value at ~ 630 K. The temperature range of lignin decomposition is broader and extends from 450 K to 1170 K, with a less pronounced maximum of the weight loss rate [21, 22]. The comparative analysis of the results of the weight loss rates and temperatures of the thermal decomposition of hemicellulose, cellulose and lignin for wood biomass samples allows suggestion that the first peak of weight loss rate for wood samples at $t = 480$ s can be due to the decomposition of hemicellulose with the peak weight loss rate at $T = 560$ K; its next peak at $t = 980$ s refers to $T = 620$ K, when cellulose decomposes, whereas the peak at $t = 1245$ s is associated with the thermal decomposition of lignin with the peak in the range 690–730 K (Fig. 2*a*).

The time-dependent measurements of weight loss rates (WLRs) for the wheat straw lignin samples show the characteristic delay of the primary stage of thermal decomposition (Fig. 2*b*). This allows for the conclusion that the wheat straw lignin is more resistant to thermochemical conversion and decomposes more slowly than wood and wheat straw pellets. A similar delay of thermal decomposition is observed for simulated biomass samples, when the lignin content increases in a mixture of cellulose and lignin [23]. The analysis of thermal degradation of lignin has shown the formation of an endothermic peak at 370–450 K due to the release of moisture followed by two broad exothermic peaks with the first peak from 550 K to 660 K and the second one at about 690 K (tail up to 770 K [24]). From the time-dependent measurements of the thermal decomposition of wheat lignin (Fig. 2*b*) it follows that the first weak WLR peak during the thermal degradation of wheat lignin pellets appears at $t \approx 200$ s, which can be attributed to the endothermic release of moisture at 360–450 K. More pronounced WLR peaks appear at $t \approx 650$ s, $t = 1170$ s and $t = 1645$ s due to the thermal decomposition of the remaining lignin and to the combustion of char residues.

A detailed study of the influence exerted by hemicellulose, cellulose and lignin on the thermal degradation of biomass samples [19, 22] evidences that

hemicellulose is less stable than cellulose owing to its amorphous nature, whereas cellulose requires higher activation energy because of its strong inter-molecular and intra-molecular hydrogen bonding. The comparative WLR measurements for softwood, wheat straw and wheat straw lignin samples confirm (Fig. 2) that the higher content of hemicellulose and cellulose in biomass results in faster decomposition, while the higher content of lignin leads to delayed ignition. In addition, FTIR analysis of the composition of gaseous species has shown that the variations in biomass composition give rise to those in the composition of the gaseous species released during their thermal decomposition, i.e. the higher content of hemicellulose or cellulose in biomass results in higher release of CO and CO₂, whereas the higher lignin content – in higher CH₄ release [19].

Considering the influence of the biomass composition on the rates of thermal decomposition it should be emphasized that the variations in the mentioned composition and rates are closely linked with the formation of combustion conditions developing downstream the combustor. The higher average rate of thermal decomposition requires a higher rate of air supply into the combustor. The A/F ratio estimation has shown that at the average biomass WLRs of 0.17–0.25 g/s the near-stoichiometric combustion conditions in the flame reaction zone can be achieved at the secondary air supply rates of 1.5–2.0 g/s.

3.2. Combustion of biomass samples: kinetics of the formation

Complex measurements of the time-dependent biomass WLR variations, temperature in the flame reaction zone and heat production rates at different stages of biomass thermal degradation show a direct correlation between the former and the main flame characteristics (Figs. 2*a,b*; 3*a,b*).

According to [16, 25], five sequential stages exist in the combustion of different biomass pellets: initial smouldering; flaming (early and late) of the volatiles; after-flame smouldering; and final glowing of char. For all samples, the first stage of initial smouldering refers to the primary endothermic processes of heating, drying and release of light volatiles that have low energy and combustion heat values. For the softwood and wheat straw samples this primary stage lasts about 300–350 s with transition to the flaming combustion at $t > 500$ s (Fig. 3*a,b*).

