CHEMICAL ENGINEERING TRANSACTIONS
VOL. 52, 2016

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

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

ISBN 978-88-95608-42-6; **ISSN** 2283-9216
DOI: 10.3303/CET1652186

Combustion Characteristics of Modified Plant Biomass Pellets

Inesa Barmina[a], Raimonds Valdmanis[a], Maija Zake[a], Alexandr Arshanitsa[b], Yegor Akishin[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 objective of this experimental study is to investigate the thermo-chemical conversion of modified biomass pellets of different origin (spruce, aspen and wheat straw). The modification of biomass pellets includes the microwave (mw) pre-treatment of these biomass samples and spraying of waste cooking and mineral oils on the surface of the mw pre-treated pellets. The initial and modified pellets were characterized in terms of the elemental composition, heating values, energy density (bulk), moisture, and ash contents. The results show that for all biomass types mw pre-treatment as well as spraying of waste oils on the surface of pre-treated pellets results in an increase of the carbon content and heating values of the samples relative to the original biomass pellets with direct impact on the gasification and combustion characteristics of these pellets. The experimental study of the effect of biomass pellets modification on their gasification/combustion characteristics includes complex time-dependent measurements of the biomass weight loss rate, temperature, heat production rate, combustion efficiency and products composition. Due to the variations of the elemental composition and heating values of the produced biomass pellets, a correlating increase of the volume fraction of CO_2 and produced heat energy at thermo-chemical conversion of biomass was observed. The results of the complex experimental measurements allow to conclude that the proposed modification of plant biomass pellets including their mw pre-treatment with further spraying of waste oils is an effective tool to convert biomass into a fuel with improved combustion characteristics.

1. Introduction

Highly intensive use of the fossil fuels (natural gas, coal, petroleum) for energy production leads to the depletion of fossil fuels reserves and increases the carbon dioxide (CO_2) concentration in the Earth's atmosphere (Nussbaumer, 2010). One of the available and usable renewable fuels with carbon-neutral sources of energy is biomass. However, different types of biomass (wood, straw, bark) have different contents of hemicellulose, cellulose, lignin with the corresponding difference in their elemental and chemical composition, ash content and heating values. Woody biomass typically has a higher content of cellulose (by ~ 45 %) and lignin (by ~ 25 %) with a higher carbon content and a higher heating value, whereas straw biomass has a higher content of hemicellulose (by ~ 30 %) with a relatively low lignin content (15 %), lower carbon content and heating value (Barmina et al., 2013a). The variations of the elemental and chemical composition of biomass promote the correlating variations of combustion characteristics of different types of biomass. One of the ways to improve the fuel properties of plant biomass is the biomass pelletization and torrefaction (Uslu et al., 2008). The advantages of both pelletization and torrefaction technologies were joined by authors using the microwave pre-treatment of wood and wheat straw pellets, which was realized in a rotated microwave reactor of original design (Arshanitsa et al., 2016a). The comparative study of the modification of the chemical composition of the wood matrix by thermal pre-treatment at different temperatures using the microwave pre-treatment and convective heating has clearly revealed a non-thermal promoting effect of the microwave pre-treatment on the condensation processes of the lignocellulosic matrix in a temperature range of 510 − 550 K (Arshanitsa et al., 2016b).

Please cite this article as: Barmina I., Valdmanis R., Zake M., Arshanitsa A., Akishin Y., Telysheva G., 2016, Combustion characteristics of modified plant biomass pellets, Chemical Engineering Transactions, 52, 1111-1116 DOI:10.3303/CET1652186

