IGNITION PARAMETERS OF POPLAR WOOD

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ABSTRACT

The article details a research of initiatory parameters of poplar wood (*Populus tremula* L.). Researched were samples with dimensions of 100 × 100 × 20 mm, dried at a temperature of 103 ± 2 °C to water content of 0 wt%. The orientation of samples during the test was horizontal. The initiatory parameters (critical heat flux density and surface temperature in the time of initiation) were set on a conical calorimeter using a testing procedure in accordance with ISO 5660-1:2015. The testing procedure according to the ISO standard was supplemented by a thermocouple of NiCr-Ni type, which measured the surface temperature of the sample during the test. Critical heat flux density was set by using an ignition initiator (critical heat flux for piloted ignition, in accordance with ISO 5660-1:2015) and without an ignition initiator (critical heat flux for autoignition, modified testing procedure). Critical heat flux density was defined from statistical dependence of initiation time exponentiated by -1/2 from the heat flux density. Critical heat flux density for piloted ignition was 10.70 kW·m^{-2} and critical heat flux density for autoignition was 28.90 kW·m^{-2}. The average surface temperature of the sample in the moment of piloted ignition was 335 ± 59 °C, and in the moment of autoignition 533 ± 63 °C.

Keywords: Critical heat flux density, fire risk assessment, ignition temperature, integral model of ignition, poplar wood.

INTRODUCTION

Initiatory material parameters are considered important input data for the area of safe material and product handling (in all phases of the life cycle), investigation of fire reasons and fire modelling. They are crucial for the definition of safety standards for manipulation with material or product in order to prevent initiation and consecutive fire. BABRAUSKAS (2003) considers the initiatory parameters as the most important fire characteristics of material, as if there is no initiation, there is no fire.

Despite the mentioned importance of the initiatory characteristics, there have been used two principally different groups of initiatory parameters in the science, development and technical practice. The first group of initiatory parameters is based on critical temperature, and the second on critical heat flux density.

Critical temperature is the minimum temperature which causes the initiation of material, while critical heat flux density is the minimum density of heat flux necessary for material initiation. In line with the terminology ISO 871:2006, the critical temperature is divided into flash-ignition temperature and spontaneous-ignition temperature. Flash-ignition

temperature is according to ISO 871:2006 defined as the minimum temperature at which, under specified test conditions, sufficient flammable gases are emitted to ignite momentarily on application of a pilot flame. Spontaneous-ignition temperature is defined in accordance with the mentioned standard as minimum temperature at which, under specified test conditions, ignition is obtained by heating in the absence of any additional ignition source.

Critical heat flux density can be divided into critical heat flux density with usage of additional initiatory source (critical heat flux density for piloted ignition) and critical heat flux density without usage of additional initiatory source (critical heat flux density for autoignition).

Currently, the critical temperature is being defined entirely by a device and using procedure in line with ISO 871:2006. The disadvantage of this method is the fact that assessed as critical is not the temperature of the material surface, but the temperature of the surrounding (air) flow around the sample. This fact represents a significant disadvantage of the testing procedure and the device in accordance with ISO 871:2006, therefore the submitted work suggests own methodology for critical temperature measurement on the material surface at the moment of initiation.

