STATYBINĖS KONSTRUKCIJOS IR TECHNOLOGIJOS
ENGINEERING STRUCTURES AND TECHNOLOGIES
ISSN 2029-2317 print / ISSN 2029-2325 online
2011 3(3): 91–104
doi:10.3846/skt.2011.11

INVESTIGATION INTO THE INFLUENCE OF IMPREGNATION ON PINE TIMBER COMBUSTION USING A CONE CALORIMETER AND LARGE SCALE TESTS

Jerzy Gałaj[1], Zbignev Karpovič[2], Waldemar Jaskółowski[3]

[1]Fire Technique Division, Fire Safety Engineering Faculty, The Main School of Fire Service, Słowackiego 52/54 street, 01-629 Warsaw, Poland
[2]Dept of Labour Safety and Fire Protection, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania
[3]Fire Development and Extinguishing Division, Fire Safety Engineering Faculty, The Main School of Fire Service, Słowackiego 52/54 street, 01-629 Warsaw, Poland
E-mails: [1]jerzy.galaj@gmail.com; [2]zbigis@gmail.com; [3]wjaskolowski@aol.pl

Received 27 July 2011; accepted 25 August 2011

Abstract. Fire safety is one of the main requirements with respect to the regulations on the buildings involved into the category of human hazards. Human safety measures are applied equally to inhabitants, users, customers, spectators, etc., as well as to fire brigades taking part in the activities connected with rescue actions. Methods for emission research were applied to estimate thermo-kinetic parameters related to smoke and toxic gases. The methods fall into two types: full scale methods reflect fire conditions and small laboratory scale methods having a significantly lower degree of reflection. This paper presents the results of studies on the influence of BAK-1 and Flamasepas-2 fire retardants produced in Lithuania and applied for timber on the selected parameters of the fire environment. Experimental studies were conducted using a cone calorimeter (small scale) in the closed compartment equipped with measuring devices (full scale). The undertaken studies have demonstrated that considering some parameters, such as heat release rate (HRR), a positive effect of the lower amount of the released heat can be obtained. Unfortunately, in case of the major part of the studied parameters, including time to ignition, CO concentration and extinction parameter reflecting smokiness, worse results (shorter time, higher CO values and higher extinction coefficient) have been observed for the treated timber rather than for the non-impregnated one. The obtained results have showed combustion with piloted ignition. In case of no piloted ignition, the results were slightly different. For all studied specimens treated with fire retardants, no ignition was observed and tests were terminated following 15 minutes. CO concentration and extinction parameter (smokiness) were higher for non-impregnated timber. Full scale experiments have confirmed the above provided information; moreover, it has been found that the application of fire retardant has no significant impact on temperatures in the compartment.

Keywords: pine timber, fire retardant, treatment, fire, toxicity, heat source, combustion product, carbon monoxide.

1. Introduction

Fire is an out-of-control phenomenon creating a direct danger to human's health and life. There are factors to be encountered that endanger not only people inside the building but also those performing rescue works during fire occurrence. These factors include (Buhanan 2002; Kolbrecki 2000):

– toxic combustion products,
– flame and high temperature (heat),
– reduction in oxygen concentration,
– instability of constructions,
– reduced visibility (smoke).

Each of the above introduced factors and its effect on escape behaviour is briefly discussed below.

Time available for escape is a period between the time of ignition and that following conditions preventing occupants from safe evacuation. In the United States of America and Great Britain, more than 50% of all deaths in fires have been caused by toxic combustion products constituting smoke (Stec, Hull 2010; Brushlinsky *et al.* 2009).

