COMBUSTION GASES AND HEAT RELEASE ANALYSIS DURING FLAME AND FLAMELESS COMBUSTION OF WOOD PELLETS

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Abstract

With the growing prices of fossil fuels, alternative fuels produced of biomass come to the fore. They are made of waste materials derived from the processing of wood and wood materials. The main objective of this study was to analyse the fire-technical characteristics of wood pellets. The study analysed three dust samples acquired from wood pellets made of various types of wood biomass. Wood pellet dust is produced when manipulating with pellets. During this process a potentially hazardous situations may occur. Biomass is chemically composed mostly of hemicellulose, cellulose and lignin. During straining of the biomass by heat flux, combustion initiation occurs. Also, there was a change in the composition of material throughout combustion gases production, and the amount of heat generated by a flame or flameless combustion. Measurement of fire characteristics was conducted according to ISO 5660-1 standard using a cone calorimeter. Two samples of wood pellet dust were tested under the heat flux of 35 $kW.m^{-2}$ and 50 $kW.m^{-2}$. The process of combustion, the time to ignition, the carbon monoxide concentration and the amount of released heat were observed.

Key words

biomass, heat release rate, flame combustion, flameless combustion

INTRODUCTION

In chemical terms, wood is best defined as a three-dimensional biopolymer composite composed of an interconnected network of cellulose, hemicelluloses, and lignin with minor amounts of extractives and inorganics. The major chemical component of a living tree is water, but on a dry-weight basis, all wood cell walls consist mainly of sugar-based polymers (carbohydrates, 65–75 %) that are combined with lignin (18–35 %). Overall, dry wood has an elemental composition of about 50 % carbon, 6 % hydrogen, 44 % oxygen, and trace amounts of inorganics. Simple chemical analysis can distinguish between hardwoods (angiosperms) and softwoods (gymnosperms), but such techniques cannot be used to identify individual tree

species because of the variation within each species and the similarities among species. In general, the coniferous species (softwoods) have a higher cellulose content (40–45 %), higher lignin (26–34 %), and lower pentosan (7–14 %) content when compared to deciduous species (hardwoods) (cellulose 38–49 %, lignin 23–30 %, and pentosans 19–26 %), (1).

Pellets are among the fine fire fuels produced from wood chips and sawdust, usually without adding other binders. By compression of wood, a high density, roughly around 1.4 t.m^{-3} can be achieved, resulting in high calorific value of 17-21 MJ.kg^{-1}. The moisture in the pellets reduces heat value (2).

Materials do not come into production in optimal condition, but as sawdust, shavings and pieces of wood. Before pelletizing, they have to be homogenized. The homogenization mainly takes place in the high-performance hammermill, in some cases, the crusher is omitted and replaced by a separator. When the material is extruded, it generates a considerable heat which softens and relaxes lignin in the raw material. The water content should be around 10 %; sawdust having a higher water content should be dried. The process of pellets production is pressing (3).

Ignition source consisting of radiant heat flux or a hot air stream (convective heating) is relatively simple. The main issues with sources of this kind involve aspects of proper design of test apparatuses. Otherwise, the heat fluxes can be treated in a simple way according to elementary heat transfer theory. Flames, burning buildings, and other similar heat sources require some study before they can be described by their heat fluxes. Even though the principles governing ignition sources are often poorly known (4).

In addition to the chemical composition, the physical properties of wood and wood-based materials also affect the combustion process. Each of the properties has a significant effect on combustion, although not all are affected to the same degree (5). In general, biomass burning properties can be classified as microscopic and macroscopic., The thermal, chemical and kinetic data of the examined biomass sample are included into the microscopic features. However, the macroscopic properties of biomass as fuel include heating value, moisture content, particle size, weight and ash content (6, 7).