The formation of peak temperatures and heat production rates at overlapping the early and late flaming stages for softwood and wheat straw pellets is observed at $t \approx 550$ –800 s and $t \approx 630$ –900 s, respectively, correlating with the formation of WLR peak values at the thermal destruction of hemicellulose and cellulose. The peak values of the flame temperature in the reaction zone and of the heat production rate at flaming combustion for softwood pellets achieve $T_{\max} = 1620$ –1650 K and $Q_{\max} = 1640$ –1650 J/s, while for wheat straw pellets $T_{\max} = 1540$ –1560 K and $Q_{\max} = 1160$ –1180 J/s, thus indicating that combustion at the flaming stages is more efficient for softwood pellets, with a higher cellulose content of biomass.

The transition from the flaming to the after-flame smouldering stage takes place at $t > 800$ s for softwood pellets and at $t > 900$ s for wheat straw pellets,

resulting in a slight decrease of temperature in the flame reaction zone and of the heat production rates. The average temperature decrease at transition to the mentioned stage for softwood pellets is $\Delta T \approx 100\text{--}140^\circ$, with a more pronounced decrease for wheat straw pellets ($\Delta T \approx 240^\circ$). In contrast to the temperature variations at transition from flaming to smouldering, the measurements of heat production rate testify a more pronounced decrease for softwood pellets ($\Delta Q \approx 420\text{--}450\text{ J/s}$) as compared with wheat straw pellets ($\Delta Q \approx 320\text{--}340\text{ J/s}$). For wheat straw lignin pellets, a pronounced ignition delay is observed with the formation of the minimum temperature and heat production rates in the initial smouldering stage at $t = 430\text{--}480\text{ s}$. For wheat straw lignin, the transition to the early-flaming stage occurs at $t > 480\text{ s}$, whereas late-flaming of volatiles occurs at $t > 750\text{ s}$ when the peak flame temperature approaches 1540 K . The results show that the thermochemical conversion of wheat straw lignin requires a more extended additional heat energy supply to achieve a higher temperature of thermal degradation and provide a stable process of thermochemical conversion (Fig. 3a). The transition to the after-flame smouldering for wheat straw lignin pellets results in a $\sim 300^\circ$ flame temperature decrease, while the heat production rate downstream the combustor decreases by about 320 J/s . The transition from flaming to the after-flame smouldering for wheat straw lignin occurs at $t \approx 1170\text{ s}$, when the peak WLR is $dm/dt \approx 0.4\text{ g/s}$.

A more pronounced and sharp decrease in the temperature and heat production rates for all samples is observed at the final glowing stage, which takes place at $t > 1300\text{ s}$ for softwood pellets, at $t > 1500\text{ s}$ for wheat straw pellets, and at $t > 2000\text{ s}$ for wheat straw lignin, being characterized by a more extended char conversion stage. The estimation of the produced heat energy downstream the water-cooled sections at the thermochemical conversion of wood, wheat straw and wheat straw lignin pellets evidences the direct correlation between the produced heat energy and the LHV of the biomass samples, which can be approximated by a linear dependence at high R^2 values (Fig. 3c).

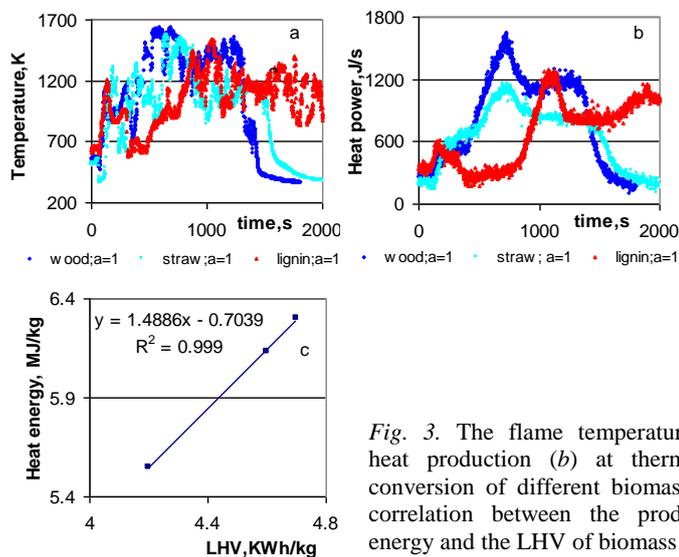


Fig. 3. The flame temperature (a) and heat production (b) at thermochemical conversion of different biomass samples; correlation between the produced heat energy and the LHV of biomass pellets (c).

