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TEMPERATURE FIELD EVOLUTION IN WOOD SAMPLES DURING THE FLAME SPREAD EXPERIMENTS

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Research article

Abstract: Vertical, horizontal and 45° upward flame spread experiments over the small scale beech and pine wood samples were performed. Wood samples were of two geometries - square cross section prisms (15 x 15 mm) and a thin rectangular cross section prisms (5 x 40 mm) - and of three different lengths - 10, 15 and 30 cm. Samples were ignited by a heptane source fire extinguished immediately when the wood samples ignited. During the flame spread an internal temperature profiles along the centreline of the samples were measured by a set of thermocouples. Flame spread was observed in all sample positions except the horizontal orientation of the beech and pine square prism samples. Experimental data will serve for a validation of the pyrolysis models in the Computational Fluid Dynamics (CFD) flame spread models.

Keywords: Wood, flame spread, temperature field, fire modelling.

Introduction

CFD fire modelling gradually evolved to a mature instrument that it can be nowadays successfully used in fire protection engineering (Yeoh and Yuen, 2009). It does not replace the faster and easier to use hand calculation formulas or semi-empirical models, but it represents an alternative providing very detailed information, nowadays due to strong computational resources, in a tolerable time.

The common CFD fire models can be used to predict heat, mass and smoke transfer from the ignition source (Rein, 2007), but also solve fire extinguishing problems, fire detection and alarm systems problem, humans evacuation under the fire conditions (Xing, 2012) and last but not least spread of the fire from the ignition source.

Fire development modelling being a widely discussed topic in the current fire research presents a significant challenge. The overall performance of the fire spread models depends on the convective/radiative heat transfer, combustion chemistry, gas phase fluid mechanics, turbulence and proper description of pyrolysis model that is typically the main obstacle in the fire development modelling (Lautenberger and Hostikka, 2010).

Pyrolysis model quantifies the rate at which gaseous volatiles are released from the condensed phase to the gas phase. Consumed by the combustion reaction the gaseous volatiles further contributes to the heating of the condensed phase thus further supporting the volatiles release (burning) and the spread of the fire over the virgin material.

Ghorbani et al. (Ghorbani et al., 2013) classify pyrolysis models to three groups - fully empirical ones, semi-empirical models and comprehensive formulations. The semi-empirical models are the mostly used in the CFD fire models. The semi-empirical models are based on the simplified description of the underlying physics and the material properties are consider to be model specific parameters rather than true physical and chemical properties of the material. Ghorbani et al. (Ghorbani et al., 2013) further discuss and question the ability of semi-empirical models to perform outside the range of the bench scale experiments conditions that were used for calibration of the model parameters.

Obtaining the full set of the material parameters necessary to be used as a pyrolysis model input presents a difficult task. Lautenberger and Fernandez-Pello (Lautenberger and Fernandez-Pello, 2011) summarized the experimental tools and optimization techniques that can be applied to determine material pyrolysis properties intended to use in the fire spread modelling. Optimization methods based on the curve fitting using the bench scale experimental data present a way that overcomes the need of multiple specialized laboratory tests to evaluate each particular material property. Successful examples of using the optimization techniques to determine

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pyrolysis parameters were presented, e.g., for wood, polyvinyl chloride (PVC), polymethyl methacrylate (PMMA) and graphite by Matala (Matala, 2008), carpet material, polyester reinforced with glass fibre and panels used in commercial aircraft manufacturing by Webster (Webster, 2009), PMMA, single-wall corrugated board and chlorinated polyvinyl chloride (CPVC) by Chaos (Chaos, 2011).

The above presented overview shows that a lot of attention is given to the development and validation of the pyrolysis models against the bench scale experimental data. However, the overall performance of the fire spread model needs to be validated also against the real fire spread experimental data. Fire spread model is typically evaluated against heat release rate measurements (HRR), temperature measurements or a pyrolysis front position data. Wong (Wong, 2013) presented a very comprehensive flame spread dataset from extensively instrumented experiments including measurements of heat release rate, plume centreline temperature and velocity, heat flux to wall, near-wall temperature, flame height, flame spread progression, mass loss and burn pattern of combustible wall panel placed on the inert wall and ignited by a liquid source fire. He proposed a methodology to validate a complex fire models by dividing the flame spread problem into 4 components - the turbulent buoyant fluid flow, the gas phase kinetics, the flame heat transfer to burning and unburned fuel and the condensed-phase pyrolysis. Each problem is assessed first against experimental data and thus the overall fire spread predictive capability of the model can be evaluated.

This contribution do not aim to present such a comprehensive and instrumentally costly analysis of the fire spread problem, but presents an experimental data on the flame spread over the small scale beech and pine wood samples. The data will serve for a validation of the pyrolysis model estimation procedure using the bench scale data (presented in Hasalová et al., 2012) measured with the same wood samples.