When assessing the safe temperature point which still enables usage of the material, in selected practical applications the surrounding temperature is not important nor the surface temperature in the ignition moment, but the temperature at which certain chemical and physical changes start (monitored changes may depend on the aimed material application). However, when considering wood and wood-based materials (generally nearly all organic polymers) the scale of chemical and physical changes is significantly depending not only from temperature, but also from the action time period; setting the low temperature limit of irreversible changes in physical and chemical features of material is extremely complicated and this issue has not been solved by any exact scientific study yet. Research of the impact of low temperatures onto changes of selected chemical and physical properties of wood has been done by e.g. REINPRECHT et al. (1999), REINPRECHT and VIDHOLDOVÁ 2011, DZURENDA and DELIISKY (2012), KAČÍKOVÁ et al. (2013) and KAČÍK et al. (2012, 2016). According to REINPRECHT and VIDHOLDOVÁ 2011 the temperature factor influencing the properties of wood significantly depends on the environment (inert or oxidation). DZURENDA and DELIISKY (2012) researched the impact of low temperatures (up to 70 °C) and original humidity on colour changes in beech timber. According to the quoted authors, drying of beech timber from absolute humidity of 70% to 8% in a drying chamber with the temperature during the drying in interval 37 to 65 °C does not influence any change of timber colour. KAČÍKOVÁ et al. (2013) and KAČÍK et al. (2012, 2016) researched the impact of thermal treatment of wood onto changes of its chemical composition. The results of scientific work of the quoted authors proved that with increasing temperature (from 113 to 271 °C) also increased: mass loss, total crystallinity index of cellulose, total colour difference, and the content of lignin and extractives, whereas a degree of polymerization of cellulose, modulus of rupture, modulus of elasticity, lightness difference, and the content of holocellulose, cellulose and hemicelluloses all decreased with thermal treatment.

Critical heat flux density is calculated differently for thermally thin and thermally thick materials. Thermally thin materials can be considered those which are heated to nearly the same temperature in its whole cross-section at the moment of initiation. On the other side, thermally thick materials achieve the critical temperature only on the surface. Border thickness, from which material is considered thermally thick, can be calculated in line with formula (1), which was deduced and described by BABRAUSKAS and PARKER (1987):

$$L = 0.6\frac{\rho}{q} \text{ (mm)} \tag{1}$$

Where L is thickness from which material is considered thermally thick (mm), ρ is material density (kg m^{-3}) and q is heat flux density touching the material surface (kW m^{-2}).

Formula (1) does not consider all the parameters which influence material thermal thickness (especially thermal conductivity index and specific thermal capacity), despite this fact it offers a relatively precise forecast of the material thermal thickness. The issue of thermal conductivity of wood is detailed in the scientific work of DELIISKI and DZURENDA (2015).

Before calculating critical heat flux density, it is necessary to measure the initiation time for at least three densities of the heat flux. Followingly, for thermally thin materials shall be created statistical dependency of initiation time exponentiated by -1 (reversed value) from heat flux density, and for thermally thick materials shall be created statistical dependency of initiation time exponentiated by -1/2 or -0.55 from heat flux density. Critical heat flux density shall be calculated by the substitution of zero value as the result of the initiation time exponentiation by -1, -0.55 or -1/2 (theoretically resembles the infinite time of initiation) into the created statistical dependency (MIKKOLA 2009).

Critical heat flux density and surface temperature at the initiation moment are mutually bound. The interrelation between critical heat flux density and surface temperature at the initiation moment can be expressed by formulas (2 to 4). Formula 2 was devoted by QUINTIERE (1992). Formulas (3 and 4) were devoted by MIKKOLA and WICHMAN (1989). Formula (3) is applicable for thermally thin materials, and formula (4) is applicable for thermally thick materials.

$$t_{ig} = \frac{2}{3} \lambda \rho C_P \left(\frac{T_{ig} - T_0}{q} \right)^2 \ (s) \tag{2}$$

$$t_{ig} = \rho C_P L \frac{T_{ig} - T_0}{q} \ (s) \tag{3}$$

$$t_{ig} = \frac{\pi}{4} \lambda \rho C_P \left(\frac{T_{ig} - T_0}{q} \right)^2 \ (s) \tag{4}$$

Where t_{ig} is initiation time (s), λ is the factor of material heat conductivity (kW·m^{-1}·K^{-1}), ρ is material thickness (kg·m^{-3}), C_P material specific thermal capacity (kJ·kg^{-1}·K^{-1}), T_{ig} is the temperature on the material surface at the initiation moment (°C), T_0 is surrounding the environment temperature (°C), q is the heat flux density touching material surface (kW·m^{-2}) and L is the material thickness (mm).