3.3. Variations of the combustion product composition in dependence on the process stage

The time-dependent variations of the product composition and combustion efficiency at the end-stage of flame formation ($L/D \approx 7$) correlate with such variations of combustion conditions in the flame reaction zone at thermochemical conversion of biomass samples. By analogy with the main stages of the flame temperature and heat production rate variations, those of the flame composition evidence the formation of the initial stage of smouldering, overlapping of the first and last flaming stages, after-flame smouldering and glowing stages.

The FTIR analysis of the gas-phase species composition at the primary stage of combustion at the bottom of the combustor ($L/D \approx 0.3$) has shown that, for all samples, the formation of the initial smouldering stage correlates with the intensive release of low-energy light volatiles at the thermal decomposition of biomass samples, with the formation of the main combustible species: CO, CH₄, H₂ as well as the main products: H₂O and CO₂ (Figs. 4*a,b*; 5).

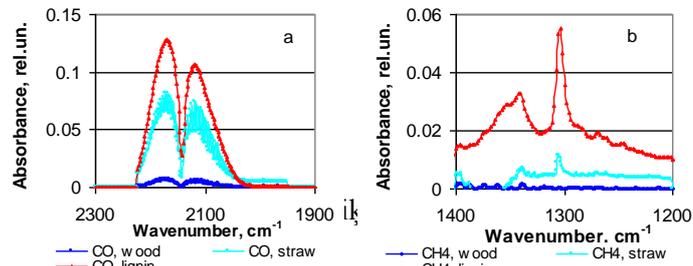


Fig. 4. Typical composition of the products at the bottom of combustor during the transition from smouldering to flaming conditions ($t \approx 400$ s): absorbance of CO (a) and CH₄ (b).

Faster transition from initial smouldering to flaming conditions was found for softwood pellets, while a more extended transition ($t \approx 400$ s) was observed for wheat straw lignin samples, indicating higher values of CH₄ and CO absorbance for the fixed duration of their thermochemical conversion (Fig. 4).

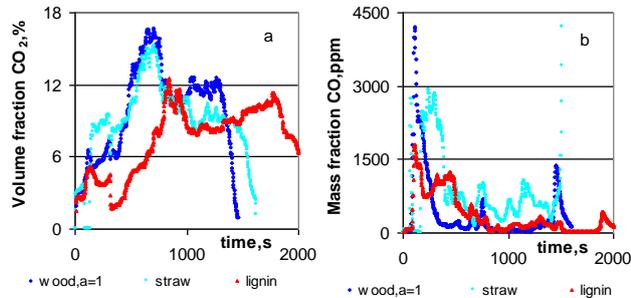


Fig. 5. Composition variations of the main products: CO₂ volume fraction (a); CO mass fraction (b).

The transition from primary smouldering to flaming combustion of the volatiles downstream the combustor initiates a fast increase in the CO₂ volume fraction, with a correlating decrease in the CO mass fraction in the products (Fig. 5). The formation of peak values of the CO₂ volume fraction for all samples

correlates with the peak flame temperature, heat production rates and WLRs at the thermal decomposition of biomass (Figs. 2*a*; 3*a,b*; 5*a*).