Ability to predict wood behaviour under the fire conditions is of a great interest as the wood is commonly used as a construction and household material. In this work internal temperature profiles of the small scale beech and pine wood samples of different shapes, thickness and spatial positions are measured. A number of experimental data on the wood thermal decomposition can be found in literature (Park et al., 2010; Reszka, 2008), however, our motivation to perform the flame spread experiments described in this paper was to ensure material integrity throughout the whole procedure of determining the pyrolysis model parameters, the performance of the pyrolysis model compared to bench scale experimental data and the consequent application to a real flame spread problem, when all experimental data required are measured using the same wood samples.

Materials and methods

Experimental apparatus

All experiments were carried out in the laboratory experimental apparatus consisting of a box (dimensions 600 x 1000 x 610 mm) open to the surroundings at the front side to enable venting. The inside walls of the box are covered with fire resistant ceramic fibre slabs. Combustion products are collected by the hood equipped with the thermometer to monitor the combustion products temperature.

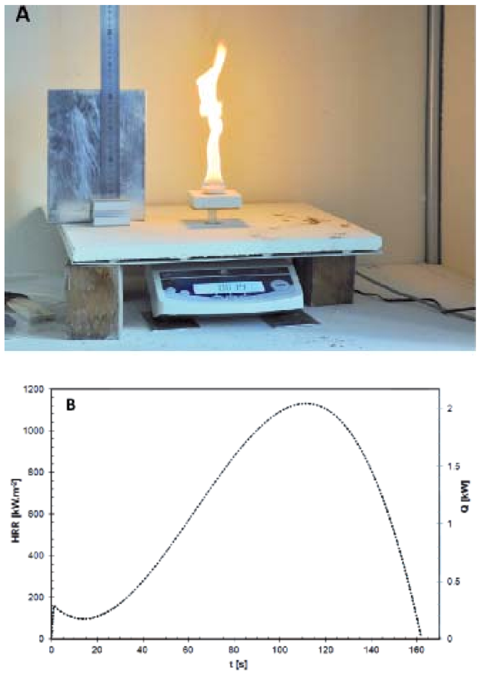

Fig. 1 (A) Mass Loss rate measurement experimental set up, (B) heptane pool heat release rate

Liquid fuel source - Mass Loss Rate measurements

Wood samples were ignited by a small heptane pool source fire (48 mm in diameter, 6.5 ml heptane volume) placed under one end of the wood sample (13 cm below the lower edge of the sample). As soon as the wood ignited, the source fire was extinguished. Such experimental procedure corresponds to the early phase of the fire development - situation

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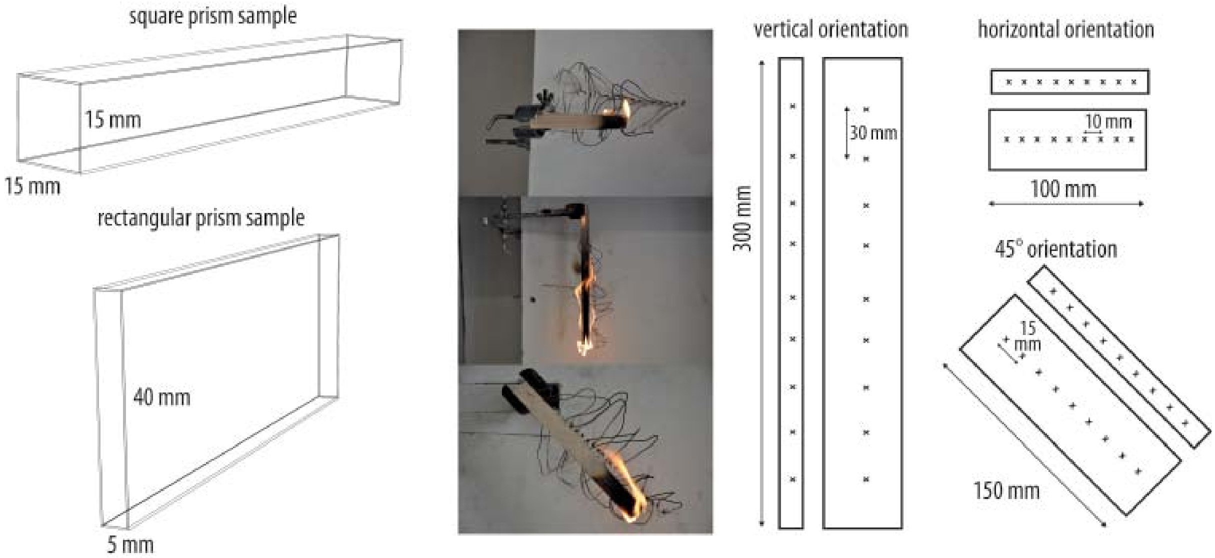

Fig. 2 The square and rectangular prism samples dimensions for different orientation. The cross symbols denote the thermocouples position

sometimes referred to as the flame spread problem. No significant source of thermal radiation that would propagate burning was present near the sample and the heat transfer to the sample occurs solely from the near field flames. When modelling flame spread very fine grid in the near flames area is required, otherwise heat transfer would not be solved accurately enough to propagate burning.