Formulas (2 to 4) theoretically enable the calculation of critical temperature on material surface at the initiation moment from critical heat flux density and initiation time. The mentioned calculation is complicated by the fact that in real conditions the heat conductivity factor, specific thermal capacity and material density are depending on temperature. Moreover, the surface temperature of wood and wood-based materials is higher than the temperature of their thermal decomposition. From the above mentioned it is clear that it is not correct to speak about λ, ρ and C_P of wood, but about λ, ρ and C_P of products of wood thermal decomposition. Therefore, formulas (2 to 4) shall be used for the product calculation of λ C_P ρ or ρ C_P from the initiation time, heat flux density and surface temperature at the initiation moment. The product of λ $C_P \rho$ can be named as material thermal inertia.

The aim of the submitted scientific study is the definition of critical heat flux density for piloted ignition and for autoignition and surface temperature at the initiation moment of thermally thick poplar wood (*Populus tremula L.*).

EXPERIMENTAL

In the research were used samples of poplar wood (*Populus tremula L.*) with dimensions of $100 \times 100 \times 20$ mm. Before the test, the samples were dried to a water content of 0 wt% at temperature 103 ± 2 °C and consecutively conditioned in an exicator at a temperature of 20 ± 1 °C, over 24 hours. The average density of the researched samples (by water content of 0 wt%) was 452 ± 17 kg·m^{-3}. The surface of the samples was treated by grinding with a vibration grinding machine using grinding paper with granularity of 80 and 120. The orientation of the samples during the test was horizontal. The samples were thermally loaded by heat radiation on the tangential plane.

Time to ignition for three densities of heat flux (30, 40 and 50 kW·m^{-2}) was set on a conical calorimeter by a testing procedure in accordance with ISO 5660-1:2015. Time to ignition was set by two testing procedures. In the first testing procedure, a spark initiator was used (testing procedure in accordance with ISO 5660-1:2015). The second testing procedure was without the spark initiator (modified testing procedure). Critical heat flux density was calculated from the initiation times at tested heat flux densities in line with the procedure by MIKKOLA (2009). According to the author, this calculated value of critical heat flux shall be increased by 3 kW·m^{-2} (empirically found value representing heat loss). The testing procedure also applied results of scientific works by MIKKOLA and WICHMAN (1989), DELICHATSIOS *et al.* (1991), DELICHATSIOS and CHEN (1993), SPEARPOINT and QUINTIERE (2001) and SHI and CHEW (2013), which have proven that for the creation of a reliable statistical dependency of initiation time from heat flux density (and following the calculation of critical heat flux density), are sufficient values of time initiations measured in three heat flux densities. Measurement at all heat flux densities and both testing procedures (with and without additional spark initiator) were repeated five times. The average values are listed at the end.

From equation (1) after the substitution of samples density (452 ± 17 kg·m^{-3}) and studied heat flux densities (30 to 50 kW·m^{-2}) it is clear that the studied samples behaved as thermally thick materials under the testing conditions.

The testing procedure in line with ISO 5660-1:2015 was added by a thermocouple of type K NiCr-Ni), which measured the sample surface temperature during the test. Initiation of samples was evaluated visually.

RESULTS AND DISCUSSION

Dependency of initiation time from heat flux density of poplar wood, with the usage of an additional spark initiator, is demonstrated in Fig. 1; without the additional spark initiator in Fig.2.

In Fig. 1 and 2, from statistical dependencies of the initiation time exponentiated by -1/2 from heat flux density, are calculated the critical heat flux density for piloted ignition and critical heat flux density for autoignition. Apart from the critical heat flux densities, Fig. 1 and 2 also detail determination factors. Their values approach 1 which indicated very

strong statistical dependency of the initiation time exponentiated by -1/2 from heat flux density.

Such calculated critical heat flux densities, according to MIKKOLA (2009), shall be increased by 3 kW·m^{-2}. After consideration of this precondition, studied poplar wood has its critical heat flux density for piloted ignition 9.70 kW·m^{-2} a critical heat flux density for autoignition 28.90 kW·m^{-2}.