Under conditions that include the requirements (initiation source with sufficient energy, formation of combustion gases, sufficient amount oxygen), this leads to the development of the burning process (mostly flammable). The development of flame ignition is a process where gradually increasing number of new sections of material are ignited. It occurs spontaneously at the expense of the heat which is released in the combustion zone. Development of flame depends mainly on pyrolysis. Pyrolysis means the decomposition under lack of oxygen, caused by heating of the material (depolymerization, statistical degradation and split off functional groups). If the degradation is associated with the weight loss of solid material and the formation of volatile products, it is an active pyrolysis. The ability of gasification of the polymeric material is given by particular chemical and physical structure and depends on the input and generated heat (8).

If the temperature of the sample, speed of chemical reactions and the amount of the gaseous products is sufficient, a flame combustion appears. If the solid during heating fails to produce gaseous pyrolysis products by burning, smouldering occurs. Some solid materials burn with visible flame very hardly, but they tend to smoulder and glow (9).

The thermal degradation of hemicellulose occurs in the temperature range of 220-300 °C. Together with the destruction of the C-O-C bonds, an abruption of a C-C bond may occur. Around the temperature of 223 °C, a rapid exothermic process of partial condensation was observed. At higher concentration of O_2, the thermal decomposition top moved to lower

temperatures. While the behaviour of broadleaved trees xylan was comparable to cellulose, the polyoses of coniferous wood were comparable to lignin (10).

Isolated and identified products of the cellulose thermolysis suggested that the heat effect takes place in dehydrating reaction. Dehydration takes place in the presence of catalysts in the temperature range of 180 to 270 °C. The main thermolysis decay process of cellulose depolymerization, which is in progress at temperatures above 200 °C, causes formation of anhydrides - glucase (levoglucase). The presence of free radicals during cellulose heating is indisprovable due to the fact that the presence of oxygen leads to thermal oxidation of cellulose by the peroxide chain mechanism propagation and this is described by this reaction (10):
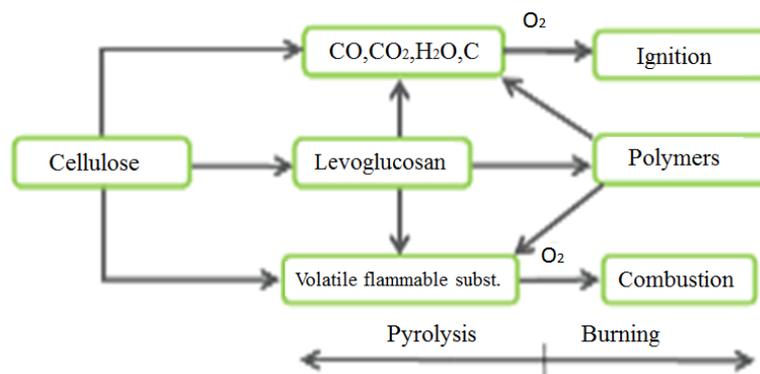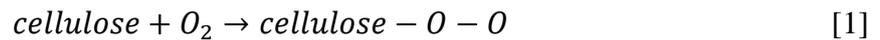
$$cellulose + O_2 \rightarrow cellulose - O - O \qquad [1]$$

