CHEMICAL ENGINEERING TRANSACTIONS

VOL. 39, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong

ISBN 978-88-95608-30-3; **ISSN** 2283-9216

DOI: 10.3303/CET1439255

The Effect of Birch-Bark Addition on the Elemental Composition and Combustion Characteristics of Different Types of Biomass Pellets

Inesa Barmina[a], Maija Zake[a], Raimonds Valdmanis[a], Alexandr Arshanitsa[b], Valentin Solodovnik[b], Galina Telysheva[b]

[a]Institute of Physics, University of Latvia, 32 Miera Street, Salaspils-1, LV-2169, Latvia
[b]Latvian State Institute of Wood Chemistry; 27 Dzerbenes Street, Riga, LV-1006, Latvia
mzfi@sal.lv

The main aim of this paper is improvement of the combustion characteristics of different biomass types (wood and agriculture residues, herbaceous biomass) by adding birch outer bark or bark (up to 20 %) to raw biomass with densification of the produced mixture. Produced pellets are experimentally characterized by elemental analysis determining the composition, higher and lower heating values, bulk and energy density. The results of elemental analysis of the pelletized mixture show that for all biomass types an addition of birch outer bark or birch bark to raw biomass results in an increase of the carbon content and heating values of produced samples relative to original biomass pellets with direct impact on the gasification and combustion characteristics of swirling flame flow. A more pronounced increase of the heating values (up to 18.8 %) after addition of outer birch bark or bark to raw biomass (20 %) is detected for wheat straw pellets indicating a lower carbon and lignin content in raw biomass. Less effective variations of the heating values at birch bark or outer birch bark addition (up to 13 %) are detected for woody biomass – grey alder pellets with a higher carbon and lignin content in raw biomass. In accordance with the variations of the elemental composition and heating values of the produced samples with birch bark or birch outer bark addition, a correlating increase of the heating values, heat power and total produced heat energy at thermo-chemical conversion of pelletized mixtures downstream the swirling flame flow with the high level of the correlation coefficient (up to 96 %) are observed. Moreover, the increase of the total amount of the produced heat energy results in the correlating increase of the volume fraction of CO_2 and combustion efficiency, while the air excess, the mass fraction of CO and free hydrogen in the products decrease indicating that the birch-outer bark or bark addition to biomass promotes the enhanced combustion of the volatiles and can be used for more effective and cleaner heat energy production at thermo-chemical conversion of different biomass types.

1. Introduction

Biomass is one of the major renewable energy resources today, contributing approximately to 10-14 % of the world annual energy consumption (Harun and Afzal, 2010). Woody biomass represents the most available and usable renewable energy source determining up to 40 % of the biomass energy potential (Zhang et al., 2011). As a result of the increased use of wood for energy production during last decades, the supply of wood residues to energy producers became insufficient. Therefore, other types of lignocellulosic biomass, such as straw, reed canary grass, energy crops, barks, as well as their mixtures are being tested as the energy sources to produce fuels (bio gas, bio oil, briquettes, pellets, etc.) which are suitable for clean and effective energy production The useful energy that can be produced at thermo-chemical conversion of biomass (pyrolysis, gasification, combustion) is strongly dependent on its chemical composition (the content of cellulose, hemicellulose and lignin) and elemental composition (carbon, hydrogen, nitrogen, sulphur, moisture and ash content) determining the heating value of biomass and the composition of the products (Sheih and Fan, 1982; Stepanov, 1995). Woody biomass typically has a

Please cite this article as: Barmina I., Zake M., Valdmanis R., Arshanitsa A., Solodovnik V., Telysheva G., 2014, The effect of birch-bark addition on the elemental composition and combustion characteristics of different types of biomass pellets, Chemical Engineering Transactions, 39, 1525-1530 DOI:10.3303/CET1439255

