DEVELOPMENT OF COMBUSTION DYNAMICS AT THERMOCHEMICAL CONVERSION OF BIOMASS PELLETS

Inesa Barmina, Raimonds Valdmanis, Maija Zake
University of Latvia
mzfi@sal.lv

Abstract. Experimental study of combustion dynamics was aimed to provide control and analysis of the main effects determining the development of swirling flow dynamics at thermo chemical conversion of biomass pellets (wood and wheat straw). The presented experimental study is carried out in a batch-size experimental device with a heat output up to 2 kW along with test experiments in a pilot device with a continuous supply of biomass pellets and a heat output up to 20 kW. The experimental study of combustion dynamics includes the time-dependent measurements of the main flame characteristics at thermo-chemical conversion of biomass pellets, which involve complex measurements of the swirling flow velocity, temperature and composition fields' formation, along with estimation of main factors, affecting the development of combustion dynamics and a heat energy production. Considering the upstream and downstream swirl flow effects on the formation of the flame reaction zone it is shown that the swirling air flow can be used as an effective tool to enhance the mixing of the axial flow of volatiles with an air swirl and the enhanced thermo chemical conversion of renewable fuels – biomass pellets of different elemental and chemical composition (wood and wheat straw).

Keywords: biomass pellets, thermal decomposition, combustion dynamics.

Introduction

The swirling flows are used in many technological devices to improve mixing and stabilization of the jet flows and to control the combustion characteristics. The applicability of swirling flows to develop a clean and effective fuel combustion is analysed in [1-3] providing a detailed research and numerical modelling of the swirl effects on the formation of swirling flow dynamics. It is shown that limited mixing of the jet flows with an air swirl is observed at the low swirl number ($S < 0.6$), which allows to develop a staged fuel combustion with a reduced flame temperature and the NO_x emission levels (< 15 ppm). [1]. On the contrary, the enhanced mixing of the jet flow with an air swirl can be obtained by increasing the swirl number ($S > 0.6$) resulting in the formation of a toroidal recirculation zone and swirl flow reversing [2; 3], which is confirmed by the experimental study of swirling flows and flames at thermo chemical conversion of biomass pellets [4]. Note that increasing the swirl intensity promotes the enhanced heating of the axial fuel flow with the reverse flow of the hot products, determining a faster ignition and combustion of combustible flame species, at the same time promoting the development of flow instability [3]. Hence, whereas the high swirl intensity is known to be beneficial for the combustion dynamics, the high swirl number can lead to some undesirable effects, such as the formation of a processing of vortex core and swirl flow flashback, depending on constructive solutions of the device, fuel and swirling flow supply type and rates. Therefore, to provide the effective control of swirling combustion, it is important to evaluate the key factors determining the formation of the flow field and the main combustion characteristics, in particular, whether the formation of the fuel flow can be related to the biomass thermal decomposition determining the formation of the axial flow of volatiles.

With this account, comprehensive complex measurements of the formation of swirling downstream and upstream flows and of the formation of the axial flow of volatiles at thermal decomposition of biomass pellets are made to assess the main factors determining the formation of clean and effective heat energy production at thermo chemical conversion of renewable fuels – different types of biomass pellets (wood and wheat straw).

Experimental setup and methods

Thermo chemical conversion of biomass pellets (wood and wheat straw) is studied experimentally using a batch-size pilot device with a heat output up to 2 kW. The pilot device combines a biomass gasifier, producing the axial flow of volatiles and a combustor, downstream of which the swirling combustion of volatiles develops [4]. In addition, the tests experiments on heat energy production and the combustion characteristics at the swirling combustion of volatiles were carried out using a technological device with the continuous supply of biomass pellets and a heat output up to 20 kW

(Fig. 1). The device combines a Pelltech burner (1), a combustor (2) and a chimney (3). The openings in the test device (4) were used to make local measurements of the main combustion characteristics – i.e. the formation of flow velocity, temperature and composition profiles.