Moreover, the microwave pre-treatment of lignocellulosic biomass results in an increase of the biomass heating value and provides greater homogeneity of the biomass composition with a higher heat output at thermo-chemical conversion of biomass in comparison with raw biomass (Barmina et al., 2013b). Due to the decrease of the biomass density, a less pronounced effect of the microwave pre-treatment on the biomass energy density was observed. The use of motor or vegetable oils as additives for the wood pellet production has a negligible effect on the heating value of the produced pellets (Tarasov et al., 2013). Oppositely, a significant growth of the heating values and energy density of the microwave pre-treated pellets has been achieved by their further pre-processing with waste oils (Arshanitsa et al., 2016a). The general objective of this paper is the experimental study of the effects of biomass pellets modification, including microwave pre-treatment with further spraying of waste cooking and mineral oils on the surface of the mw pre-treated pellets, on their gasification/combustion characteristics with the aim to improve the combustion characteristics and increase the heat energy production at thermo-chemical conversion of these biomass pellets.

2. Experimental setup and procedures

2.1 The main characteristics of biomass pellets

The commercial spruce fuel pellets (d = 8.0 mm) and fuel pellets (d = 6.0 mm) produced by pelletizing ground wheat straw and debarked aspen wood in a laboratory mill KAHL-14175 (3.0 kW) were used as a material for investigations. Each of pellet batches was pre-treated in a rotated microwave reactor (1.3 kW) at the temperatures 520 K (wood pellets) and 500 K (wheat straw pellets). Waste cooking and mineral oils were sprayed onto the surface of the mw-pretreated spruce pellets in a dosage of 15 %. The microwave treatment and oil spraying procedures are presented in details elsewhere (Arshanitsa et al., 2016a).

The C, H, N and ash contents in biomass were measured according to LVS EN 15104:2011, LVS EN 14775:2010 standards correspondingly. The data indicated on biomass dry basis are presented in Table 1. The higher heating values (HHV) of the pellets were calculated by a regression equation proposed by Friedl et al, 2005. The energy density was calculated by multiplying the HHV and bulk density values of the pellets.

Table 1: Main characteristics of initial and modified pellets

Biomass	Moisture %	Ash %	C %	O %	H %	N %	HHV MJ/kg	Energy density MWh/m^3
Spruce (B)	7.4	0.3	49.16	45.15	5.25	0.14	17.95	12.02
Aspen (F)	7.5	1.4	48.24	44.89	5.24	0.23	17.72	11.70
Wh. straw (A)	6.5	3.7	47.40	42.84	5.28	0.74	17.54	12.27
Mw-pre-treated								
Spruce (B-T)	≤ 1	0.55	55.45	38.85	5.00	0.15	21.72	12.54
Aspen (F-T)	≤ 1	1.6	54.55	38.68	4.95	0.22	21.32	12.36
Wh. straw (A-T)	≤ 1	4.2	51.72	38.11	5.14	0.83	20.35	12.48
Mw-pre-treated with spraying of waste oils (MO - motor oil, CO - cooking oil)								
Spruce (B-T/WMO)	≤ 1	0.55	59.30	34.13	5.86	0.16	24.00	16.00
Spruce (B-T/WCO	≤ 1	0.55	58.77	34.17	6.37	0.14	24.20	16.10

2.2 The pilot device for the combustion of pelletized biomass

The effect of the biomass pellets modification on their gasification/combustion characteristics was experimentally studied using a small-scale experimental device with a heat output up to 2 kW (Barmina et al, 2015). The experimental device is composed of a biomass gasifier and a combustor of inner diameter of 60 mm. The biomass gasifier is filled with biomass pellets (m = 240 - 300 g). Additional heat energy (1.2 kJ/s) is supplied by the propane flame flow (2) into the upper part of the biomass layer to initiate the thermo-chemical conversion of biomass pellets. The primary air with the 0.57 g/s average rate and average air excess ratio α = 0.3 - 0.5 is supplied below the layer of biomass pellets to support the process of biomass gasification. The secondary swirling air with the average air supply rate 0.6 g/s and swirl number S < 0.6 is supplied to the bottom of the combustor.