higher content of cellulose (up to 40-45 %) and lignin (20-28 %), determining a higher carbon content and a higher heating value of woody biomass, while agriculture residues and herbaceous biomass have a higher content of hemicellulose (up 30 %) with a relatively low lignin content (7-17 %), lower carbon content and heating value (Wes, 1995; Bridgman et al., 2008; Vassilev et al., 2012). The experimental study of thermo-chemical conversion of different types of pelletized biomass at swirl-enhanced mixing of the axial flow of the volatiles with air swirl has shown (Barmina et al., 2013) that pellets of agriculture residues or herbaceous biomass with the relatively higher content of thermolabile constituents (hemicellulose and cellulose) and lower content of lignin have a higher rate of thermo-chemical conversion with faster release of the volatiles at relatively low temperatures ranging from 450 K to 500 K, while the lower amount of the produced heat energy is obtained. A more extended thermo-chemical conversion up to the temperature 850 K with a higher value of the produced heat energy is observed for pellets with a higher carbon and lignin content in biomass. Considering the fact that different biomass types have very different elemental and chemical composition determining the variations in rate of their thermo-chemical conversion and produced heat energy, mixtures of different types of raw biomass can be made up selecting the components in order to produce a pelletized mixture with more appropriate characteristics for their thermo-chemical conversion and heat energy production. As for example, an experimental study and analysis of the main characteristics of pelletized samples of herbaceous biomass, woody biomass and their binary mixture showed (Barmina et al., 2012) that the variations of the elemental and chemical composition of the pelletized mixture promote the correlating variations of the thermo-chemical conversion rate determining the formation of the volatiles, transition from flaming to char conversion stage and heat energy production. It should be stressed that the variation of the composition of the biomass mixtures has a decisive influence on the suitability of the mixture for palletisation. Preliminary experimental studies have revealed that the addition of birch outer bark to herbaceous, woody or straw biomass makes it possible to enhance the particle and bulk densities of the pelletized mixture of biomass suggesting that suberin present in high amount (up to 30-40 %) in birch bark and birch outer bark acts as a binding material enhancing the mechanical strength and energy density of the pelletized mixture. Moreover, the addition of birch bark or birch outer bark to herbaceous, woody or straw biomass allows producing pellets with a higher heating value resulting in a higher heat energy production at thermo-chemical conversion of pelletized mixtures. The general objective of this paper is a more detailed study and analysis of the effects of birch bark or birch bark addition (up to 20 %) on the main characteristics of agriculture residues, woody and herbaceous biomass as fuels with the aim to improve the combustion characteristics and heat energy production at thermo-chemical conversion of pelletized mixtures.

2. Experimental setup and procedures

2.1 Biomass granulation, palletisation and main characteristics of produced pellets

The experimental study of the effects of birch bark or birch outer bark addition (up to 20 %) to different biomass types (woody biomass, herbaceous biomass, agriculture residues) on the combustion characteristics starts with an analysis of the effects of birch bark addition on the granulation and densification regimes and main characteristics of a pelletized mixture determining the variations of the elemental composition, heating values, bulk and energy density of the produced samples. A laboratory scale flat die pellet mill KAHL (3.01 kW) was used for pelletizing ground biomass mixes. Prior to the pelletizing tests, all biomass samples were dried by 10-12 %, ground in a Retch SK100 cutting mill (the sieve size 2.0 mm) and mixed using a HTL mixer. The bark birch outer bark was separated by flotation of the ground birch bark in water. The choice of birch bark or birch outer bark as an addition to biomass is due to the high content of suberin – aliphatic saturated and unsaturated carbon C_{18} – C_{22} oxy- and epoxy-acids and betulinol ($C_{30}H_{50}O_2$) present in them. The presence of these constituents reveals the high calorific value of birch outer bark (~34 MJ/kg on DM) and birch bark (~28 MJ/kg on DM), which is much higher in comparison with other plant biomass species (15-20 MJ/kg on DM). Moreover, during granulation of a biomass mixture with a high content of suberin, when the temperature of this biomass mixture approaches to 100 °C, the processes of condensation of suberin with a component of the biomass ligno carbohydrate complex proceeds with the correlating increase of the mechanical resistance of the pelletized biomass produced (Sudakova et al., 2008; Kislicin, 1994). Those birch bark and birch outer bark components can be characterized as multifunctional additives improving the fuel characteristics (heating value, energy density) of pelletized biomass as well as its mechanical characteristics. The main properties of the pelletized mixtures are presented in Table 1.

Table 1: Main characteristics of pelletized biomass mixtures

Biomass	Moisture %	Ash %	C %	O* %	H %	N %	LHV %	Energy density GJ/m^3
Grey alder (G.a.)	6.4	0.90	51.20	41.44	6.03	0.43	17.7	10.6
G.a.+birch outer bark	5.0	0.76	54.90	36.82	7.13	0.39	20.0	13.0
G.a.+birch bark	5.5	0.91	53.59	38.17	6.90	0.43	19.2	12.2
Reed canary grass	7.8	3.39	44.44	44.94	6.61	0.62	14.8	9.8
R.c.g.+birch outer bark	6.1	2.80	49.60	39.95	7.07	0.58	17.2	11.0
R.c.g.+birch bark	7.0	3.02	48.20	41.33	6.85	0.60	16.4	10.8
Wheat straw (W.s.)	9.4	7.11	41.80	44.25	6.15	0.69	13.5	7.0
W.s.+birch outer bark	6.9	5.82	47.50	39.22	6.70	0.76	16.2	11.1
W.s.+birch bark	8.1	6.00	46.10	40.63	6.49	0.78	15.4	10.5
Birch bark	3.7	1.56	61.30	28.98	7.59	0.57	26.4	n/d
Birch outer bark	2.8	2.80	68.30	19.63	8.90	0.37	32.0	n/d