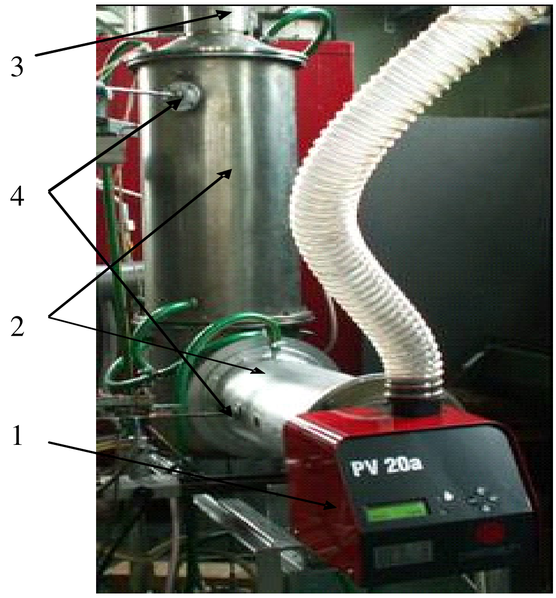

Fig. 1. **The test device for the experimental study the thermo chemical conversion biomass pellets:** 1 – Pelltech burner; 2 – combustor; 3 – chimney; 4 – openings for the diagnostic tools

The experimental study of the flame characteristics in the small scale pilot device and in the technological device combines the local measurements of the flow velocity, the flame temperature, composition of the products and produced heat energy. The local measurements of the flow velocity components were made out using a Pitot tube and a Testo 435 flow meter with an accuracy of ± 1 %. Pt/Pt/Rh thermocouples were used for the local online measurements of the flame temperature with an accuracy of ± 5 % using a date recording PicoLog-1012 board. The products temperature, composition and the combustion efficiency were measured online by a Testo-350XL gas analyzer providing accuracy of ± 1 % for the average volume fraction of CO_2 and of about ± 5 % for the mass fraction of CO, NO_x. The produced heat energy was calculated from the calorimetric measurements of the cooling water flow using the thermo sensors AD 560 for the measurements of the water flow temperature with online data registration by a data plate Quick DAQ. The average values of all parameters were estimated from 30 measurements.

Results and discussion

The development of combustion dynamics at thermo-chemical conversion of biomass pellets downstream the small-scale pilot device is determined by the complexity of the processes developing at thermal decomposition of biomass pellets and combustion of volatiles. First of all, the development of combustion dynamics at thermo chemical conversion of biomass pellets depends on the formation of the swirling flow field. For the small-scale pilot device, which combines a biomass gasifier and a combustor, the formation of the swirling flow field is determined by the development of the biomass thermal decomposition producing the axial flow of volatiles and by the swirl-enhanced mixing of the axial flow with the secondary air swirl, providing the development of the swirling flow field downstream of which the thermal conversion of volatiles occurs. The results of previous research show that, with the constant axial flow of volatiles the formation of the swirling flow field is highly influenced by the swirling air supply rate determining the formation of the downstream and upstream swirling air flows, which develop above and below the swirling air nozzles [4]. The upstream air swirl propagation near the channel walls up to the biomass layer slows down the axial flow of volatiles by increasing the air swirl number and swirl intensity close to the surface of biomass pellets, which is located at the distance L/D = -1.5 under the bottom of the combustor (Fig. 2,a-c). The local increase of the air swirl intensity at the surface of the biomass layer promotes the enhanced mixing of the upstream air swirl with the axial flow of volatiles produced at the biomass thermal decomposition.

Moreover, the upstream swirl reflection from the biomass layer is responsible for the enhanced convective mass transport of combustible volatiles downstream the flow centreline determining the development of the axial reaction zone at ($r/R < 0.5$), where it gradually mixes with the downstream air swirl advancing the radial expansion of the reaction zone. The modelling experiments of cold non-reacting flows have shown that the peak values of the average values of the tangential swirl flow velocity and swirl intensity of the downstream flow are detected close above the swirling air nozzle - at $L/D \approx 0.75$ with the fast decay further downstream (Fig. 2-b, c), whereas the peak values of the tangential flow velocity and swirl intensity of the downstream flow are detected close to the channel walls. Hence, the dominant mixing of the axial reaction zone with the downstream flow develops along the outside part of the reaction zone, which is responsible for the radial flame flow expansion in the downstream regions, the development of which occurs with a slightly reduced and nearly constant average value of the axial flow velocity and residence time of reactions (Fig. 2-a).

