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INFLUENCE OF SPRUCE WOOD FORM ON IGNITION ACTIVATION ENERGY

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ABSTRACT

This article deals with the evaluation of the Norway spruce wood (*Picea abies* (L.) Karst.) form influence on its activation energy of spontaneous ignition. The dust, solid and pellet forms of the samples were investigated. The mass of each sample was (3 ± 0.05) g and the water content was 0 wt %. The spontaneous ignition activation energy was calculated from the dependence of the ignition time on the inverse value of thermodynamic temperature (Semenov method). This dependence was measured in the hot-air (Setchkin) furnace according to ISO 871: 2006. The lowest spontaneous ignition activation energy (44.1 kJ.mol^{-1}) was measured for the dust form and the highest activation energy (59 kJ.mol^{-1}) was measured for the pellet form of spruce wood. Thus, the obtained results proved that the form of spruce wood has a significant influence on its spontaneous ignition activation energy. Further obtained results proved that the activation energy of spontaneous ignition is almost independent on the temperature.

KEYWORDS: Activation energy, dust, fire investigation, fire risk assessment, pellets, spontaneous ignition, spruce wood.

INTRODUCTION

Initiation is a key phase from a fire protection point of view. The crucial importance of the initiation phase in the field of fire protection results from the fact that if no initiation takes place, the fire will not start (Babrauskas 2003). The importance of the initiation phase, considering the consequences of industrial combustion on the environment, is analysed in scientific works of Ladomerský et al. (2003), Liu et al. (2013) and Kanga et al. (2014) , which prove that most of the toxicologically important products of incomplete combustion (primarily carbon monoxide) are formed during the initiation phase.

The most investigated ignition properties of solid materials currently include the spontaneous ignition temperature, flash ignition temperature (Qu et al. 2011, Zachar et al. 2012, Osvaldová and Osvald 2013) and critical heat flux (Shi and Chew 2013, Xu et al. 2013, Martinka et al. 2013). A comparison of the results of scientific works of Qu et al. (2011), Zachar et al. (2012) and Shi and Chew (2013) proves that, under the real conditions, it is possible to cause the ignition of materials at temperatures of 100-150°C lower than the spontaneous ignition temperature and flash ignition temperature determined by ISO 871: 2006. The causes are most likely the low mass of the sample (3 g) and short duration of the test (600 s) defined in ISO 871: 2006.

The further important disadvantage of the spontaneous ignition temperature and flash ignition temperature is their problematic applicability in the fields of fire dynamics modelling, fire investigation, as well as in the evaluation of the material ignition phase in the field of industrial combustion. Critical heat flux appears to be a more appropriate parameter in this regard. According to Babrauskas and Grayson (2009), critical heat flux is subdivided into the critical heat flux of auto ignition and critical heat flux of pilot ignition. The disadvantage of critical heat flux is its dependency on the thermal thickness of a material and heat flux intensity. The topic of material thermal thickness and its influence on critical heat flux is described in detail in scientific works of Delichatsios et al. (1991), Carvel et al. (2011) and Hrčka and Babiak (2012).

One of the most exact ignition characteristics currently appears to be the activation energy of spontaneous ignition. The activation energy of spontaneous ignition is defined as the minimum energy which is required to be supplied to a material in order to achieve spontaneous ignition. According to Tureková and Balog (2001) and Rantuch et al. (2014) the advantage of the above property is its only negligible dependence on the sample mass (provided the sample mass is more than one gram). The low level of activation energy dependency on the sample mass allows for a broad utilisation of ignition activation energy in the fields of fire dynamics modelling, fire investigation, as well as in the evaluation of the material ignition phase in the field of industrial combustion.

The aim of the paper is to investigate the influence of the form of Norway spruce wood (*Picea abies* (L.) Karst.) on the spontaneous ignition activation energy.

MATERIAL AND METHODS

Samples of Norway spruce wood (*Picea abies* (L.) Karst.) were used for the research in the form of dust, solid wood and pellets. The mass of the samples was (3 ± 0.05) g. The water content of the samples was 0 wt %. The fractional composition of the dust samples is in Tab. 1. The bulk density of the dust samples was 250 kg.m^{-3}, the density of solid wood samples was 320 kg.m^{-3} and the density of the pellets was 665 kg.m^{-3}. Prior to the test, the dust sample was freely poured into the sample pan, with the dimensions according to ISO 871: 2006, and thickened to the required bulk density on a vibration table. The solid wood samples had dimensions of 20 x 20 mm, with the third dimensions adjusted such that the sample had the required mass. The pellets were hot-press produced from spruce wood without bark and additives. The temperature during hot-press production was 120 ± 5°C. The diameter of the pellets was 6 mm and the length was adjusted such that the sample had the required mass.

Tab. 1: Fractional composition of dust samples.