For comparison, critical heat flux density for piloted ignition of the majority of trees and wood-based materials, according to SCUDAMORE *et al.* (1991), LYON (2004), TEWARSON *et al.* (2004) and BABRAUSKAS (2009) in between 10 to 15 kW·m^{-2}.

In published scientific works, critical heat flux density for autoignition was studied on a significantly smaller scale as critical heat flux density for piloted ignition. However, comparison of the achieved results to the results of scientific works of SHI and CHEW (2013) states that critical heat flux density for autoignition of poplar wood is comparable to critical heat flux density for autoignition of majority of trees.
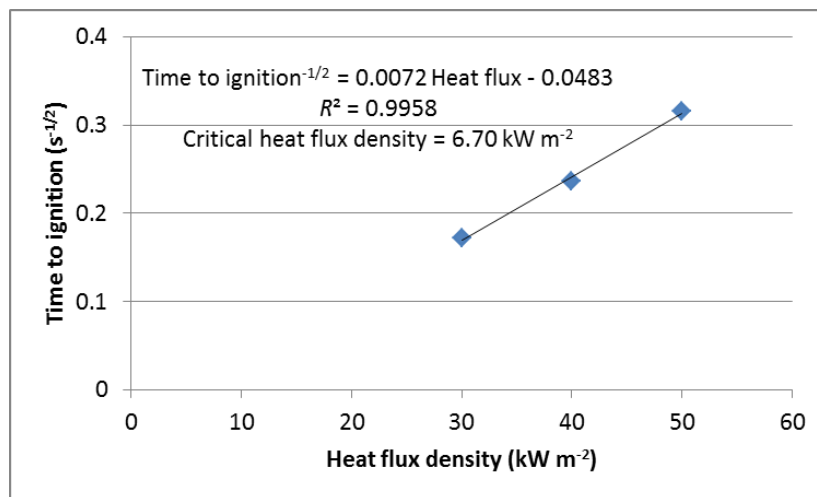

Fig. 1 Dependency of initiation time of poplar wood exponentiated by -1/2 from heat flux density using spark initiator.
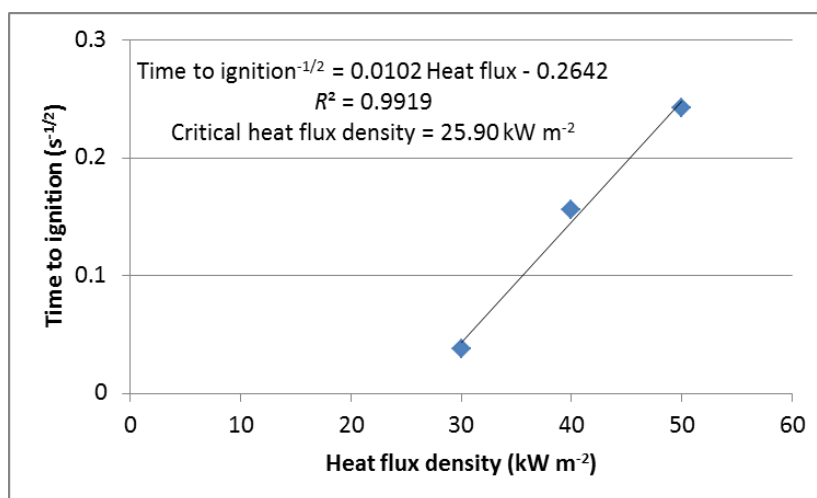

Fig. 2 Dependency of initiation time of poplar wood exponentiated by -1/2 from heat flux density without using spark initiator.

The course of temperature from the sample surfaces is shown in Fig. 3 to 8.