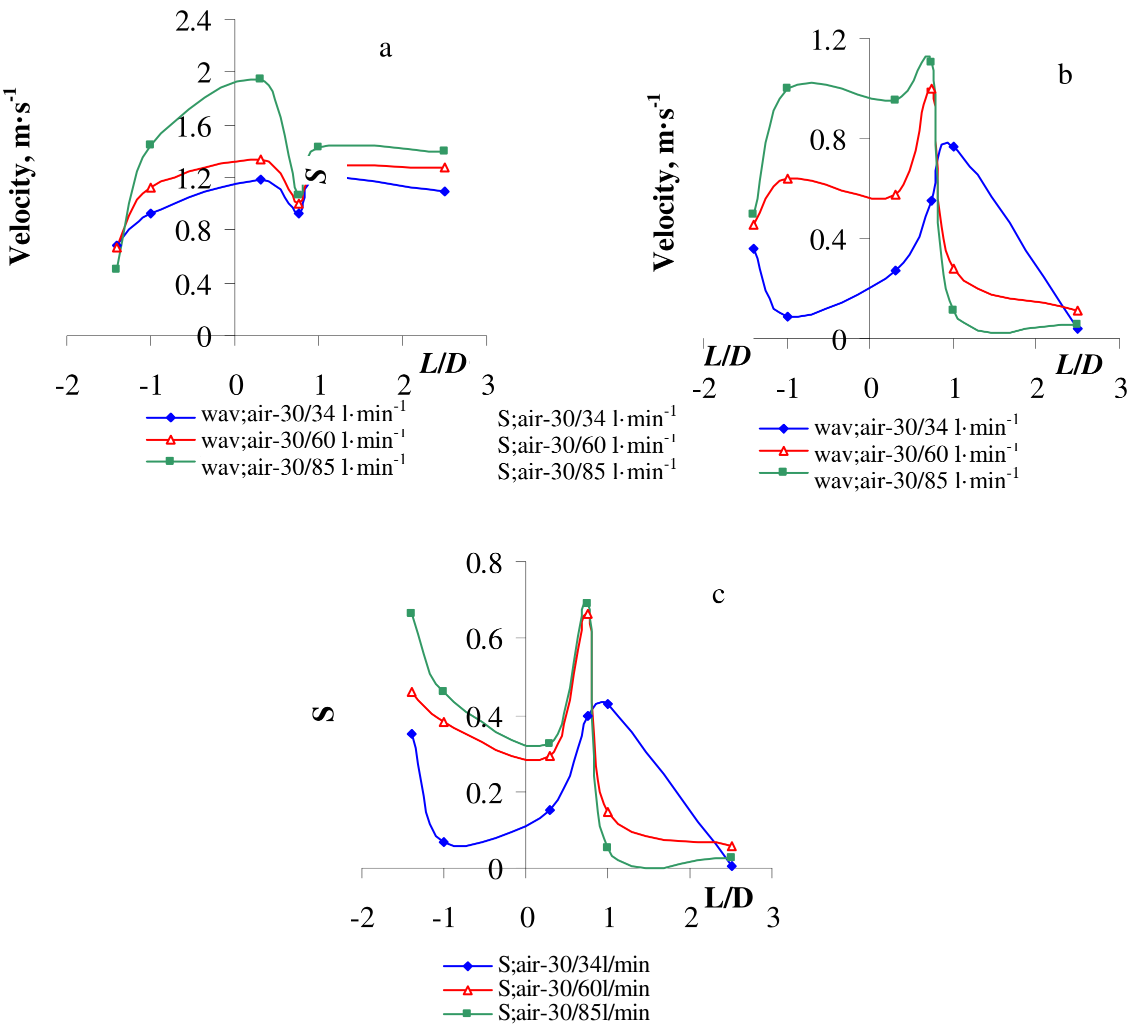

Fig. 2. **The effects of swirling air supply on the formation of the downstream and upstream swirling flows and on swirl intensity**