To be able to evaluate the amount of the heat released from the liquid source fire to the wood sample, experiments measuring the mass loss rate (MLR) of the heptane were performed. The laboratory scales Denver SI-603 with 0.01 g precision were placed to the centre of the experimental box and protected against the fire and heat by the ceramic fibre slab from the top (Fig. 1). The mass loss was continuously recorded by the PC. Assuming the heptane heat of combustion, Δh_c, keeps constant value of 44600 kJ.kg^{-1} (Babrauskas, 2002), heat released when burning, $\dot{Q}$, was calculated as $\dot{Q} = m \Delta h_c$, where m being the heptane mass loss in kg.s^{-1}. Dividing the amount of the heat released by the pool area, heat release rate (HRR, kW.m^{-2}) was obtained (Fig. 1B). Heptane HRR is the key model input information when modelling the flame spread as it controls heating and ignition of the wood samples.

Wood samples

Beech and pine wood were chosen as representatives of the hard and soft wood species, respectively. Pine wood, readily available, easy to cut/curve is often used for construction lumber. Pine wood has a high content of the resin, high calorific value and thus it is a good fuel source. Beech wood has a straight grain with a fine to medium uniform texture. It responds well to bending, it is often used by woodworkers for lumber, veneer, flooring, furniture etc. It is also very suitable as a fireplace wood - easy to ignite, it burns with a very bright flame and the charcoal glows for a long time (Wood Handbook, 2010).

Wood samples of two different geometries used in experiments were of a bar form: a) square prism with the 15 x 15 mm cross section and b) rectangular prism with a 5 x 40 mm cross section. The original wood samples were 70 cm long, purchased at the common retail chain and cut to the shorter pieces according to the orientation of the sample during the experiment. Before the samples were cut, the average moisture content was measured to be 8 and 6.5 % for the pine and the beech wood, respectively. The average density of the wet pine and beech wood was 548 and 740 kg.m^{-3}, respectively.

Samples were positioned to the holder in 3 different orientations (Fig. 2) - horizontally (10 cm long samples), vertically (30 cm long samples) and under the 45 degree angle (15 cm long samples). From the back side, 9 type K thermocouples (0.8 mm diameter) were placed in the holes evenly distributed along the centreline of the sample long edge (10, 15 and 30 mm spacing for 10, 15 and 30 cm long samples). Under one end of the sample, heptane poolwas placed and ignited. When the flames from the wood sample were observed, heptane was extinguished.