Fig. 3 to 5 demonstrate temperatures from the sample surface during the testing procedure using a spark initiator, and Fig. 6 to 8 without the spark initiator.
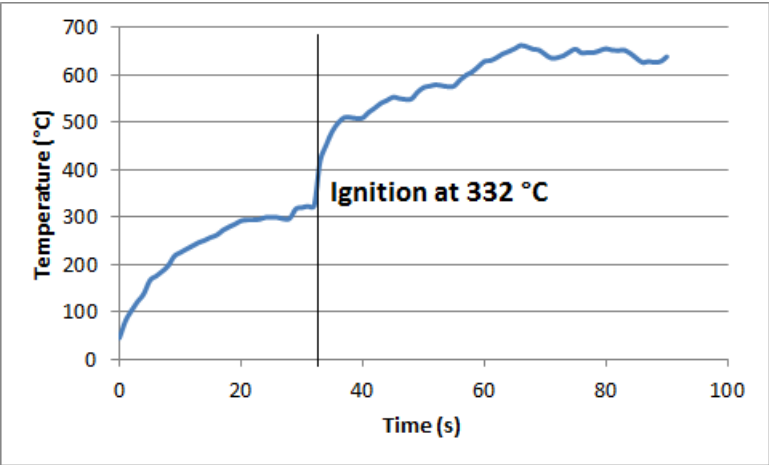

Fig. 3 Temperature on the surface of poplar wood loaded by heat flux with density of 30 kW·m⁻² using spark initiator.

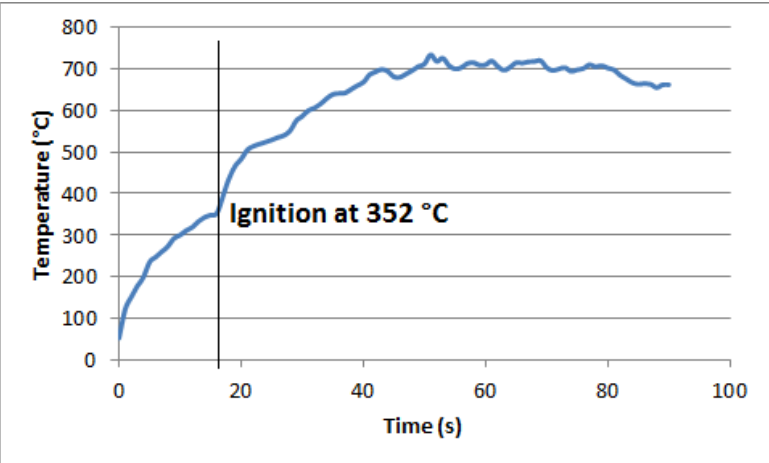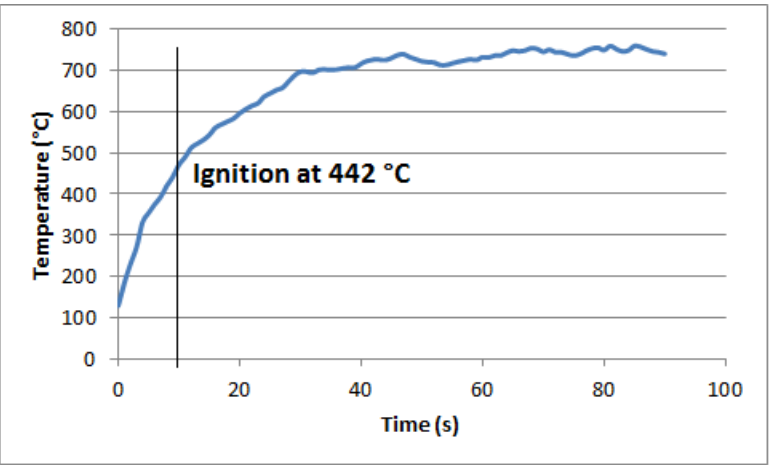**Fig. 4 Temperature on the surface of poplar wood loaded by heat flux with a density of 40 kW·m⁻² using spark initiator.**