With the nearly equal gasification conditions of biomass pellets, the development of the flame reaction zone is very sensitive to the variations of the secondary air supply rate determining the variations of the downstream and upstream swirling flows as well of the air/fuel (*A*/*F*) ratio in the flame reaction zone. The results show that with the constant average weight loss rate of wood pellets (0.15 g·s^{-1}) increasing the secondary air supply from 30 to 90 l·min^{-1} results in an increase of the *A*/*F* from 6.1 to 12.2 along with the increase of the air excess ratio from $\alpha = 1.01$ to $\alpha = 2.02$. An increase of the air excess ratio in the flame reaction zone results in a decrease of the average and peak values of the combustion efficiency, produced heat output and volume fraction of CO_2 with the correlating decrease of the mass fraction of CO in the products from 990 to 45 ppm (Fig. 3). The observed decrease of the volume fraction of CO_2 and mass fraction of CO allows to suggest that increasing the secondary air supply rate with enhanced formation of the swirling upstream cold air flow (Fig. 2-b) promotes the cooling of the biomass layer with a significant impact on the biomass thermal decomposition. As result of the biomass cooling, the axial mass flow of combustible volatiles decreases, which directly affects the development of combustion dynamics promoting the delay of the ignition and combustion of volatiles with the correlating decrease of the produced heat output (Fig. 3-b).