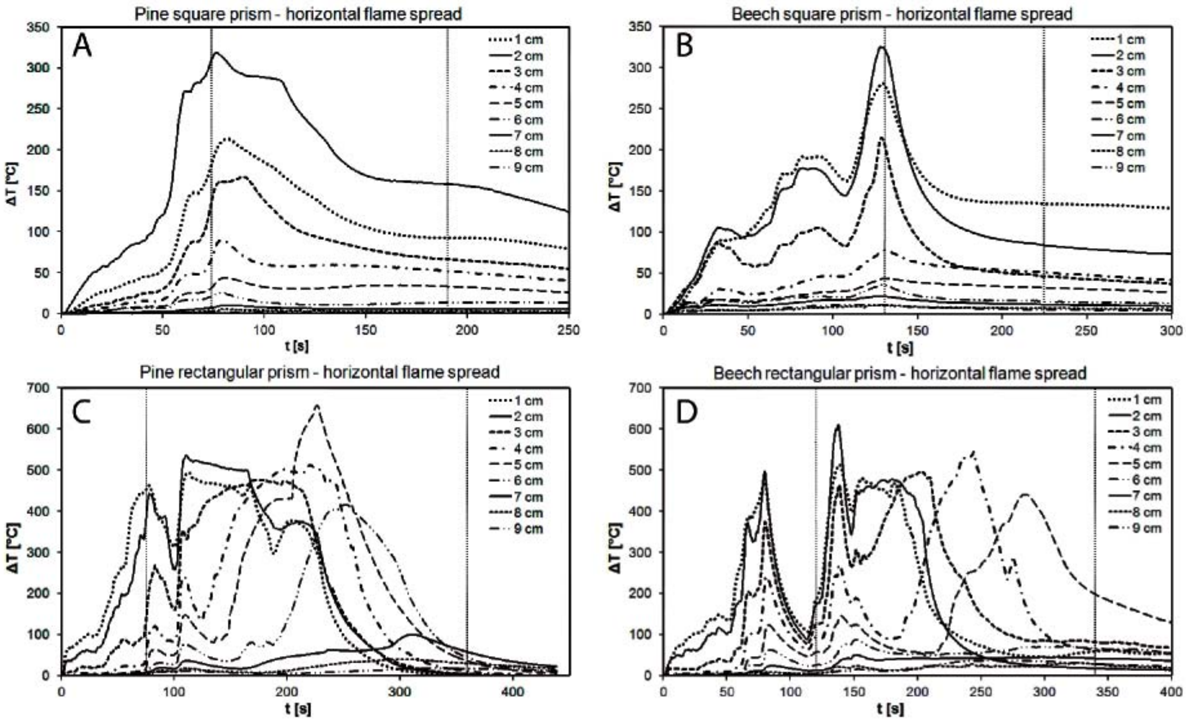

Fig. 3 Internal temperature profiles for horizontal position: (A) pine square prism, (B) beech square prism, (C) pine rectangular prism, (D) beech rectangular prism

The internal temperature was recorded through the entire experiment, i. e., from the igniting of the heptane until the wood stopped burning and the internal temperature of the sample gradually decreased. Experiments were carried out with both wood specie, both sample geometries and all sample orientations.

Results

The internal temperature profiles presented in this section are presented as a difference of the actual sample temperature and the temperature at the beginning of the measurement to minimize the possible error caused by the changes of the thermocouple reference junction temperature between individual experiments.

The reference junction was protected from the heat originating from the burning samples by the ceramic fibre slab, however, it was found that its temperature varied by 3 to 5 °C during the measurement. Together with the error caused by the calibration of the thermocouples, the overall error of temperature measurements was estimated to be ± 10 °C.

In every internal temperature profile plot, two vertical dotted lines mark the time, when the heptane source fire was extinguished and when wood flaming stopped.

Horizontal flame spread

The temperature field evolution within the pine and beech wood samples positioned horizontally is shown in Fig. 3. Both pine and beech square prism samples (Fig. 3 A, B) ignited from the source fire, but after the source fire was extinguished, the samples gradually stopped flaming and the internal temperature started to decrease. The internal temperature of the wood at the time heptane was extinguished equalled in both cases approximately 300 °C, that is the threshold value between the second and the third stage of wood pyrolysis (White and Dietenberg, 2010). During the second stage (200 - 300 °C) overall pyrolysis reactions are endothermic, however, exothermic reactions of char and flammable volatiles occurs simultaneously. The third stage of pyrolysis (300 - 450 °C) is characterized by the significant release of the flammable volatiles. In the performed experiments, the volatiles release rate was insufficient to support propagating of burning after the source fire was extinguished and thus no horizontal flame spread was observed (Fig. 4). It took approximately two times longer to heat the beech prism to the same temperature as the pine prism.

Fig. 3C, 3D shows internal temperature profiles in the pine and beech rectangular prism. Contrary to the square prisms, the horizontal flame spread along

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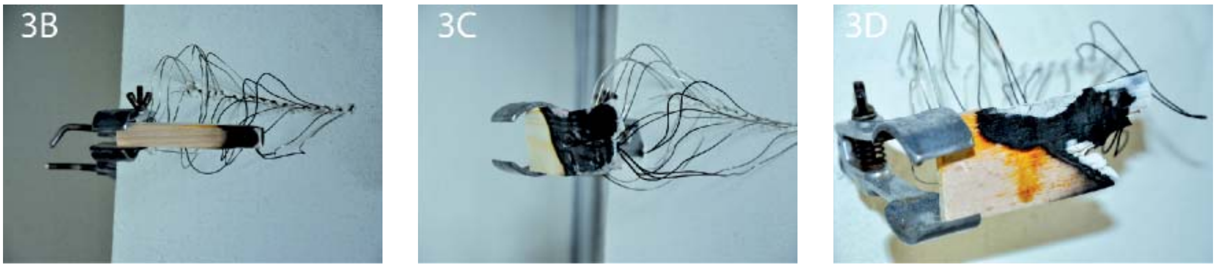

Fig. 4 Samples after the horizontal flame spread experiment. Samples are denoted according to the internal temperature profiles in Fig. 3: (3B) Beech square prism, (3C) pine rectangular prism, (3D) beech rectangular prism

the samples was observed. Internal temperature of the pine rectangular prism (Fig. 3C) recorded at the measuring points above the source fire (measuring points 1 and 2) increased fast to more than 400 °C. After 75 seconds from the heptane ignition, flames coming from the wood were observed and the source fire was extinguished. The wood temperature decreased under 300 °C in 20 seconds, but the volatiles release rate was sufficient to propagate burning and temperature thus increased sharply. The horizontal flame spread over the pine rectangular prism was observed. Moving from the ignition point along the sample, internal temperature profiles copy the similar trend. At the measuring points where flaming combustion was observed the temperature gradually increased above 450 °C and keep relatively constant for the period when the wood residue undergoes further degradation and oxidization until only ash remains, after that the wood started to cool down and temperature gradually decreased. The sudden drop of the temperature recorded at some measurement points after 150 seconds was caused by a cracking of the sample and the thermocouple release out of the sample. The sample was not entirely engulfed in the flame. The internal temperature profiles at the sample side distant from the point of ignition shows only a very small increase in the temperature at the second half of the experiment. Approximately two thirds of the sample burned.