Particle dimension (μm)	Fraction (wt %)
56 - 71	25
71 - 100	25
100 - 150	25
150 - 200	25

Firstly, the spontaneous ignition temperature was determined for all the samples in an ISO 871: 2006 hot-air furnace, using a modified test procedure. The standard test procedure according to ISO 871: 2006 is based on the determination of the minimum air flow temperature around the sample which causes sample ignition. The standard air flow rate is 25 mm.s^{-1},the sample mass is 3 ± 0.2 g and the test duration is 10 minutes. According to the standard procedure, the sample is inserted into the furnace through an upper opening after the lid is open. After the sample is placed into the furnace the upper opening is closed by the lid. The modification meant that the sample is inserted into the furnace through a permanently-open top opening situated in the lid, i.e. during the modified procedure the lid is not fully closed. The modification of the test procedure removed the key deficiency of the standard test procedure which is the decrease of the furnace temperature in tens of degrees Celsius when a sample is being inserted into the furnace and the lid is open. The modified test procedure meant that there was practically no change of the furnace temperature during the insertion of a sample.

The other modification is based on the different requirements on the sample mass (3 ± 0.05 g). In addition to the standard test procedure, the time to ignition was measured together with the ignition temperature during the modified procedure. Subsequently, the ignition time (each repetition for a new sample) was measured at temperatures higher by 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100°C than the initially established ignition temperature. The ignition time was measured for each of the sample forms and temperature in five repetitions and the results are the average values.

Exponential equations for the statistical dependency of the ignition time on the inversed value of thermodynamic temperature were derived from the measured values. The pre-exponential factor in the derived equations was numerically equal to the pre-exponential (frequency) factor A (-) from Eq., from which the ignition activation energy Ea (J.mol^{-1}) was determined for the tested samples. The Eq. is an analogy to the Arrhenius equation. The background to Eq. 1 is in (Semenov 1959).

$$\tau = A \cdot e^{\frac{E_a}{R \cdot T}}$$

where: τ - the ignition time (s),
R - the universal gas constant ($\text{J.K}^{-1}\text{.mol}^{-1}$),
T - thermodynamic temperature (K).

RESULTS AND DISCUSSION

The dependency of the ignition time on the inverse value of thermodynamic temperature is illustrated in Fig. 1. Fig. 1 also depicts the equations of the exponential statistical dependency of the ignition time on the inverse value of thermodynamic temperature together with the square value of the correlation coefficient (R^2).

The spontaneous ignition activation energies were calculated using Eq. for all the temperatures tested (from the ignition temperature up to the ignition temperature increased by 100 °C).

The dependency of the spontaneous ignition activation energy on temperature is shown in Fig. 2 and the average values of the ignition activation energy together with the spontaneous ignition temperature are illustrated in Tab. 2. The obtained values are approximately in agreement with the results stated by Zachar et al. (2012) and Chrebet (2012).

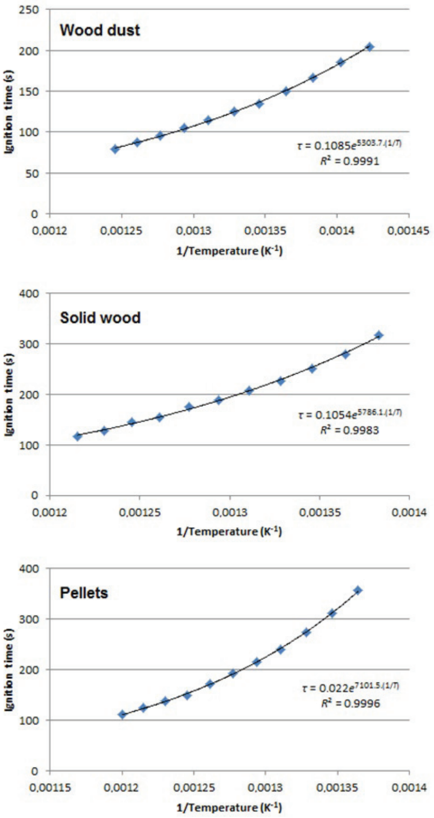

Fig. 1: Dependency of ignition time on inversed value of thermodynamic temperature for Norway spruce wood in form of dust, solid wood and pellets.

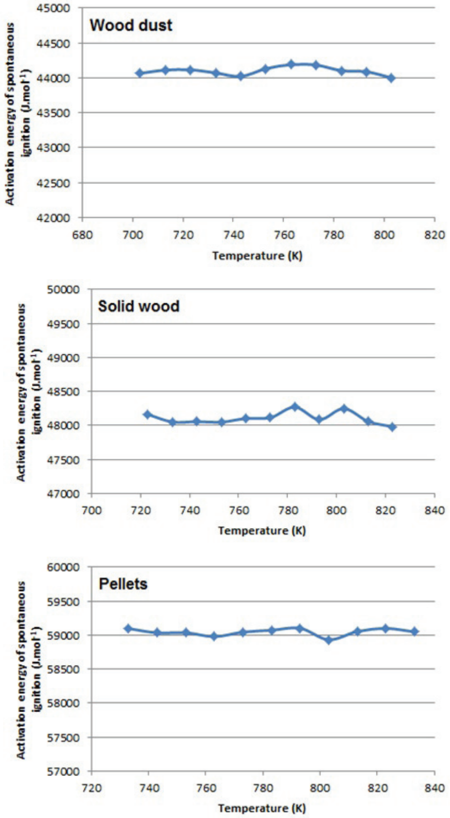

Fig. 2: Dependency of ignition activation temperature of examined spruce wood form on temperature.