Unfortunately, this opinion is not sufficiently stressed in fire studies, standards and other legal documents. For instance, in building standards, fire models are based on the structural properties of the building, building materials and evacuation routes. Recently, though the effect of finishing materials has been assessed, the impact of toxic combustion products has not been sufficiently and accurately considered. Time to ignition, heat conductivity, flame propagation, and in some cases, smoke produced of building materials have been taken into account. The above mentioned parameters connected with the fire hazard of building materials can be obtained performing standard tests. The toxicity of building materials can be determined by applying other standards, depending on legal documents valid in the given country or region. For instance, in Europe, the classification of building materials based on reaction to fire is obligatory (EN 13501), which does not consider the emission of combustion products during fire. The impact of toxic combustion products is taken into account in fire models by means of transportation. For example, the International Maritime Organization (IMO) classifies finishing materials applied in ships according to the toxicity of the emitted fire smoke (IMO 1998). Similar requirements with regards to toxicity evaluation during fire are used for finishing materials in aircrafts (Airbus Industry document ABD0031).

Generally, it can be concluded that still there are no standards or other legal documents including regulations regarding fire smoke toxicity generated during the fire in the building (Gann 2004).

Gaseous combustion products form a toxic mixture from smoke during fire, which has a big influence on time required for evacuation from the building. Smoke significantly reduces visibility and obstructs breathing. The most important combustion product, with regards to which toxicity is estimated, is carbon monoxide (Tewarson 2002; Tuovinen 2002). The results of material combustion and release of gaseous combustion products described in literature often consider small scale methods. However, in order to validate them, they should be compared with the study results obtained in a full scale and under real conditions prevailing during fire (Stec, Hull 2010). Peacock *et al.* (2004) have stated that toxic combustion products emitted during real fire are rarely described and found in literature (Hansen 2002; Konecki 2007).

The determination of risk to human's health and life is caused by material effects during fire and is crucial from the stand point of fire safety engineering. A correct estimation of the concentration of gaseous products during real fires in a full scale is not easy. The results currently taken into account significantly differ from those occurring during fires. Laboratory studies conducted in a small scale usually are suitable for comparing emitted combustion products.

In the recent decades, the number of studies conducted in a full scale has significantly decreased. Taking into account the whole range of full scale studies, only in a few cases (see a list below), concentrations of combustion products are obtained (Stec, Hull 2010):

a) ISO 9705: "Room corner test";
b) ISO 24473: "Open calorimeter";
c) EN 13823: "Single burning item" (SBI);
d) IEC 60332-3-10/EN 50266-1: "Large scale cable test";
e) IMO: "Fire test of a fixed gaseous fire extinguishing system" and IMO: "Sprinkler test".

All the above mentioned methods can be modified; for example, to determine larger quantities of gaseous combustion products. Full scale studies described above belong to standard studies. There are other full scale studies estimating risk emerging in the buildings during different types of fires: fire in the room with furniture (Konecki 2007), fire in the hospital, propagation of gaseous combustion products in corridors (Robinson *et al.* 2007; Hertzberg *et al.* 2005), fire in transportation (Hammarstrom, Axellson 2008; Arvidson *et al.* 2008), fire in industry (Blonqvist, Persson 2008; Persson, Blonqvist 2007) etc.

The consequences of fire such as extinguishing before spreading may be reduced by performing effective prevention actions during the emergence of fire (Buhanan 2002). One of the possibilities of implementing effective prevention is the usage of materials protecting from the impact of fire, i.e. fire retardants (Ozkaya *et al.* 2007; Gu *et al.* 2007). For building materials, i.e. timber constructions impregnated with fire retardants, time to flame combustion is longer and flame propagation rate is lower (Karpovič 2009a; Gu *et al.* 2007). The field of fire protection examines fire resistance of ceramics (Abraitis, Stankevičius 2007; Žurauskienė, Nagrockienė 2007), concrete (Chung *et al.* 2007; Abramowicz, Kowalski 2007), ferro-concrete (Zavalis, Šneideris 2010; Bednarek, Ogrodnik 2007), steel (Bednarek, Kamocka 2006), the application of the zone model for investigating the combustion of different flammable materials (Gałaj 2007), the combustion of polymeric materials (Konecki, Półka 2009) as well as the impact of isolating materials on timber strength (Bednarek, Kaliszuk-Wietecka 2007), the combustion of timber treated with fire retardants, the effectiveness of fire retardants (Karpovič 2009b; Półka 2008), the hazardousness of pine timber and cork-oak while fuming (Karpovič, Šukys 2009), the variability of charring along wooden wall studs (Just, Tera 2010) and reaction-to-fire of nine different wood species having different density and thickness (Harada 2001). Lewin (2005) emphasized the need for research on timber treated with fire retardants. There are many unanswered questions concerning the protection of timber against fire. One of the above discussed issues is the toxicity of timber impregnated with fire retardants during thermal degradation. The toxicity of timber impregnated with fire retardants has been partly analysed in work by Šukys and Karpovič (2010).