Fig. 1 *Pyrolysis and combustion of cellulose (1)*

METHOD AND MATERIALS

Time to ignition (T), mass loss (m_A) and concentration of carbon monoxide (CO) from dust samples was determined according to ISO 5660-1:2002 Heat release rate (cone calorimeter method). To determine the dust properties, we used dust samples with a diameter less than 500 μm, and these samples were prepared by sieve analysis. Samples placed in a circular vessel with thickness of 15 mm were subjected to a specific irradiance level. The surface of the sample (78.5 cm^2) was heated and then it started to produce pyrolysis gases. Ignition by a spark igniter was not observed. The ignition time is an important thermal material property. It is experimentally measured as the interval between the beginning of the test and the presence of a flame and flameless combustion on the material surface (11). The produced gases were collected in a hood and transported away through a ventilation system. The heat release was measured by using the data of the measured oxygen concentration in the produced smoke. The concentration of CO and the mass loss for each samples of different heat rate is illustrated by the graphs shown in Figure 4. Time for testing the samples was 800 seconds. It should be noted that the final weight of the sample at the end of the test depends on the selected heat flux and of combustion process (flameless and flame combustion). Table 3 shows the results of samples examinations of dust with different heat fluxes.
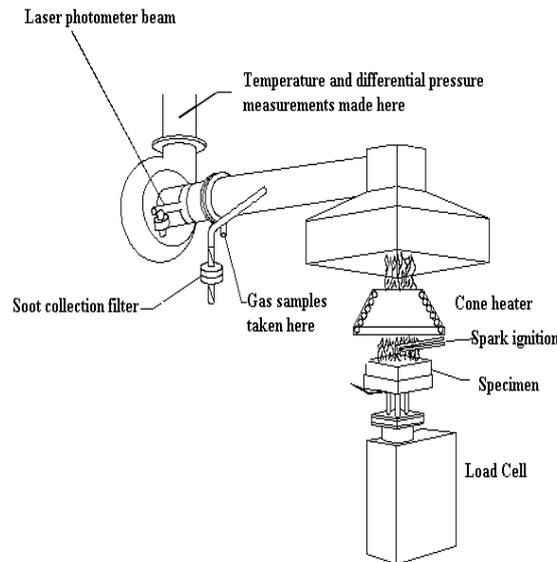
Fig. 2 *Scheme of test equipment - Conical Calorimeter*

Three different samples of industrially produced pellets were used for the analysis. Table 1 shows the properties of the test samples.

PROPERTIES OF TESTED SAMPLES   Table 1

Dust samples	Pellet dimensions		Water content (%)	Bulk density (kg/m³)	Calorific value (MJ/kg)	Mechanical resistance (%)	Ash content (%)
	Diameter (mm)	Length (mm)					
Sample A	8.0	10-40	6.65	640	17.6	88.4	0.61
Sample B	6.0	10 – 40	7.70	650	18.7	99.4	0.51
Sample C	6.0	10 – 40	7.09	650	18.7	99.5	0.17

For the sufficient amount of powder from the pellets, samples were prepared in the laboratory by a knife mill that is used for homogenization of the material. Sharp blades are straight and contain the right angle in the direction of rotation. Blades are thin and the cutting edge is inclined at an angle of 15 degrees. The speed of rotation is between 2000-10000 rpm. Constant speed during grinding is maintained by the control unit. The aim of grinding is to reduce the size of the input materials to a size that is suitable for the specific laboratory analysis. More material is used during the preparation of laboratory samples for laboratory analysis. After homogenization, the resulting samples should constitute a representative sample of powder so that the results may be reproducible in laboratory analysis. Description and a close view of the test samples are shown in Table 2.

DESCRIPTION OF TEST SAMPLES   Table 2

	Sample A	**Sample B**	**Sample C**
Sample description	*pellets made of coniferous trees with grass*	*pellets made of coniferous trees with bark*	*pellets made of coniferous trees without bark and grass*
Close view of sample			

RESULTS AND DISCUSSION

Biofuel dust samples in the form of pellets are different due to the starting materials used in their manufacture. Table 3 shows the measurement results from the dust test samples of the pellets strained by the heat fluxes of 35 and 50 $kW.m^{-2}$. Concentrations of carbon monoxide (CO), the amount of heat in the samples and the burning behavior of samples were recorded during measurements.