Fig. 5 Temperature on the surface of poplar wood loaded by heat flux with a density of 50 kW m⁻² using spark initiator.
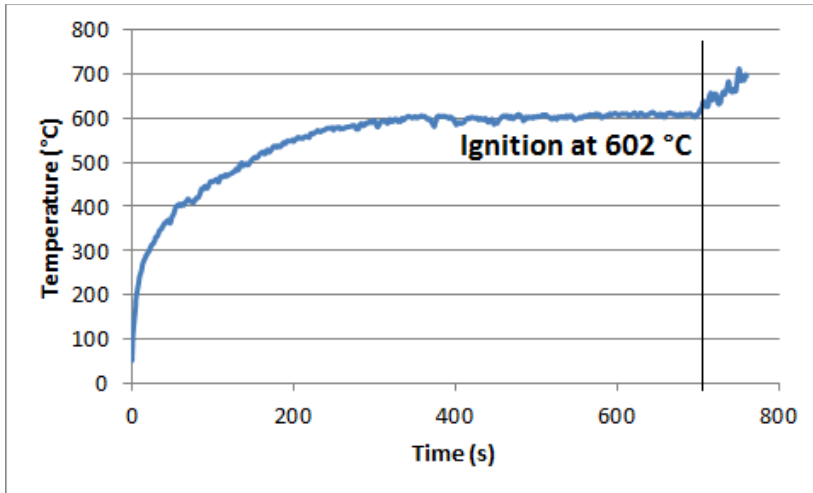
**Fig. 6 Temperature on the surface of poplar wood loaded by heat flux with a density of 30 kW·m⁻²
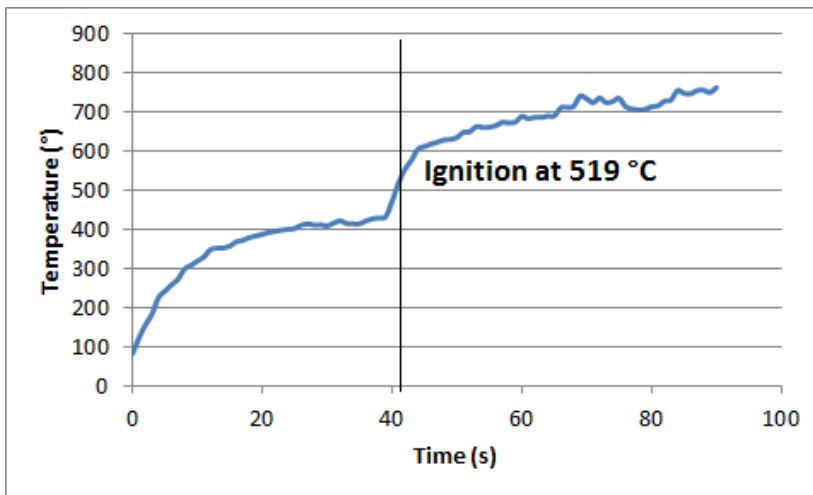without using spark initiator.**

**Fig. 7 Temperature on the surface of poplar wood loaded by heat flux with a density of 40 kW·m⁻²
without using spark initiator.**

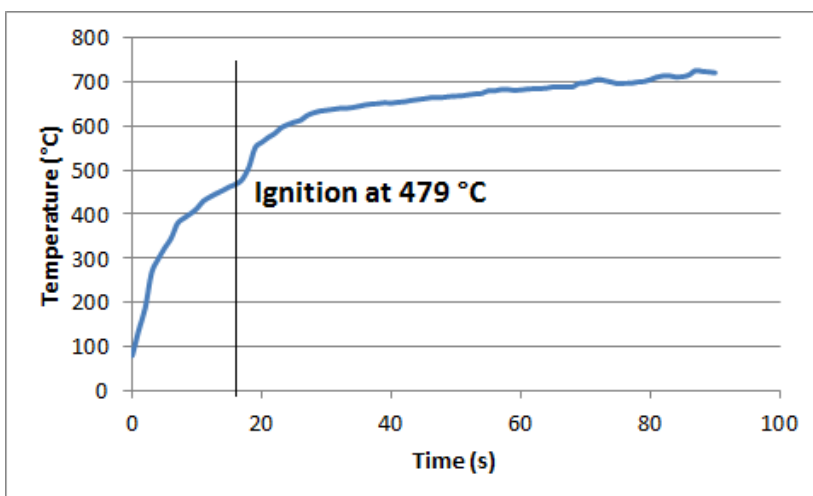**Fig. 8 Temperature on the surface of poplar wood loaded by heat flux with density of 50 kW·m⁻²
without using spark initiator.**