The present paper presents a sequence of studies on the influence of fire retardant agents in a form of two types of fire retardants BAK-1 and Flamasepas-2 applied for timber produced in Lithuania. The aim of this work was to conduct small scale studies using a cone calorimeter and full scale studies applying the closed compartment and suitable measuring equipment. The main objective of analysis was to compare the values of fire parameters (HRR, CO concentration, extinction coefficient etc.) selected during the combustion of non-impregnated and impregnated pine timber using two above mentioned fire retardants and employing two methods.

The authors have focused on drawing a conclusion of applying some fire retardants for pine timber used for building engineering based on the conducted studies.

2. Small Scale Tests: Tested Materials and Testing Methods

Small scale tests were performed in the Main School of Fire Service using a cone calorimeter (open test). The testing method using the cone calorimeter is based on the fact that the total combustion heat is essentially proportional to the amount of oxygen required for combustion. The calculated ratio shows that the use of 1 kg of oxygen releases 13.1×10^3 kJ of heat.

To investigate the influence of impregnation on combustion properties, tests for the following three main groups of specimens were performed:

– non-treated pine timber,
– pine timber treated with fire retardant Flamasepas-2,
– pine timber treated with fire retardant BAK-1.

Fire retardants applied for the treatment of pine timber specimens were manufactured and used in Lithuania.

The dimensions of all specimens were 100×100×20 mm. Each specimen was exposed to the surface heat source of 30 kW/m^2. The tests were performed two times (with and without piloted ignition) for the same type of timber.

The samples were tested in a horizontal position. For each specimen, the following values were obtained: time to ignition (TTI [s]), maximum heat release rate (HRR_{max} [kW/m^2]), time to maximum heat release rate (T_{HRRmax} [s]), total heat released (THR [MJ/m^2]), mass loss rate (MLR [g/s]), specific smoke extinction area (SEA [m^2/kg]) and efficient heat of combustion (EHC [MJ/kg]). Besides changes in HRR, mass loss, the concentration of oxygen, carbon monoxide, dioxide etc. were obtained. General views of the cone calorimeter and specimens before and during the tests are shown in Figs. 1–3.