With the near-stoichiometric combustion conditions ($\alpha \approx 1$), the formation of the highest peak value of CO₂ volume fraction after the ignition of volatiles is observed for softwood pellets (16.7%), which have a higher content of thermo-labile carbohydrates in the biomass. The peak value of CO₂ volume fraction slightly decreases to 15.2% for wheat straw and to 12.4% for wheat straw lignin pellets with the highest content of thermo-stabile lignin components in biomass (Table 1). Despite the higher carbon content in lignin as compared with cellulose, its thermal degradation proceeds rather slowly; besides, a comparatively high portion of lignin carbon is burned at the after-flame glowing stage (char combustion), with a lower rate of thermochemical conversion in contrast with the fast flaming combustion stage of volatiles. The mass fraction of CO volatiles during transition from initial smouldering to flaming conditions decreases to 80–100 ppm for the wood pellets, to 130–140 ppm for wheat straw, and to 40–50 ppm for wheat straw lignin pellets (Fig. 5*b*).

For all samples, a slight increase of the CO mass fraction with a correlating decrease of the CO₂ volume fraction in the products is observed at the after-flame smouldering stage. With reference to [16, 25], the CO mass fraction for all pellets is relatively high at the final glowing stage, indicating a reverse correlation between this fraction in the products and the lignin content of biomass. The latter is responsible for the higher CH₄ yield, while an almost negligible amount of CO is produced at the thermal decomposition of lignin [19, 26]. A similar correlation between the lignin content in biomass and the CO mass fraction in the products is observed at the flaming and smouldering stages. A more pronounced increase of the CO mass fraction (up to 4500 ppm) at the final glowing stage ($t > 1400$ s) is revealed for the wheat straw samples, which have the minimum of lignin and the maximum of ash (Tables 1 and 2). A less pronounced increase of the CO mass fraction in the products is found at the final stage of the thermochemical conversion of softwood (up to 1300 ppm) and of wheat straw lignin samples (up to 350 ppm) which have a higher lignin content of biomass, a higher LHV of the pellets and the minimum ash content (Tables 1 and 2). At this stage of biomass thermochemical conversion, the formation of CO is a result of the surface reaction at char conversion, which appears as the glowing combustion of chars at 670–720 K. In accordance with [13], the high levels of CO in the products can result from the formation of an ash layer above the char that excludes oxygen from the surface reactions and slows down the rate of CO₂ formation. The variations in the flame composition at the final stage of the glowing combustion of wheat straw pellets confirm that the increase in the mass fraction of unburned CO correlates with the rapid decrease in the CO₂ volume fraction in the products (Fig. 5*a,b*), the decrease in the flame reaction zone temperature, the heat production rate (Fig. 3*a,b*) and the combustion efficiency (below 70%), whereas the air excess at the final stage of glowing combustion increases up to 500%. The results show that composition of the products at the end stage of glowing combustion can be improved providing propane co-fire of the volatiles, with the resultant increase in the flame temperature, heat production rate and combustion efficiency [26].

In addition to the formation of hazardous CO and organic emissions at the smouldering and glowing stages of the biomass pellets combustion, for all stages of

the thermochemical conversion of the examined biomass samples the formation of nitrogen oxides NO_x emission with the highest value of NO_x in the products has been found for the wheat lignin samples when the peak mass fraction of NO_x at the flaming stage approaches 400 ppm (Fig. 6a).

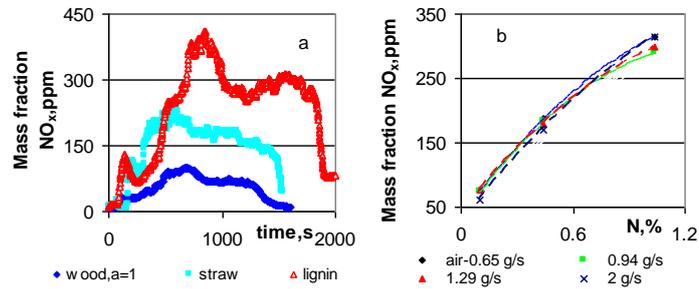


Fig. 6. NO_x mass fraction variations in the products at thermochemical conversion of biomass pellets (a); correlation between the nitrogen content of biomass pellets and the mass fraction of NO_x emission in the products at different secondary air supply rates in combustor (b).