2.2 Pilot device for the combustion of pelletized biofuels

A kinetic study of the combustion characteristics of the pelletized biofuel was carried out using a batch-size pilot device composed of a gasifier and a combustor of internal diameter 60 mm (Barmina et al, 2013). The biomass gasifier is filled with biofuel pellets (m = 230-300 g). To initiate the thermo-chemical conversion of pellets, the propane flame flow as an external heat energy source was used with the average heat energy supply rate 1.2 kJ/s. Below the layer of biofuel pellets the primary air supply at the average rate 0.5-0.6 g/s was introduced to support the biomass gasification developing at the average air excess ratio α ≈ 0.5-0.7. To provide the enhanced mixing of the axial flow of the volatiles with air and complete the combustion of the volatiles at the average air excess ratio in the flame reaction zone α ≈ 1.8-2.3, the secondary swirling air was supplied into the bottom of the combustor through the tangential air nozzles at the average air supply rate 1-1.2 g/s and air swirl number S ≈ 0.65-0.7. The formation of the flame velocity profiles at different distances (L/D) from the secondary swirling air nozzle determining the development of combustion dynamics downstream the combustor with the peak value of the flame temperature close to the flame axis (R=0) is shown in Figure 1.

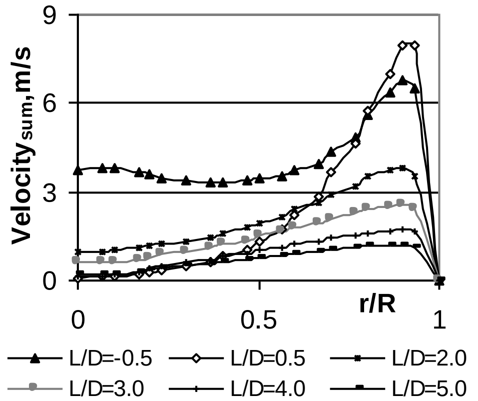

Figure 1: The formation of the swirling flow velocity profiles downstream the combustor

3. Results and discussion.

The experimental study of the effect of addition of birch bark or birch outer bark on the gasification and combustion characteristics of raw biomass under nearly equal gasification and combustion conditions in the swirling flame reaction zone was carried out for selected raw feedstock – grey alder biomass (G.a.), reed canary grass (r.c.g.) and wheat straw (w.s.) biomass and their mixtures with birch bark (bb.) and birch outer bark (b.ob.). The main characteristics of these biomass samples are listed in Table 1. The main combustion characteristics of these biomass samples - the average temperature of the flame reaction zone, the average and peak values of heat power, produced heat energy, peak values of $CO_{2\ max}$ with the minimum value of CO_{min} at flaming combustion of the volatiles, the average values of nitrogen oxides and combustion efficiency for the produced samples of pelletized mixtures are listed in Table 2.

Table 2: The main combustion characteristics of the pelletized biomass samples with addition of 20 % birch bark or birch outer barks to feedstock (grey alder, reed canary grass or wheat straw)

Biomass	dm/dt g/s	P_{av} /P_{max} kW	Q_{sum} MJ/kg	T_{av} K	CO_{2max} %	CO_{min} ppm	NO_{xav} ppm	Eff_{av} %
Grey alder (G.a)	0.160	1.5/2.0	10.90	1,344	11.1	56	142	84.2
G.a.+birch bark	0.137	1.45/1.87	11.38	1,097	13.2	43	166	91.0
G.a.+birch outer bark	0.140	1.6/2.1	13.17	1,005	13.5	54	199	91.5
Reed canary grass (R.c.g.)	0.149	1.2/1.5	9.50	1,050	11.0	973	171	87.0
R.c.g.+birch bark	0.104	1.19/1.78	10.80	1,050	10.7	130	226	89.0
R.c.g.+birch outer bark	0.137	1.25/1.7	10.27	1,190	13.8	32	195	90.9
Wheat straw (W.s.)	0.210	0.9/1.16	7.90	1,190	15.2	221	214	75.0
W.s.+birch bark	0.120	1.14/1.6	9.95	1,090	11.5	71	288	90.0
W.s.+birch outer bark	0.115	1.1/1.52	9.74	930	12.3	43	311	91.0