MEASUREMENT RESULTS   Table 3

Heat flux $[kW.m^{-2}]$	Samples	Weight of the sample before test [g]	The maximum amount of heat released during the measurement $[kW/m^2]$	The total amount of released heat during the measurement $[kW/m^2]$	Ignition time [s]	Flameless / Flame combustion	End of flame combustion
35	A	45.07	35.0812	14.3067	25±2	Flameless	-
	B	45.25	30.6206	15.4420	27±2	Flameless	-
	C	46.17	30.4568	14.9449	29±2	Flameless	-
50	A	41.45	254.7070	66.7791	8±2	Flame	714
	B	44.45	218.5633	52.3854	13±2	Flame	629
	C	43.16	199.8383	57.6232	13±2	Flame	609

The concentrations of carbon monoxide (CO) are shown in Figures 3 to 5. Flame combustion was not observed during thermal straining of the samples with heat flux of 35 $kW.m^{-2}$. The amount of released heat during flameless combustion is shown in the Figure 3. The maximum amount of released heat in the sample A is 35.0812 $kW.m^{-2}$ in 80th second from the start of measurement and the concentration of carbon monoxide is 0.0017 %.
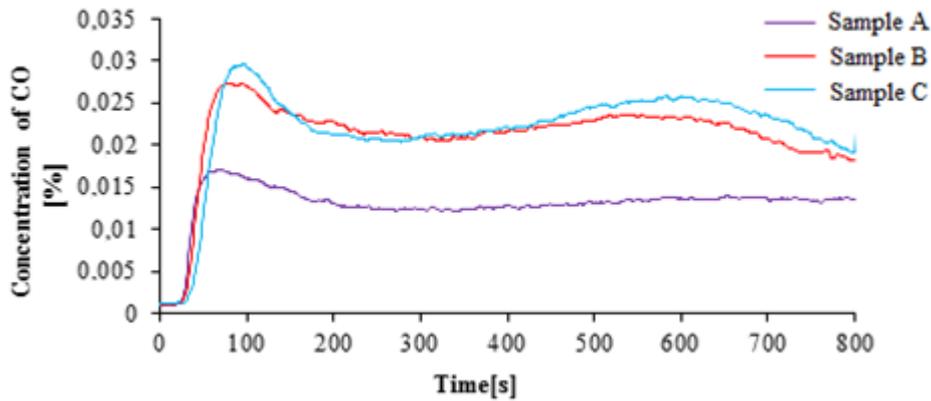

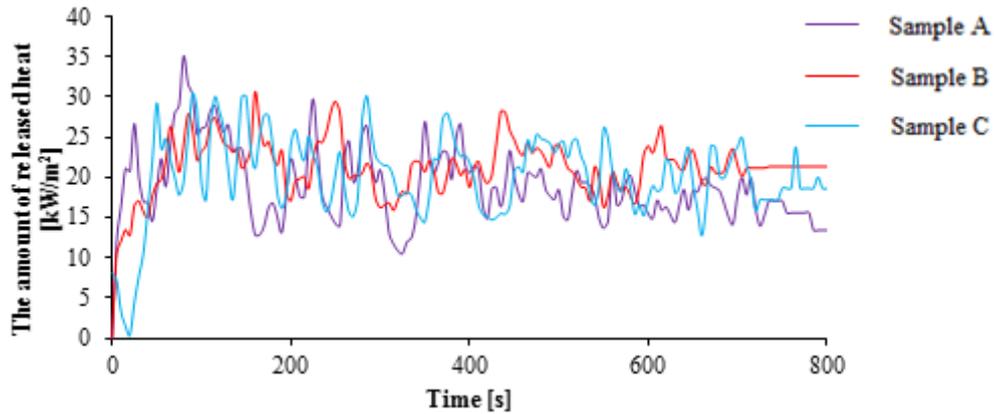***Fig. 3*** *The dependence of CO production on the presence of heat flux (35 $kW.m^{-2}$)*

Fig. 4 *The amount of released heat of test samples A, B and C during thermal straining with the heat flux of 35 kW.m^{-2}*