The experimental study of the influence of the biomass pellets modification on their gasification/combustion characteristics combines complex measurements of the biomass weight loss rate, flame temperature, produced heat energy (Q_{sum}) and products composition. The flame temperature was measured by Pt/Pt-Rh thermocouples. The heat output was estimated from the calorimetric measurements of the cooling water flow along with online data registration using the PC-20 TR plate. An infrared FTIR spectrometer Varian 640-IR and a gas analyzer Testo 350XL (CO, CO_2, H_2 and NO_x) were used to control the product composition at biomass thermo-chemical conversion. The measurements of infrared band absorption of the components CO

(2,169 cm^{-1}), CH_4 (3,017 cm^{-1}), C_2H_2 (729 cm^{-1}) and C_2H_4 (949 cm^{-1}) were used for spectral analysis of gases produced at the biomass thermal decomposition. The weight loss rate (dm/dt) of biomass at its thermo-chemical conversion was measured using a test facility which consists of a moving rod equipped with a pointer.

3. Results and discussion

The experimental study of thermo-chemical conversion of biomass pellets before and after their modification reveals that the mass conversion of the biomass pellets is a multistage process, including the steps of unsteady heating, drying, thermal decomposition (gasification) of biomass and burnout of combustible gases and determining the time-dependent variations of the biomass weight loss and weight loss rates (Figure 1(a)), which depend on the main characteristics of the biomass pellets (Table 1). The measurements of the composition of volatiles close to the surface of the biomass pellets using FTIR spectroscopy showed that the weight loss rate of the biomass pellets correlated with an increase of the IR band absorption of hydrocarbons C_xH_y, CH_4 and CO with the highest release of hydrocarbons at the thermo-chemical conversion of spruce pellets with the highest lignin content (Figure 1(b)). Besides, as follows from Tables 1 and 2, the higher carbon content and the higher heating value of the spruce pellets provide the higher average volume fraction of CO_2 in the products and the higher heat output at the thermo-chemical conversion of spruce pellets, whereas the higher nitrogen content in wheat straw pellets contributes to an increase of the average value of the NO_x mass fraction in the products.

Table 2: Main gasification/combustion characteristics of the modified biomass samples.

Biomass	dm/dt g/s	CH_4 rel.un.	CO rel.un.	C_2H_2 rel.un.	Q_{sum} MJ/kg	CO_{2av} %	CO_{av} ppm	NO_{xav} ppm	$Eff._{av}$ %
Spruce (B)	0.19	0.0063	0.032	0.021	11.89	13.21	121	67.2	87.3
Aspen (F)	0.16	0.0228	0.058	0.054	9.16	12.00	792	102.8	87.0
Wh. straw (A)	0.15	0.0088	0.053	0.031	8.92	11.94	250	250.7	88.8
Mw-pre-treated biomass									
Spruce (B-T)	0.22	0.028	0.029	0.015	14.44	15.19	375	75.3	87.8
Aspen (F-T)	0.21	0.0556	0.125	0.089	10.96	15.31	758	108.5	87.6
Wh. straw (A-T)	0.17	0.0368	0.104	0.058	11.25	15.17	300	262.4	87.6
Mw-pre-treated with spraying of waste oils (MO - motor oil, CO - cooking oil)									
Spruce (B-T/WMO)	0.20	0.086	0.128	0.181	15.37	15.30	179	88.9	87.0
Spruce (B-T/WCO	0.22	0.077	0.127	0.193	15.80	16.10	250	73.6	87.7