As follows from Figs. 3a and 6a, the peak value of nitrogen emissions refers to the formation of the peak flame temperature. Such correlation allows for suggestion that the NO_x formation downstream the combustor is due to the basic reactions between nitrogen and oxygen producing thermal NO_x via the temperature-sensitive Zeldovich mechanism. Moreover, the results show that the formation of NO_x during the biomass thermochemical conversion is highly affected by the nitrogen content of biomass (Table 1), indicating that the higher nitrogen content of biomass determines the formation of higher NO_x mass fraction in the products (Fig. 6b). The regression analysis confirms this correlation (expressed by a parabolic rate law at a high value of $R^2 \approx 1$ for the wide range of the secondary air supply rate variations in combustor, Fig. 6b).

Finally, it should be stressed that a very important parameter that must be taken into the account at thermal decomposition of different biomass types is the ash content of biomass (Table 1). The higher ash content in the biomass pellets results in a correlating increase in the ash residues. For lignin pellets, the average mass of ash residues reaches 7–8%, whereas for wheat straw pellets and stoichiometric combustion conditions it is about 3%.

4. CONCLUSIONS

Based on the results obtained the following conclusions can be drawn.

The integrated gasifier and the combustor have been developed for complex experimental research into the gasification, combustion and heat production processes for different types of biomass pellets (softwood, wheat straw and wheat straw lignin) under controllable operation conditions during the gasification and combustion of the biomass.

The thermochemical conversion of biomass pellets develops as a multistage process, the main steps of which include biomass thermal decomposition in the gasifier, combustion of the volatiles downstream the swirling flame flow, and char conversion depending on the content of hemicelluloses, cellulose and lignin in the biomass. Higher rate of thermochemical conversion and heat energy production

was found for pellets with higher content of hemicellulose and cellulose in the biomass, whereas more extended thermochemical conversion with a higher value of the produced heat energy – for the samples with highest lignin content in the biomass.

The direct correlation is found between the variations of LHV and the produced heat energy per mass unit (expressed by a linear dependence at $R^2 \approx 1$).

The most complete combustion of volatiles in the flame reaction zone with minimum CO and H₂ mass fractions in the products is achieved in the stage of primary flaming combustion of volatiles, whereas a higher content of volatiles in the products was detected at the after-flame smouldering and char glowing stage of biomass with more pronounced increase of the CO mass fraction for the wheat straw samples.

The flaming stage of volatiles with the peak value of temperature promotes intensive formation of NO_x emissions by Zeldovich's mechanism. The analysis of correlation between the NO_x mass fraction in the products and the nitrogen content in the biomass has shown a higher mass fraction of NO_x in the products at the thermal conversion of wheat straw and wheat straw lignin pellets with a higher nitrogen content in biomass.

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GRANULĒTAS LIGNOCELULOZES BIOMASAS TERMISKĀS SADALĪŠANĀS UN DEGŠANAS PROCESU EKSPERIMENTĀLIE PĒTĪJUMI

I. Barmina, A. Līckrastiņa, M. Zaķe,
A. Aršanica, V. Solodovņiks, G. Teliševa

K o p s a v i l k u m s

Pētījumu galvenais mērķis ir iegūt tīru un efektīvu siltumenerģijas ražošanu, izmantojot dažādas izcelsmes biomasas granulas (koksnes, kviešu salmu, kviešu salmu lignīna) ar atšķirīgu elementāro sastāvu, siltumspēju, hemicelulozes, celulozes un lignīna saturu, veicot detalizētu šo granulu termiskās sadalīšanās un degšanas procesu izpēti. Eksperimentālie termiskās sadalīšanās un degšanas procesu pētījumi ir veikti, izmantojot eksperimentālo iekārtu ar integrētu gazifikatoru un degšanas kameru. Granulētās biomasas termiskās sadalīšanās un degšanas procesu kinētiskie pētījumi ietver granulu masas zudumu mērījumus biomasas gazifikācijas procesā un korelējošās degšanas zonas temperatūras, saražotā siltuma daudzuma un degšanas produktu sastāva mērījumus dažādās gazifikācijas un degšanas procesa stadijās, izvērtējot biomasas elementārā un ķīmiskā sastāva ietekmi uz šiem procesiem.

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