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Data in Fig. 3 to 8 demonstrate different dependency of critical temperature on the surface from heat flux density for piloted ignition and for autoignition. During autoignition, the higher heat flux density, the higher temperature on the surface of poplar wood in the initiation moment. On the other hand, for autoignition with rising heat flux density, the surface temperature of poplar wood in the initiation moment is descending. The reason for the described differences is principally the different initiation mechanism of material during piloted ignition and autoignition. Critical heat flux density for piloted ignition represents a minimum heat flux density necessary for thermic decomposition of material at a speed which volatiles thermic decomposition which reaches a lower flammability limit. On the other side, critical heat flux density for autoignition represents a minimum heat flux density necessary for the initiation of decomposition products. At higher heat flux density, the surface temperature of the material rises faster than at lower heat flux density, and in the same time the initiation time decreases. As a result of material thermal inertia there is necessary higher temperature in order to reach a critical speed of thermic decomposition in shorter initiation time than in longer initiation time (at lower heat flux density). At autoignition the initiation ability of decomposition products of thermic decomposition by incandescence with rising heat flux density. Therefore, in the initiation moment, the surface temperature of the sample decreases with increasing heat flux density. At high heat flux densities, it is highly probable that the initiation process of wood flame burning loaded only by incandescence (without additional initiation source) is influenced by a glow of the surface layer. This issue is detailed in scientific work by OSVALDOVÁ *et al.* (2014).

Results of scientific work by SHI and CHEW (2013) state, that the temperature on the surface of wood and wood-based materials, in the moment of autoignition by incandescence with heat flux density of 50 $kW \cdot m^{-2}$ shall be ranging between 346 and 558 °C. Relatively high temperature (602 °C) on the poplar wood surface in the autoignition moment by incandescence with heat flux density of 30 $kW \cdot m^{-2}$ was probably caused by the fact that the heat flux of 30 $kW\ m^{-2}$ is only slightly higher than critical (28.90 $kW \cdot m^{-2}$). According to BALOG and KVARČÁK (1999) and ZACHAR *et al.* (2012) flash-ignition temperatures of wood and wood-based materials are ranging between 320 and 390 °C, and spontaneous-ignition temperatures of the same materials are in interval from 400 to 460 °C. On the other side, our measured values on the poplar wood surface in the moment of piloted ignition were ranging between 332 and 442 °C, and in the autoignition moment were ranging between 479 and 602 °C. The mentioned comparison proves that it is not correct to identity flash-ignition temperature and spontaneous-ignition temperature with the temperature on material surface in the initiation moment. This outcome is of a key importance especially in the area of fire reasons determination and fire engineering. This area is detailed in a scientific work by MOZER *et al.* (2014).

CONCLUSION

The article defines critical heat flux density for piloted ignition and for autoignition of poplar wood. Furthermore, is defines surface temperature in the moment of piloted ignition and autoignition of poplar wood.

Critical heat flow density for piloted ignition was 9.70 $kW \cdot m^{-2}$ and critical heat flux density for autoignition was 28.90 $kW \cdot m^{-2}$.

The average surface temperature in the moment of piloted ignition was 335 ± 59 °C; in the moment of auto ignition 533 ± 63 °C.

Achieved results prove that the surface temperature in the moment of piloted ignition rises with increasing heat flux density reaching the poplar wood surface. On the contrary, the surface temperature in the moment of autoignition decreases with increasing heat flux density touching the poplar wood surface.

Comparison of the achieved results with the results of scientific works (e.g. BALOG and KVARČÁK 1999 and ZACHAR *et al.* 2012) prove, that the surface temperature of wood and wood based materials in the moment of piloted ignition is not identical with flash-ignition temperature (set by ISO 871:2006), and the surface temperature of wood and wood based materials in the moment of autoignition is not identical with spontaneous-ignition temperature (set by ISO 871:2006).

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ACKNOWLEDGEMENTS

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