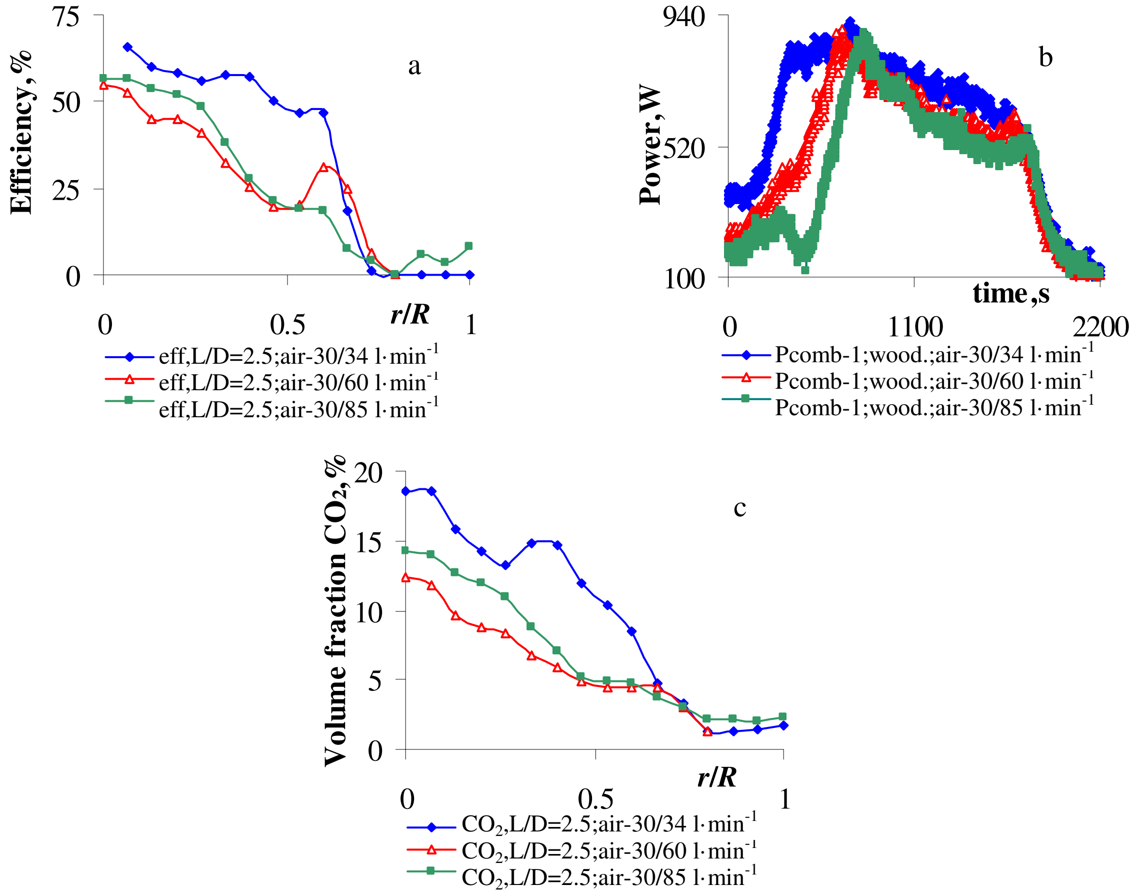

Fig. 3. **Effect of secondary air supply on combustion efficiency, produced heat output and composition of the products**

It should be stressed that with the nearly equal primary and secondary air supply rates (q_{air1} = 20 l·min^{-1}; q_{air2} = 40 l·min^{-1}) the thermal decomposition of biomass pellets and the formations of the axial flow of volatiles are also affected by the elemental and chemical composition of biomass pellets, i.e. the content of hemicelluloses, cellulose and lignin in the biomass. Comparison of the chemical composition of wood and wheat straw pellets shows [5] that wood pellets have the higher content of carbon, cellulose and lignin content, whereas wheat straw pellets have the higher content of hemicelluloses, nitrogen and ash [5]. As a result of differences in biomass pellets elemental and chemical composition, the variations in thermal decomposition of biomass pellets and in composition of the axial flow of volatiles were observed. The results of FTIR analysis have shown that the thermal decomposition of wood pellets with the higher lignin content evidences of a faster thermal decomposition with a faster release and ignition of volatiles (CO, CH_4, C_2H_2, C_2H_4), which is detected already at $t \approx$ 400-500 s. The thermal decomposition of wheat straw with the higher content of hemicelluloses leads to the delayed thermal decomposition which occurs at $t >$ 700-800 s with the dominant release of CO (Fig. 4-a, b).

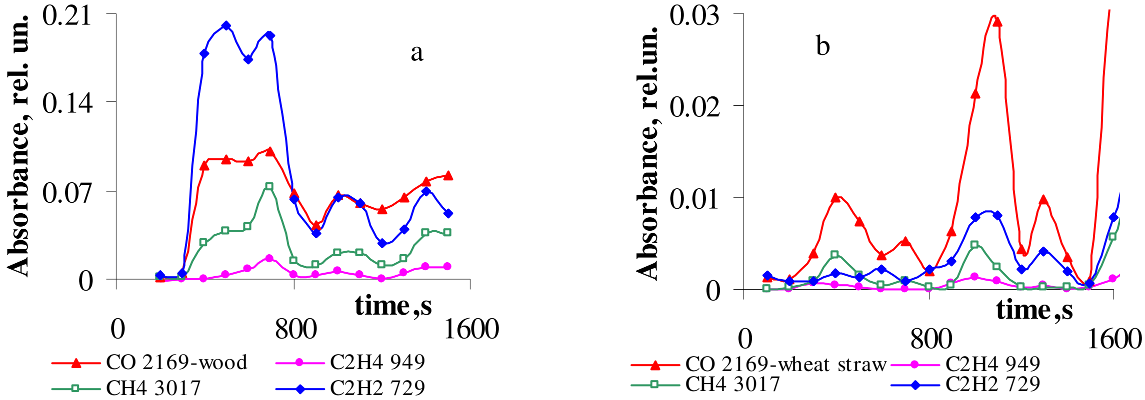

Fig. 4. **Kinetics of the formation of volatiles composition at thermal decomposition of wood and wheat straw pellets**

Moreover, the delayed thermal decomposition of wheat straw pellets with the dominant release of CO defers the ignition and the formation of the reaction zone, which is confirmed by a kinetic study of the produced heat output and composition of the products in the batch-size pilot device (Fig. 5-a,c). The influence of the elemental and chemical composition of biomass pellets on the kinetics of produced heat output and composition of the products was also observed at the thermo-chemical conversion of biomass pellets in the technological device with continuous supply of pellets into the burner and with swirl-enhanced mixing of the flame components (Fig. 5-b, d, f).