When measuring the internal temperature profiles of the beech rectangular prism (Fig. 3D), similar behaviour as described for the pine rectangular prism was observed. However, approximately from the half of the sample length, the flame was spreading only over the upper edge of the rectangular prism, whereas the flame spread over the beech rectangular prism was uniform along the whole length of the sample (Fig. 4 - 3B). At first source fire was extinguished too soon and no flaming from the wood was observed (strong decrease in the temperature at approximately 70 s). Heptane was therefore ignited again and extinguished after 50 seconds, when wood flames were clearly visible.

Vertical flame spread

Compared to the horizontal flame spread experiments the vertical flame spread was observed both at rectangular and square prism samples. In all cases significant increase in the internal temperature was displayed at all measuring points along the sample as the samples were entirely engulfed in the flames and burned along the whole sample length as can be seen in Fig. 5C. The pine rectangular prism internal temperature profiles show a very uniform evolution of the temperature. The sharp decrease at the end of the constant temperature period (between 450 to 550 °C) was again caused by the cracking of the sample, or the sample mass was already consumed at that point. The beech rectangular prism (Fig. 5D) shows behaviour very similar to the pine rectangular prism. Beech rectangular prism as well burned along the whole sample length but as observed in the previous experiments, heating of the beech prism was much slower than heating of the pine prism. Compared to the pine rectangular prism, the beech rectangular prism was heavily cracking, leading to the very fast break up of the sample. The pine rectangular prism was twisting and cracking, but did not break up (Fig. 6 - 5C).

An interesting evolution of the internal temperature profiles was observed during the pine square prism experiment (Fig. 5A). There is no decrease in the temperature after the source fire was extinguished suggesting very rapid volatiles release rate and burning at temperatures around 250 °C. The temperature in the lower part of the sample further increased for approximately 120 seconds up to maximum 350 °C as the flame was vertically spreading, then temperature started to decrease. Almost no flaming combustion was observed at that point and the wood was cooling down. Approximately by 100 seconds later the internal temperature at the measuring points located in the upper third of the sample started to decrease sharply and significant flaming in the upper third of the sample was observed (Fig. 6 - 5A). Maximum temperature measured at this second stage of burning