As follows from Tables 1 and 2, the addition of birch barks or birch outer barks to biomass for all feedstock results in an increase of the heating value of the pelletized samples with the correlating linear increase of the produced heat energy and heat power at their thermo-chemical conversion with the relatively high correlation coefficient R^2 = 0.96. Moreover, the addition of birch bark or birch outer bark advanced the increase of the combustion efficiency completing the combustion of the volatiles, increasing the volume fraction of CO_2 in the products with the correlating decrease of the mass fraction of CO in the products. The kinetic study of the heat power and composition of the products showed that the birch bark or birch outer bark addition to the biomass resulted in variations of the kinetics of the flame temperature, heat power and composition of the products at different stages of the thermo-chemical conversion of this pelletized biomass. The addition of birch bark or birch outer bark promoted the enhanced transition from flaming combustion of the volatiles at the primary stage of thermo-chemical conversion ($t < 1,000$ s) to the char conversion stage occurring at $t > 1,000$ s, with a more extended combustion of the biomass samples (Figure 2). The more pronounced flaming combustion with the correlating increase of the CO_2 volume fraction was observed for samples with a higher content of hemicellulose and with a reduced carbon and lignin content in the feedstock, i.e. for the samples of wheat straw. The addition of birch bark or birch outer bark to the wheat straw biomass with the correlating increase of carbon in the pelletized mixture provided the formation of the more extended char conversion stage lasting up to 3,000 s (Figure 2-b). Moreover, the increased nitrogen content in the mixture of wheat straw with birch bark or birch outer bark (Table 1) contributed to the correlating increase of the average value of the NO_x mass fraction in the products (Table 2). As follows from Table 2, for all samples the addition of birch bark or birch outer bark to the feedstock has resulted in the decrease of CO emission at the final char conversion stage, as it is shown for grey alder and its pelletized mixtures (Figure 2-d).

4. Conclusion

In this study, experiments were carried out providing palletisation of different biomass types – woody biomass (grey alder), herbaceous biomass (R.c.g.) and agriculture residues (wheat straw) and their mixtures added with birch barks and birch outer barks (20 %) relevant for use as fuels. The effect of the birch bark and birch outer bark addition to feedstocks on the elemental composition, heating values, energy density and combustion characteristics at swirling combustion was studied and analysed. Correlations were determined between the variation of the main characteristics of biomass samples and their combustion characteristics in the swirling flame flow with swirl enhanced mixing of the volatiles and air. For all samples with the addition of birch bark or birch bark to the feedstock, the increase in carbon content and heating value was observed resulting in the correlating increase of the heat power and produced heat energy. The addition of birch bark or birch outer bark to biomass results in more complete combustion of the volatiles with the more extended char conversion stage. A more pronounced effect of the birch bark or birch outer bark addition was observed for herbaceous biomass or agriculture residues, which have the higher content of hemicellulose, the reduced content of lignin in feedstocks and lower heating values. No significant difference was observed between the heating values of the mixtures added with birch outer bark or birch bark to the feedstocks, whereas the birch outer bark addition to biomass resulted in a more significant increase of the mechanical durability of pellets.