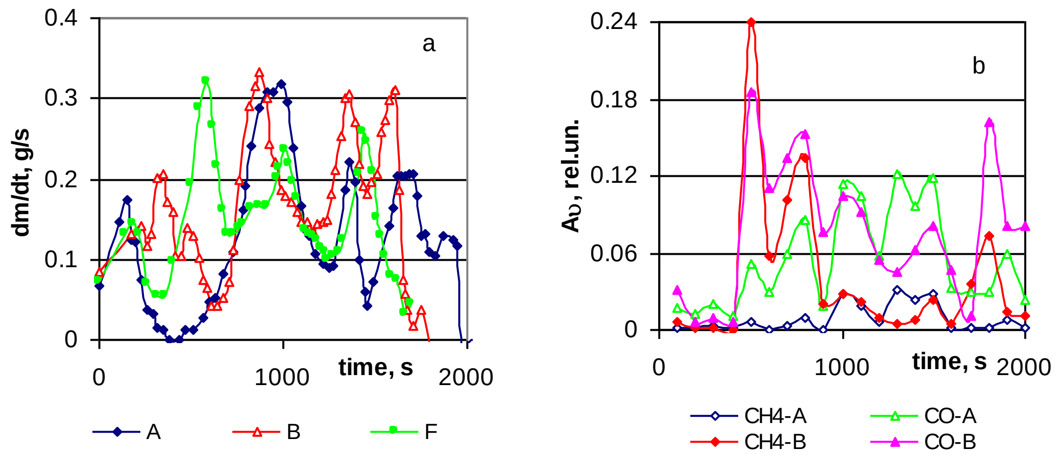

Figure 1: Time-dependent variations of the weight loss rates (a) and CH_4, CO bands absorption (b) at thermo-chemical conversion of different biomass samples: A- wheat straw pellets; B- spruce pellets; F- aspen pellets

The mw pre-treatment of spruce, aspen and wheat straw pellets first of all results in variations of their elemental composition with an increase of the carbon content and a correlating increase of HHV, while the content of oxygen in the biomass decreases (Table 1). The variations of the elemental composition and HHV of the mw pre-treated biomass samples determine the faster thermal decomposition and gasification of biomass pellets with the faster ignition and more complete combustion of the volatiles (Table 2). The comparison of the weight loss rates at the thermo-chemical conversion of the mw pre-treated and original pellets evidences of the higher weight loss rate for the pre-treated aspen (by ~ 33 %) and wheat straw (by ~ 13 %) samples with the lowest lignin content in the biomass (Figure 2-a).

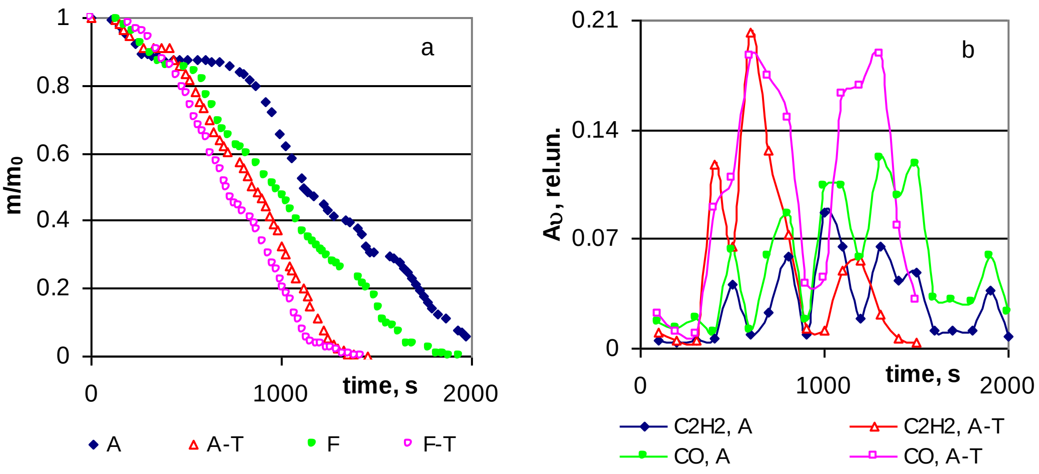

Figure 2: Effect of mw pre-treatment on the time-dependent variations of the weight loss of biomass pellets (a) and C_2H_2, CO bands absorption (b): A- wheat straw pellets; A-T- mw pre-treated wheat straw pellets; F- aspen pellets; F-T- mw pre-treated aspen pellets.