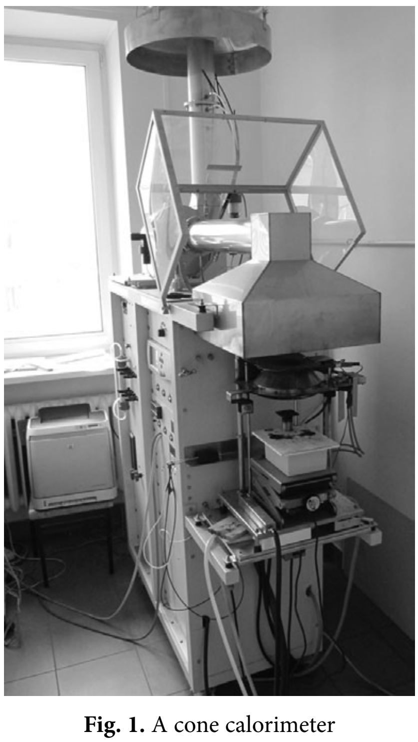

Fig. 1. A cone calorimeter

Fig. 2. Pine timber specimen prepared for experimentation

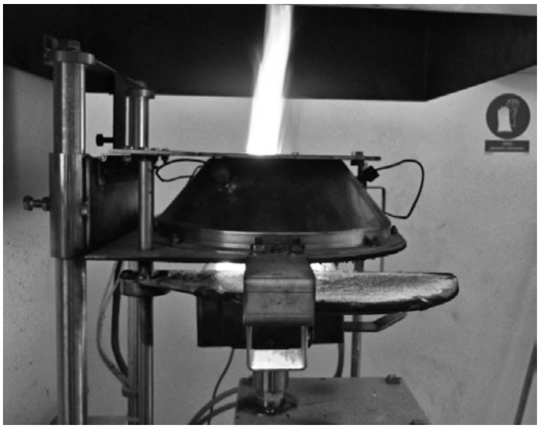

Fig. 3. Pine timber specimen during the experiment

3. Small Scale Test Results and Analysis

Maximum values and corresponding times for non-treated and treated pine timber specimens of combustion parameters such as HRR (heat release rate), EHC (effective heat combustion), MLR (mass loss rate), SEA (specific extinction area), CO_y (carbon monoxide yield) and CO_{2y} (carbon dioxide yield) are given in Table 1 to show combustion with piloted ignition and in Table 2 to indicate combustion without piloted ignition. In addition, time to ignition, the mean values of the parameters mentioned above, the total oxygen consumed, mass lost, TSR (total smoke release) and TSP (total smoke production) are included in Table 3 to point out combustion with piloted ignition and in Table 4 – without piloted combustion. The average time to ignition in case of ignition stimulus was:

a) 31 s for timber impregnated with Flamasepas-2,
b) 46 s for timber impregnated with BAK-1,
c) 74 s for non-impregnated timber.

There was no ignition of material during the combustion of each of the three samples without ignition stimulus during a 15 minute test. Thus, it can be assumed that in this case, time to ignition is equal to infinity. The results of cone calorimeter tests with piloted ignition for non-treated and treated specimens are presented in the form of graphs as a function of time: HRR (Fig. 4), THR (Fig. 5), CO concentrations in two time intervals (Fig. 6 and 7), CO production rate in two time intervals (Figs. 8 and 9) and extinction coefficient (Fig. 10).

Table 1. Maximum values of selected combustion parameters and corresponding times for non-treated and treated pine timber specimens (with piloted ignition)

Parameter	Units	Non-treated	Treated with F*	Treated with B**
		time value	time Value	time value
HRR	kW/m^2	85 204.7	1010 166.74	980 146
EHC	MJ/kg	1215 48.87	1250 70.25	1210 46.63
MLR	g/s	80 0.155	985 0.1612	960 0.145
SEA	m^2/kg	1215 264.25	995 343.75	1080 262.90
CO_y	kg/kg	1255 0.32	1250 0.39	1300 0.23
$CO2_y$	kg/kg	1215 3.533	1250 5.681	1210 3.166

* Flamasepas-2
** BAK-1

Table 2. Maximum values of selected combustion parameters and corresponding times for non-treated and treated pine timber specimens (without piloted ignition)

Parameter	Units	Non-treated	Treated with F*	Treated with B**
		time value	time value	time value
HRR	kW/m^2	545 24.42	60 11.25	900 37.26
EHC	MJ/kg	685 26.31	500 2.037	5 65.68
MLR	g/s	0 0.103	335 0.1	900 0.2075
SEA	m^2/kg	875 2546	825 1477	200 635.9
CO_y	kg/kg	875 0.423	825 0.873	200 0.4057
$CO2_y$	kg/kg	875 2.74	825 1.858	5 7.107

* Flamasepas-2
** BAK-1

Table 3. Some characteristic parameters obtained during the combustion of non-treated and treated pine timber (with piloted ignition)