The kinetic study of the main combustion characteristics and composition of the products at thermo-chemical conversion of batch-size wood and wheat straw pellets in the small-scale pilot device and the test experiments with continuous supply of pellets into the burner allow to conclude that the development of combustion dynamics at thermo chemical conversion of biomass pellets is closely linked to the variations of the biomass elemental and chemical composition with direct influence on the biomass thermal decomposition and on the composition of the axial flow of volatiles. The thermal decomposition of wheat straw pellets developed with the lower heat output, limited CO_2 formation, higher levels of CO and H_2 emission, with the higher average values of NO_x emission and higher air excess ratio in the products (Table 1). The higher air excess ratios at thermo chemical conversion of biomass pellets evidence that the process of wheat straw thermo chemical conversion can be improved by optimizing the conditions of the thermal decomposition of pellets and swirling flow dynamics.

Table 1

The main combustion characteristics of biomass samples

Biomass type	P_{sum}, **kW**	Q_{sum}, **MJ·kg^{-1}**	**CO_2, %**	**CO, ppm**	**NO_x, ppm**	**Eff., %**	α
Batch size pilot device							
wood	1.92	11.89	13.2	120	67	87.35	1.71
wheat straw	1.39	8.92	12.2	183	250	88.9	1.85
Technological device							
wood	10.59	11.66	14.03	25.67	81.93	84.8	1.69
wheat straw	6.81	8.12	10.58	269.8	307.7	82.9	2.27