The maximum amount of released heat in the sample B is 30.6206 kW.m^{-2} at the 160th second from the start of measurement and the concentration of carbon monoxide is 0.0270 % over the top of the testing sample. At the time of 90 seconds, sample C started to produce maximum amount of released heat of 30.4568 kW.m^{-2}. Concentration of carbon monoxide was 0.0016 %. Graf of released heat during flameless combustion is shown in the Figure 4. Average value of released heat for sample A is 19.2037 kW/m^2, for sample B it is 21.2993 kW.m^{-2} and for sample C it is 20.3332 kW.m^{-2}. Maximum concentration of carbon monoxide was measured to sample C at the 735th second. The concentration was 0.5622 %. During the heat flux of 50 kW.m^{-2} flame combustion occurs at all dust samples. Sample A produced the maximum amount of released heat of 254.70 kW/m^2 and this occurred at the 15th second of measurement at the carbon monoxide concentration of 0.0007 % as showed in Figure 5.
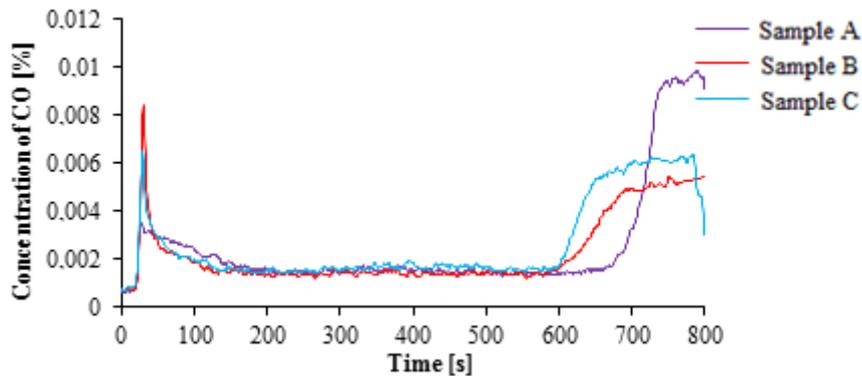

Fig. 5 *The dependence of CO production on the presence of heat flux (30 kW.m^{-2})*

Figure 6 shows a graph of heat releasing during flame combustion of sample B. The peak of released heat reached 218.56 kW.m^{-2} and it occurred at the 20th second of the measurement with carbon monoxide concentration of 0.0009 %. For sample C the maximum amount of heat release occurred at the 20th seconds and the value reached 199.83 kW.m^{-2} at a concentration of 0.0010 %.
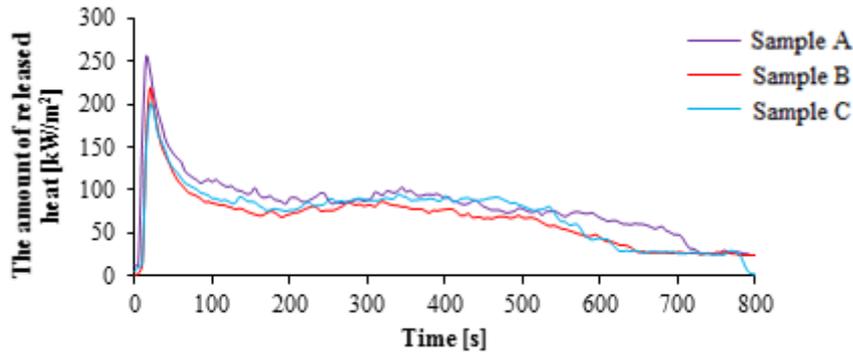
Fig. 6 *The amount of released heat of test samples A, B and C during thermal straining with the heat flux of 50 kW.m^{-2}*

During measurements of released heat using heat flux of 50 kW.m^{-2} applied to the samples, the highest amount of heat release was reached by the sample A. The average amount of heat released during the experiment for a given heat flux was the following: sample A-82.4196 kW.m^{-2}, sample B-67.4746 kW.m^{-2}, sample C-72.8943 kW.m^{-2}. Sample C achieved the highest concentration of carbon monoxide at the 620th second with the value of 1.3053 %. Heat flux density of 50 kW.m^{-2} was used.