Tab. 2: Spontaneous ignition temperatures and average activation energy of spontaneous ignition for investigated samples form.

Sample form (-)	**Spontaneous ignition temperature (°C)**	**Activation energy ($J.mol^{-1}$)**
Dust	430	44 097
Solid	450	48 106
Pellets	460	59 044

The difference between the spontaneous ignition temperature of spruce wood in the sedimented dust form and pellet form is less than 7 %; in comparison, the difference between the activation energies of the above mentioned forms of spruce wood is almost 34 %. The ignition activation energy appears therefore to be a more suitable means for comparing the resistance of materials to ignition in comparison to the ignition temperature.

Another important advantage of material ignition resistance based on the ignition activation energy is the possibility of more accurate determination in comparison to the ignition temperature. The standard ISO 871: 2006 method allows the determination of ignition temperature of the sample with the accuracy of 10°C. In comparison, the measurement of the base input quantity for the ignition activation energy calculation (ignition time) is possible with an accuracy of 1 s. This means that when the ignition time is greater than 100 s the accuracy of the measurement is better than 1 %. Despite the above fact, it is necessary to take into account the fact that the spontaneous ignition temperature required for the ignition activation energy calculation was determined with an accuracy of 10°C; at the ignition temperature of 450°C this means an inaccuracy of 2.22 %. The proposed methodology allows for the correction of this inaccuracy. The correction is based on the calculation of the ignition activation energy for a set temperature which is higher that the ignition temperature.

This methodology allows the calculation of the ignition activation energy for a given temperature (higher than the ignition temperature), even if the ignition temperature determined using the original ISO 871: 2006 procedure is almost 10°C lower than the real ignition temperature. The accuracy of the methodology depends only on the accuracy of the furnace temperature and time measurements. In the tests K-type thermocouples with an accuracy of 0.75 % were used and ignition-time measurement accuracy was 1 s. In theory, using the modified test procedure, it should be possible to determine the ignition temperature with an accuracy of 1°C. However, since wood is a non-homogenous material, it is necessary to assume variability in the ignition temperature of a few degrees Celsius. The data plotted in Fig. 2 prove that the ignition activation energy is almost independent of temperature, in the interval from the ignition temperature (determined in accordance to ISO 871: 2006) to the ignition temperature increased by 100°C. The data shown in Fig. 2 prove that the variability of the activation energy caused by temperature dependency is less than 1 %. The reason for the variability is the previously mentioned non-homogeneity of wood. Hence, a more accurate way of ignition activation energy determination is to carry out a set of calculations for temperatures ranging from the ignition temperature (determined in accordance to ISO 871: 2006) up to the ignition temperature increased by 100°C with 10°C increases. The average of the values calculated for the above temperature range will then represent the final activation energy, in the same way as in Tab. 2.

The dependency of the ignition activation energy of spruce wood on density is depicted in Fig. 3. The data in Fig. 3 indicate that the ignition activation energy of spruce wood is logarithmically dependent on the wood density. The data from Fig. 3 also indicate that with the increasing density of spruce wood its resistance to ignition also increases. This result is in agreement with the works of Osvald (1997), Kačíková et al. (2006) and Zachar (2009).

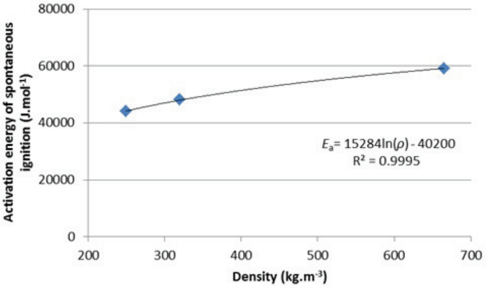

Fig. 3: Dependence of ignition activation energy of spruce wood on its density.

CONCLUSIONS

The ignition activation energy of spruce wood is determined and its dependency on temperature, density and sample physical form is examined in the study.

The obtained values indicate a logarithmical dependence of spruce wood ignition activation energy on the sample density. The lowest ignition activation energy was established for the dust form of spruce wood (44.1 kJ.mol^{-1}), a higher value for the solid form (48.1 kJ.mol^{-1}) and the highest for the form of pellets (59 kJ.mol^{-1}). The ignition activation energy of spruce wood is almost independent on temperature in the temperature interval from the ignition temperature up to the ignition temperature increased by 100°C.

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