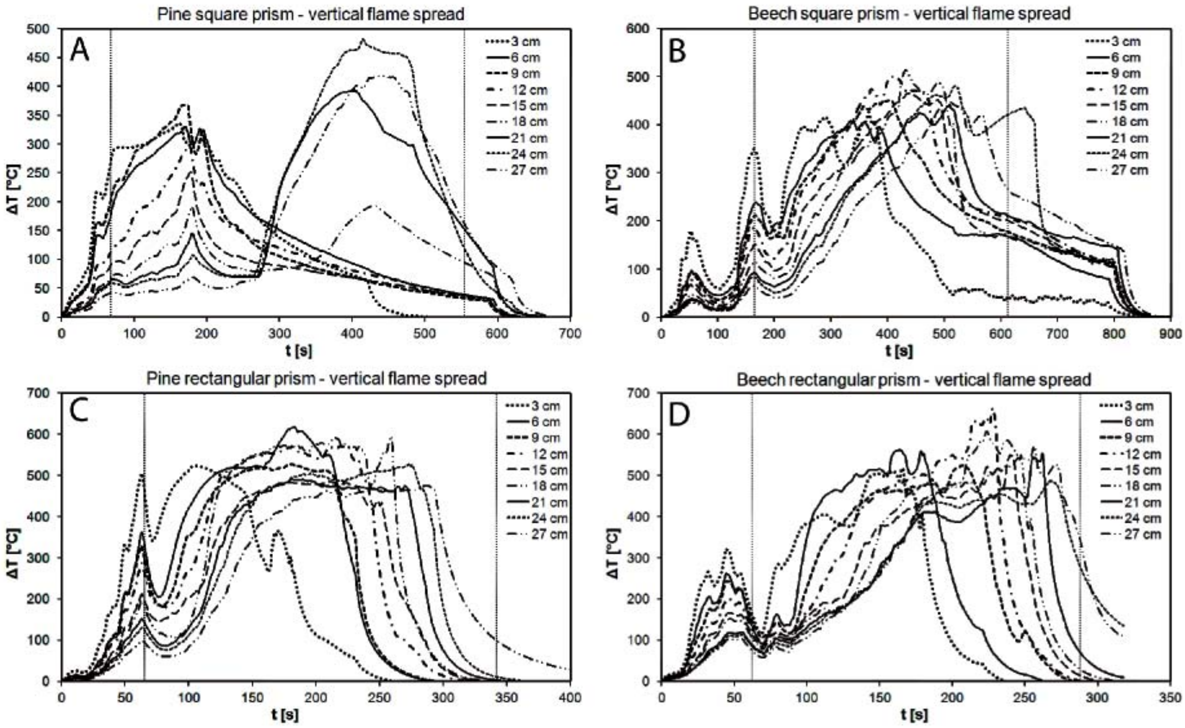

Fig. 5 Internal temperature profiles for vertical position: (A) pine square prism, (B) beech square prism, (C) pine rectangular prism, (D) beech rectangular prism

is by 100 °C higher compared to the burning in the lower part of the sample and the upper part of the sample burned to ash.

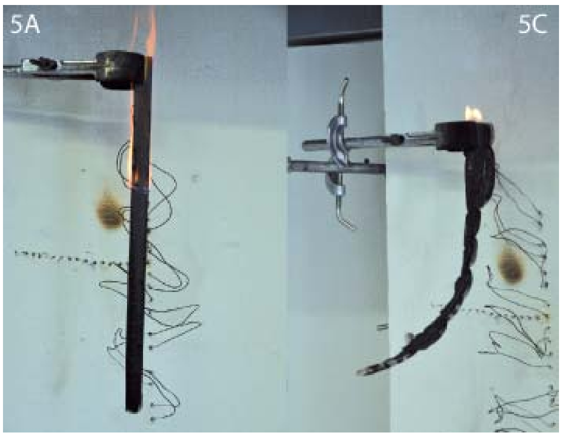

Fig. 6 Samples in the vertical flame spread experiment. Samples are denoted according to the internal temperature profiles in Fig. 5.: (5A) Pine square prism sample at the second half of the experiment, (5C) beech rectangular prism sample after the experiment

Beech prism (Fig. 5B) was burning along the whole length of the sample. Its internal temperature was gradually increasing along the sample, but no constant temperature period was recorded. When the final pyrolysis stage was reached, the temperature decreases sharply. The beech prism was significantly cracking, pieces of the prism were falling apart and the thermocouples were released out of the sample 45° upward flame spread.

Upward flame spread was observed at both pine and beech square prism samples (Fig. 7A, 7B). Although pine prism was entirely engulfed in the flame (Fig. 8), only a half of its original mass burned away as suggested by the internal temperature profiles. The temperature in the upper part of the pine sample increased to a maximum of about 300 °C, only the first three measuring points closest to the source fire recorded temperatures above 450 °C. The observed pine prism burning was non-uniform, with local centres of burning. In the case of the beech prism, approximately 85 % of its original mass burned away. At the end of the experiment only a small portion of the sample remained. Similar to the vertical flame spread, measured internal temperature profiles are not as uniform along the beech sample length as measured at the pine prism, because the sample was heavily cracking as it was burning away.

Significantly different behaviour was observed when burning the pine and beech rectangular