CONCLUSION

Biomass made of wood in the form of pellets as a source of energy is becoming the most common fuel used for houses. The reasons are acceptable input costs for equipment, automated operation and a high degree of efficiency. Biomass feedstock is maintained and homogenized in order to meet individual requirements resulting from standards. Test samples were tested at two heat fluxes of 35 and 50 kW.m^{-2} using a cone calorimeter. Properties such as time to ignition, the amount of released heat, flame and flameless combustion were measured individually for the test samples of dust from the wood pellets. During straining of all the dust samples from the wood pellets by a heat flux of 35 kW.m^{-2}, a flameless combustion occurred. The highest amount of released heat during flameless combustion was 15.442 kW.m^{-2}. This occurred while testing sample B (wood dust of coniferous wood). High concentrations of carbon monoxide throughout the test were observed during flameless combustion of the test samples. The highest peak was measured at 0.0294 % for sample C (coniferous wood dust). During thermal straining of the samples with heat flux of 50 kW.m^{-2} using a cone calorimeter, flame combustion always occurred. The amount of released heat during flame combustion of analysed samples was significantly higher compared to flameless combustion. The highest amount of heat released from sample A (coniferous wood with grass) was – 254.70 kW.m^{-2}. Most of the heat was released during the initiation of flame combustion. Subsequently a decrease of heat release as a function of time occurred in each sample. The carbon monoxide concentrations were at a high rate during the whole test of flameless combustion. During flame combustion, higher concentrations of carbon monoxide were observed when combustion was initialized and in the end of the measurements during the transition to flameless combustion. In future research, it would be advisable to test selected samples at different heat fluxes and to observe the behavior of the samples to precisely determine the fire-safety characteristics of wood pellets.

References:

1. ROWELL, M. R. 2005. *Handbook of wood chemistry and wood composites.* Florida: CRC press, 2005. ISBN 0-8493-1588-3
2. ORAVEC, M., BARTKO, M., SLAMKA, M. 2012. *Postupy intenzifikácie produkcie drevenej biomasy na energetické využitie.* (*Intensification production procedures of wood biomass intended for energy use*). Zvolen.
3. MALAŤÁK, J., VACULIK, P. 2008. *Biomasa pro výrobu energie.* (*Biomass for energy production*). Praha: Powerprint, s.r.o. ISBN 978-80-213-1810-6
4. BABRAUSKAS, V. 2003. *Ignition Handbook.* London: UK. ISBN 0-9728111-3-3
5. OSVALD, A., KORYTÁROVÁ, O. 2000. *Zmeny v štruktúre vybraných ihličnatých drevín spôsobené vysokými teplotami.* (*Changes in the structure of selected coniferous trees caused by high temperatures*). Vol. 1. Zvolen: TU. ISBN 80-228-0970-5
6. DEMIRBAS, A. 2004. Combustion characteristics of different biomass fuels. *Prog Energy Combust Science*, Vol. 30, pp. 219–230.
7. ABUELNUOR, A.A.A., WAHIDA, M.A., HOSSEINIA, S. E., SAAT, A., SAQR, K.M., SAIT and M. OSMAND, H.H. 2014. Characteristics of biomass in flameless combustion: A review. In: *Renewable and Sustainable Energy Reviews*, Vol. 33, p. 363-370.
8. BALOG, K., KVARČÁK, M. 1996. *Dynamika požárú.* (*Fire Dynamics*). Ostrava: Sdružení požárního a bezpečnostího inžinierství. ISBN: 80-86111-44-X
9. PALUŠ, J., MIKO, J., MENTEL, Š. 2000. *Rukoväť požiarneho technika.* (*Fire Technician´s manual*). Bratislava. ISBN 80-8057-218-6
10. REINPRECHT, L. 2001. *Procesy degradácie dreva.* (*Degradation processes of wood*). 3. vyd. Zvolen: TU. ISBN 80-228-1070-3
11. ISO Standard 5660-1:2002: *Heat Release, smoke production and mass loss rate – Part 1*: Heat release rate (Cone calorimeter method), The International Organization for Standardization, Geneva, 2002.

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