The variations of the mass loss rates during the thermo-chemical conversion of the pre-treated biomass pellets promote the increase of the content of combustible gases (CO, C_2H_2) in the volatiles (Figure 2-b) with a correlating decrease of the average values of the air excess ratio in the reaction zone by about 20-30 % so improving the combustion conditions and increasing the flame temperature by about 8-12 %. Moreover, as follows from Tables 1 and 2, the effect of mw pre-treatment for all biomass samples results in an increase of the carbon content and heating value of the biomass samples with a correlating increase of the produced heat energy and volume fraction of CO_2 in the products. A more pronounced effect of mw pre-treatment on the combustion of biomass pellets with an increase of the average values of the produced heat energy by about 26 % and CO_2 volume fraction by about 27 % was observed for wheat straw pellets. The similar content of nitrogen in the mw pre-treated and in the original pellets makes it possible to conclude that the effect of mw pre treatment on the nitrogen content can be neglected (Table 1). Therefore, the observed increase of the average values of the NO_x mass fraction in the products for the mw pre-treated samples by about 5-12 % can be related to the improvement of the combustion conditions in the flame reaction zone (Table 2).
The effect of the waste oil additives on the combustion behavior was studied with mw-treated spruce pellets. Further acceleration of the ignition process is observed by the spaying of waste oils (cooking or motors) on the surface of the previously mw pre-treated spruce pellets (about 15 % of the biomass weight). The volatile products at the gasification of the oil-sprayed pellets contain a higher amount of combustible hydrocarbons if compared with the products at the gasification of original and mw pre-treated pellets (Table 2). As a result, the air excess ratio in the reaction zone decreases by about 19 % improving the combustion conditions and increasing the temperature in the reaction zone by about 10 %. The improvement of the combustion conditions has increased the CO_2 volume fraction in the products and the total heat output for the sprayed spruce pellets (Figure 3, Table 2). Hence, the results of the complex experimental measurements allow to conclude that the proposed modification of plant biomass pellets including their mw pre-treatment with further spraying of waste oils is an effective tool to convert a biomass into fuel with improved combustion characteristics.

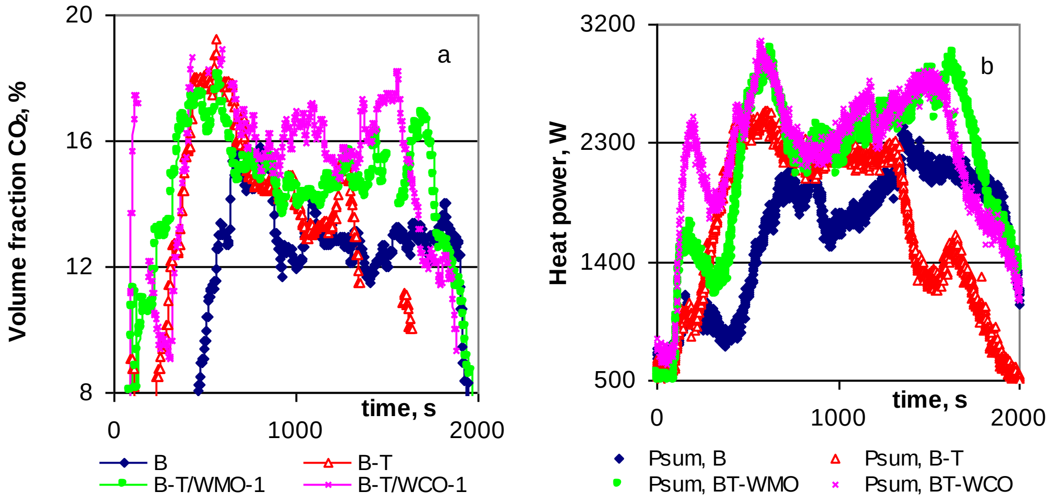

Figure 3: Effect of mw pre-pretreatment on the time-dependent variations of the CO_2 volume fraction and heat power production rate: B - spruce; B-T - mw pre-treated spruce; B-T/WMO - mw pre-treated and spilling of waste cooking spruce pellets; B-T/WCO - mw pre-treated and spilling of mineral oils spruce