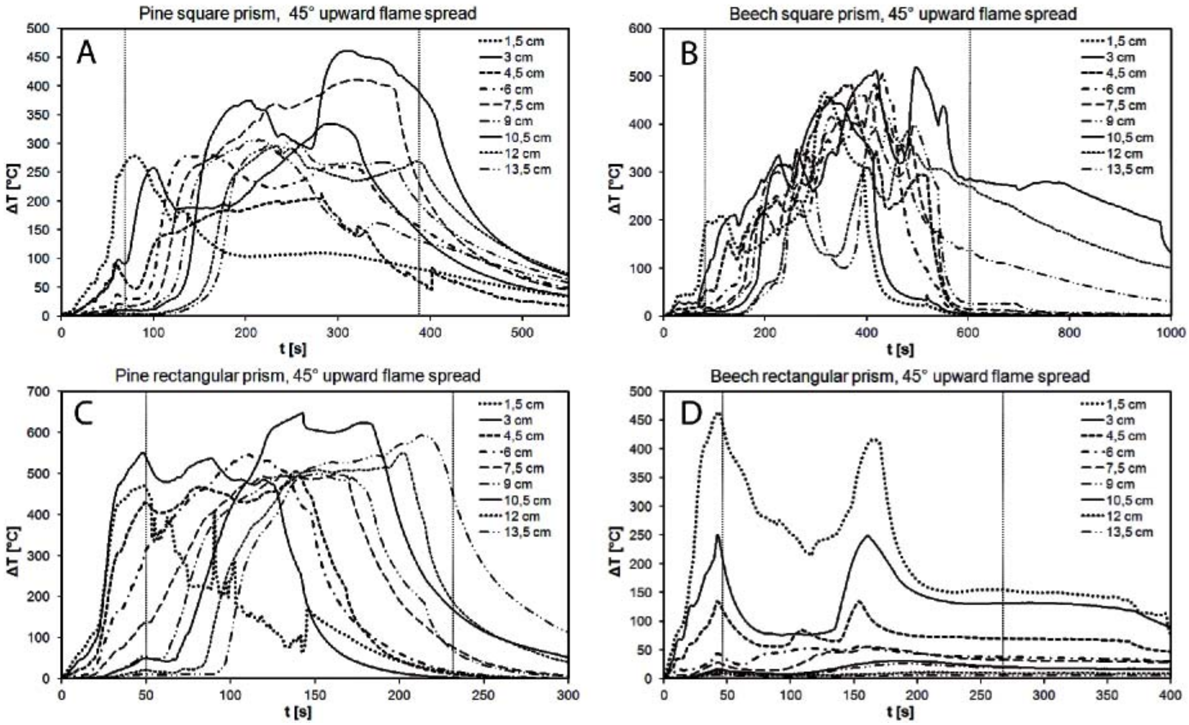

Fig. 7 Internal temperature profiles for the 45° position: (A) pine square prism, (B) beech square prism, (C) pine rectangular prism, (D) beech rectangular prism

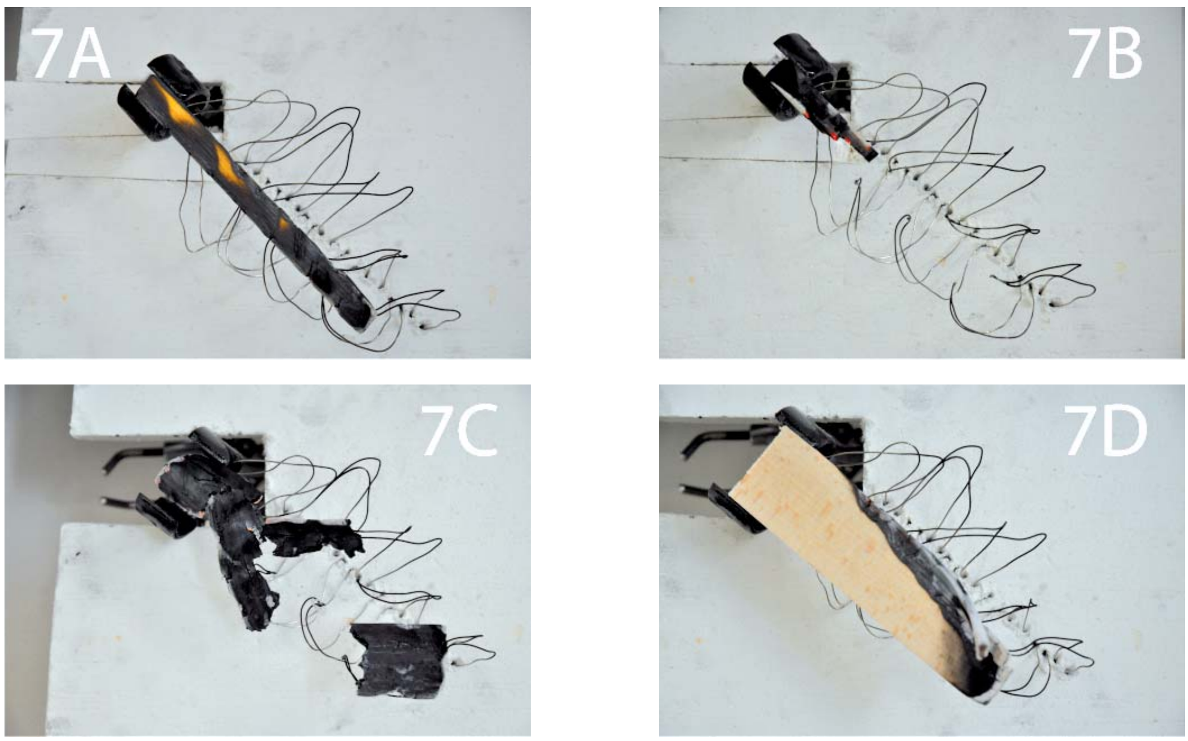

Fig. 8 Samples after the 45° upward flame spread experiment. Samples are denoted according to the internal temperature profiles in Fig.7: (7A) Beech square prism, (7C) pine rectangular prism, (7D) beech rectangular prism

prisms. The pine prism was observed to be burning uniformly along the entire length of the sample as confirmed by the internal temperature profiles (Fig. 5C). In both cases there was a sharp increase in the temperature after the source fire was ignited and no decrease in the wood internal temperature occurred after it was extinguished. However, contrary to the pine rectangular prism, beech rectangular prism thermocouple readings (Fig. 7D) do not further show a presence of the flame spread. The flaming and burning was observed visually but only along the upper edge of the sample (Fig. 8 - 7D). The thermocouple measuring points were positioned in the centre line of the sample and thus not significantly affected by the flame spread on its upper part except the measuring points 1 and 2.