No.	Parameter	Units	Non-treated	Treated with F	Treated with B
1	Time to ignition	s	74	31	46
2	Mean HRR	kW/m^2	82.74	79.87	71.42
3	Mean EHC	MJ/kg	11.04	11.27	10.38
4	Mean MLR	g/s	0.066	0.063	0.061
5	Mean SEA	m^2/kg	28.8	20.62	22.04
6	Mean CO_y	kg/kg	0.005	0.016	0.0143
7	Mean $CO2_y$	kg/kg	0.938	0.941	0.870
8	Total HRR	MJ/m^2	102.22	104.32	90.74
9	Total oxygen consumed	g	59.07	118.19	63.31
10	Mass lost	g	81.93	82.07	77.57
11	Average specific MLR	$g/s{\cdot}m^2$	7.566	8.207	8.307
12	TSR*	m^2/m^2	226.78	784.36	316
13	TSP**	m^2	2	6.93	2.79

* total smoke release
** total smoke production

Table 4. Some characteristic parameters obtained during the combustion of non-treated and treated pine timber (without piloted ignition)

No.	Parameter	Units	Non-treated	Treated with F	Treated with B
1	Time to ignition	s	∞	∞	∞
2	Mean HRR	kW/m^2	13.52	−1.048	130
3	Mean EHC	MJ/kg	2.16	−0.195	2.33
4	Mean MLR	g/s	0.055	0.0473	0.049
5	Mean SEA	m^2/kg	391.31	191.526	168.2
6	Mean CO_y	kg/kg	0.111	0.108	0.1043
7	Mean $CO2_y$	kg/kg	0.2304	0.196	0.277
8	Total HRR	MJ/m^2	12.178	0.935	11.707
9	Total oxygen consumed	g	10.5	2.71	10
10	Mass lost	g	49.71	42.73	44.37
11	Average spec. MLR	$g/s{\cdot}m^2$	6.71	5.48	5.7
12	TSR*	m^2/m^2	2200	926	844.1
13	TSP**	m^2	19.45	8.18	7.46

* total smoke release
** total smoke production

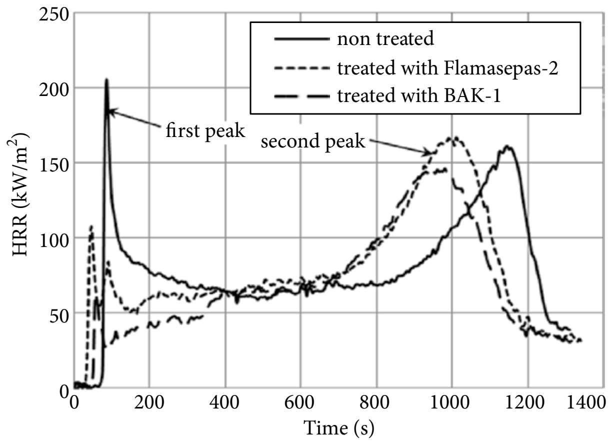

Fig. 4. Heat release rate (HRR) obtained during the combustion of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

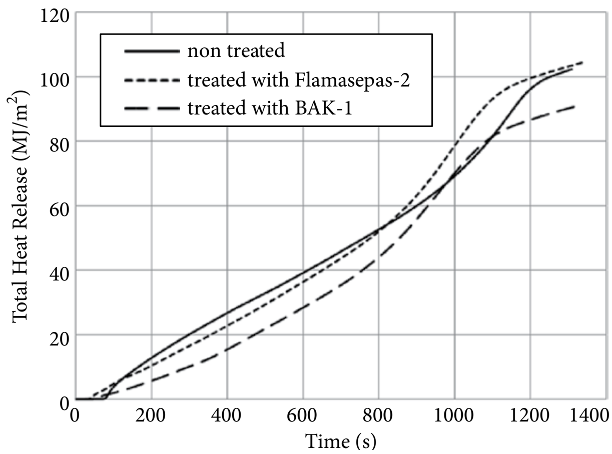

Fig. 5. Total heat release (THR) obtained during the combustion of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