4. Conclusions

The following conclusions can be drawn from the results of the experimental study:
1. The mw pre-treatment of biomass (spruce, aspen and wheat straw) pellets results in variations of the elemental composition of biomass pellets, determining an increase of the carbon content by about 6-13 % and that of heating values of the produced samples by about 12 - 14 % relative to the original biomass pellets with direct impact on the gasification and combustion characteristics of these biomass samples.
2.The faster thermal decomposition and gasification of the pre-treated samples results in improvement of the combustion conditions and in a more complete combustion of the pre-treated pellets, increasing thus the average values of CO_2 in the products by about 15 - 27 % and the produced heat energy by about 19 - 26 %.
3. The more pronounced effect of mw pre-treatment on the combustion characteristics was observed for wheat straw pellets with lower content of lignin.
4. Spraying of waste oils (cooking or motors) on the surface of pre-treated spruce pellets leads to an additional increase of the carbon content by about 7 % and of the heating values of the produced pellets by about 10 %. The higher content of hydrocarbons in the gasification products for the oil-sprayed pellets provides improvement of the combustion conditions and increases the flame temperature, which results in a more complete combustion of combustibles and in a higher volume fraction of CO_2 in the products, increasing so the produced heat energy by about 28 - 30 %.
5. The results of the complex experimental measurements allow to conclude that the proposed modification of plant biomass pellets with their mw pre-treatment and further spraying of waste oils is an effective tool to convert a biomass into fuel with improved combustion characteristics.

Acknowledgements

The authors would like to express their gratitude for the financial support from the Latvian Research Cooperation Project of the Latvian Council of Science No 623/2014.

References

Arshanitsa A., Akishin Y., Zile E., Dizhbite T., Solodovnik V., Telysheva G., 2016a, Microwave treatment combined with conventional heating of plant biomass pellets in a rotated reactor as a high rate process for solid biofuel manufacture, Renewable Energy, 91, 386-396.

Arshanitsa A., Dizhbite T., Bikovens O., Pavlovich G., Andersone A., Telysheva G., 2016b, Effects of microwave treatment on the chemical structure of lignocarbohydrate matrix of softwood and hardwood, Energy Fuels (Web), DOI:10.10 21/acs.energyfuels.5b02462 .

Barmina I., Lickrastiņa, Zake M., Arshanitsa A., Telysheva G., Solodovnik V., 2013a, Experimental study of thermal decomposition and combustion of lignocellulosic biomass pellets, Latvian Journal of Physics and Technical Sciences, 50(3), 35-48.

Barmina I., Lickrastina A., Valdmanis J., Valdmanis R., Zake M., Arshanitsa A., Telysheva G., Solodovnik V., 2013b, Effect of microwave pre-processing of pelletized biomass on its gasification and combustion, Latvian Journal of Physics and Technical Sciences, 50(4), 34-47.

Barmina I., Kolmickovs A., Valdmanis R., Zake M., 2015, Combustion Dynamics of Swirling Flame at Thermo Chemical Conversion of Biomass, Chemical Engineering Transactions, 43, 1-6.

Friedl A., Padouvas H., Rotter H., Varmuza K., 2005, Prediction of heating values of biomass fuel from elemental composition, Anal Chim Acta, 544, 191–198.

Nussbaumer T., 2008, Biomass combustion in Europe: Overview on technologies and regulations, Final Report 08-03, NYSERDA, 1-97.

Tarasov D., Shahi C., Leitch M., 2003, Effect of Additives on Wood Pellet Physical and Thermal Characteristics: A Review Article, ISRN Forestry, Article ID 876939, 1-6, DOI:10.1155/2013/876939

Uslu A., Faaij A.P.C., Bergman P.C.A., 2008, Pre-treatment technologies, and their effect on international bioenergy supply chain logistics, Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation, Energy, 33, 1206–1223.