Conclusion

The flame spread was observed in all cases examined except the horizontally positioned square prisms. Horizontal flame spread over the thin rectangular prism samples was observed, but only up to a half or to two thirds of the sample length. Significant flame spread was observed at all samples positioned vertically. Especially the thin rectangular prism samples were entirely engulfed in the flames soon from the ignition. Upward flame spread was also observed for all samples at 45°. In the case of the beech rectangular prism, however, the flames were spreading only along the upper edge of the sample.

In general, longer time interval was needed to heat up the beech samples to the temperatures supporting the release of the flammable volatiles from the wood. After reaching temperature above 450 °C the beech samples compared to the pine wood samples were heavily cracking and the thermocouples were released out of the samples making the record of the internal temperature evolution in the last stage of the pyrolysis and during cooling impossible. Beech wood was observed to be glowing for a long time.

Burning of the resin released from the pine samples was also noted during the experiments.

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References

BABRAUSKAS, V. (2002). *SFPE Handbook of Fire Protection Engineering*. 3rd ed. 2002. 3-01, Hazard calculations, p. 535-572. ISBN 087765-451-4.

GHORBANI, Z., WEBSTER, R., LÁZARO, M., TROUVÉ, A. (2013). Limitations in the predictive capability of pyrolysis models based on a calibrated semi-empirical approach. *Fire Safety Journal*, 2013, vol. 61, p. 274-288. ISSN 0379-7112.

HASALOVÁ, L., IRA, J., JAHODA, M. (2012). Measurement and evaluation of experimental data for modelling thermal decomposition of solid materials. *Chemical Engineering Transactions*, 2012, vol. 29, p. 1405-1410. ISSN 1974-9791.

CHAOS, M., et al (2011). Evaluation of optimization schemes and determination of solid fuel properties for CFD fire models using bench-scale pyrolysis tests. *Proceedings of the Combustion Institute*, 2011, vol. 33, p. 2599-2606. ISSN 1540-7489.

LAUTENBERGER, Ch., HOSTIKKA, S. (2010). *Fire Retardancy of Polymeric Materials*. 2nd ed. 2010. 20, Full-Scale Fire Modelling, p. 551-586. ISBN 978-1-4200-8399-6.

LAUTENBERGER, Ch., FERNANDEZ-PELLO, C. (2011). Optimization Algorithms for Material Pyrolysis Property Estimation. In: *Fire Safety Science Proceedings of the Tenth International Symposium: 10th International Symposium on Fire Safety Science*. 2011, p. 751-764.

MATALA, A. (2008). *Estimation of solid phase reaction parameters for fire simulation: master thesis*. Finland: Helsinki University of Technology, 2008.

PARK, W. Ch., ATREYA, A. (2010). Experimental and theoretical investigation of heat and mass transfer processes during wood pyrolysis. *Combustion and Flame*, 2010, vol. 157, p. 481-494. ISSN 0010-2180.

REIN, C., et al. (2007). *The Dalmarnock Fire Tests: Experiments and Modelling*. University of Edinburgh: School of Engineering and Electronics, 2007.

RESZKA, P., TORERO, J. L. (2008). In-depth temperature measurements in wood exposed to intense radiant energy. *Experimental Thermal and Fluid Science*, 2008, vol. 32, p. 1405-1411. ISSN 0894-1777.

WEBSTER, R. D. (2009). *Pyrolysis model parameter optimization using a customized stochastic Hill-Climber algorithm and bench scale fire test data: Master thesis*. University of Maryland, 2009.

WHITE, R. H., DIETENBERGE, M. A. (2010). *Wood Handbook*. United States Department of Agriculture Forest Service, General Technical Report FPL-GTR-190, 2010. 18, Fire Safety of Wood Construction, p. 18.1-18.22.

WONG, W. C. K., et al. (2013). A multi-component dataset framework for validation of CFD flame spread models. *Journal of Fire Protection Engineering*, 2013, vol. 23, no. 2, p. 85-134. ISSN 1042-3915.

Wood Handbook (2010). *Wood Handbook - Wood as an engineering material*. General Technical Report FPL-GTR-190, Department of Agriculture, Forest Service, Forest Products Laboratory: USA, 2010.

XING, Z., TANG, Y. (2012). Simulation of fire and evacuation in high-rise building. *Procedia Engineering*, 2012, vol. 45, p. 705-709. ISSN 1877-7058.

YEOH, G. H., YUEN, K. K. (2009). *Computational Fluid Dynamics in Fire Engineering*. 1st ed. Elsevier Inc, 2009. ISBN 978-0-7506-8559-4.