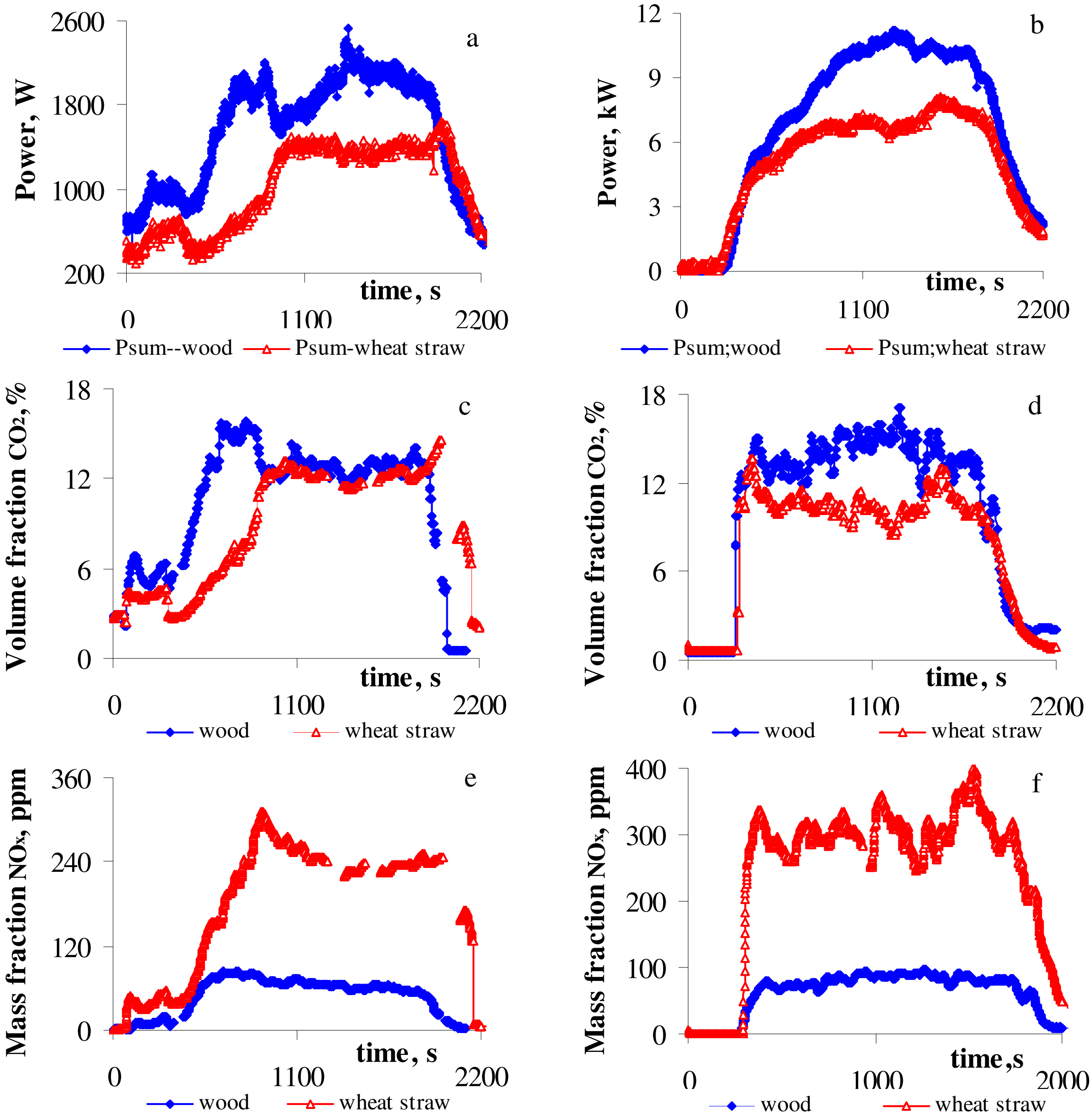

Fig. 5. **Kinetics of the heat output and composition of the products at thermo chemical conversion of wood and wheat straw pellets in the small-scale pilot device (a, c, e) and in the technological device (b, d, f)**

Conclusions

1. The development of combustion dynamics at thermo chemical conversion of biomass pellets is determined by the complexity of swirling flow dynamics, which depends on the formation of upstream and downstream swirling air flows and axial flow of volatiles produced at thermal decomposition of biomass pellets.
2. The swirl-enhanced formation of the upstream flow formation is determined by the secondary air supply rate and is highly responsible for the enhanced mixing of the axial flow of volatiles and formation of the axial reaction zone.
3. The enhanced cold upstream swirling flow formation with cooling of the biomass surface affects the thermal decomposition of biomass pellets promoting delay of the ignition and combustion of volatiles with a correlating decrease of the produced heat output. In order to ensure more effective and cleaner heat output, improvement of the biomass gasification and combustion conditions must be provided by optimizing the air supply rate and swirling flame flow dynamics.
4. Comparison of the gasification/combustion characteristics for wood and wheat straw pellets allows conclude that wood pellets with higher carbon content and heating value provides a more

intensive release of volatiles with improvement of the combustion conditions and determining a higher content of CO_2 in the products, higher temperature of the flame reaction zone and higher amount of produced heat energy. Moreover, the lower nitrogen content in wood pellets results in lower NO_x content in the products determining cleaner heat energy production.

Acknowledgments

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References

1. Cheng R.K., Yegian D.T., Miyasato M.M., Samuelsen G.S., Benson C.E., Pellizzari R. & Loftus P. Scaling and development of low-swirl burners for low-emission furnaces and boilers, Proceedings of the Combustion Institute, vol. 28, 2000, pp. 1305-1313.
2. Gupta A.K., Lilley D.G., Syred N. Swirl Flows, Abacus Press, UK, 1984, 588 p.
3. Syred N. and Beer J.M. Combustion in Swirling Flow: A Review. Combust Flame, vol. 23, 1974, pp. 143-201.
4. Abricka M., Barmina I., Valdmanis R., Zake M. Experimental and numerical study of swirling flows and flame dynamics, Latvian Journal of Physics and Technical Science, vol. 51, 2014, pp. 25-40.
5. Barmina I., Lickrastina A., Zake M., Arshanitsa A., Solodovnik V., Teysheva G., Experimental study of thermal decomposition and combustion of lignocellulosic biomass pellets, Latvian Journal of Physics and Technical Sciences, Vol. 50, N3, 2013, pp. 35-49.