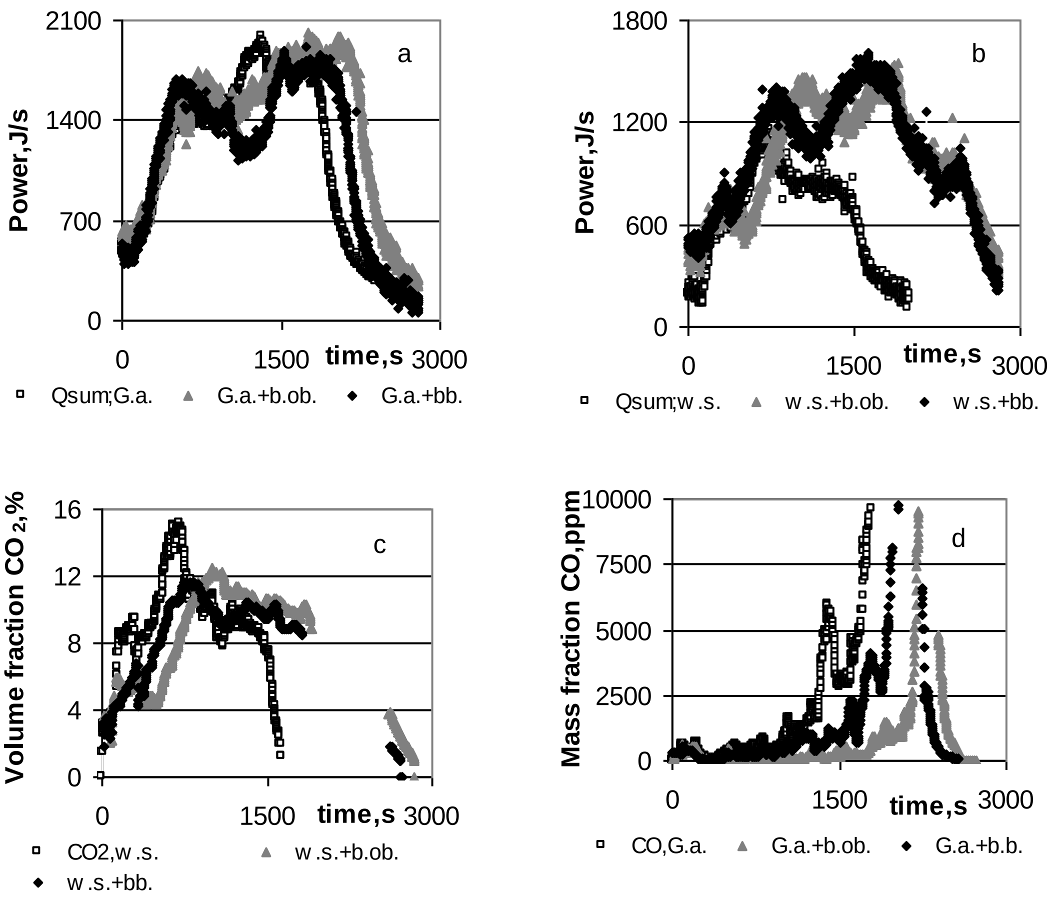

Figure 2: The effect of birch bark and birch outer bark addition to biomass on the time-dependent variation of heat power and composition of the products for wheat

Acknowledgements

The authors would like to express their gratitude for the financial support from the Latvian Research Cooperation Project of Latvian Council of Science Nr 623/2014.

References

Barmina I., Lickrastina A., Zake M., Arshanitsa A., Solodovnik V., Telysheva G., 2013. Experimental study of thermal decomposition and combustion of lignocellulosic biomass pellets. In: Latvian Journal of Physics and Technical Sciences, N3, 35-48.

Barmina I., Lickrastina A., Zake M., Arshanitsa A., Solodovnik V., Telysheva G., 2012. Effect of main characteristics of pelletized renewable energy resources on combustion characteristics and heat energy production. In: Chemical Engineering Transactions, 29, 901-906.

Belderok H. J. M., 2007. Experimental investigation and modeling of the pyrolysis of biomass, Master Thesis, Eindhoven University of Technology, 2-75.

Bridgman T.G., Jones J.M., Shield I., Wiliams P.T., 2008, Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties, Fuel, 87, 844-856.

Harun N.Y., Afzal M.T., 2010, Thermal decomposition of forest residue. Journal of Applied Science, 10, 1122-1127.

Kislicin A., 1994. Extractives of birch bark: extraction, composition, properties and application (in Russian). In: Wood chemistry, 3, 3-28.

Sheih J.H., Fan L.T., 1982, Estimation of energy (enthalpy) and exergy (availability) contents in structurally complicated materials. Energy Sources, 6(1), 1046.

Stepanov V.S., 1995, Chemical energies and exergies of fuels, Energy, 20(3), 235-242.

Sudakova A I., Kuznetsov B., Garyntseva N., Pavlenko N., and Ivanchenko N., 2008. Functional and thermal analysis of suberin isolated from birch bark (in Russian). Journal of Siberian Federal University. Chemistry 4 (2008-1) 355-362.

Vassilev S.V., Baxter D., Andersen L.K., Vassileva C.G., Morgan T.J., 2012, An overview of the organic and inorganic phase composition of biomass, Fuel, 94, 1-33.

Wes H., 2005, An Assessment of Biomass Feedstock and Conversion Research Opportunities, Technical assessment Report, Standford University, 1-22.

Zhang X., Yang W., Blasiak W., 2011, Modelling study of woody biomass: Interactions of cellulose, hemicellulose and lignin, Energy Fuels, 25, 4786-4795.