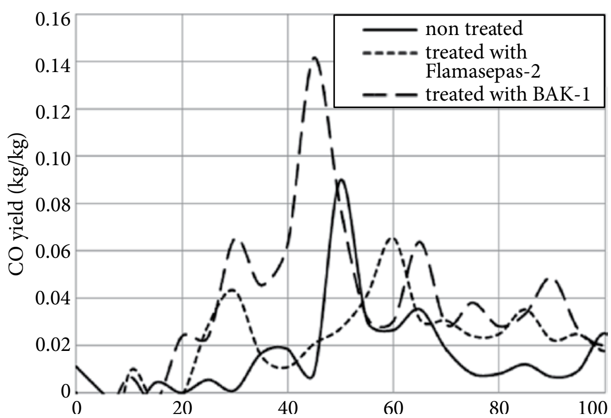

Fig. 6. A peak of CO yield obtained during the first stage of combustion (time interval: 0–100 s) of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

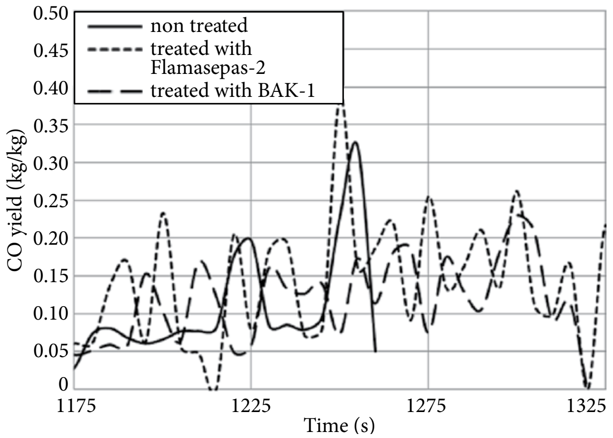

Fig. 7. A peak of CO yield obtained during the last stage of combustion (time interval: 1175–1325 s) of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

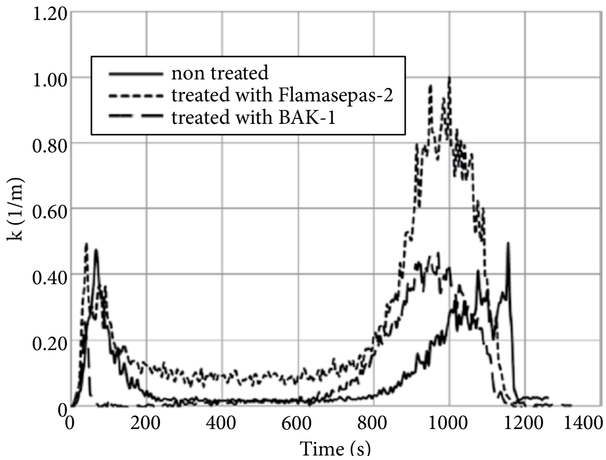

Fig. 10. The extinction coefficient obtained during the combustion of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

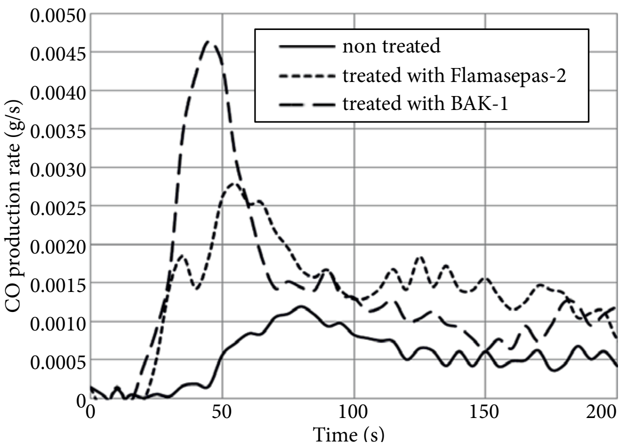

Fig. 8. CO production rate obtained during the first stage of combustion (time interval: 0–200 s) of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

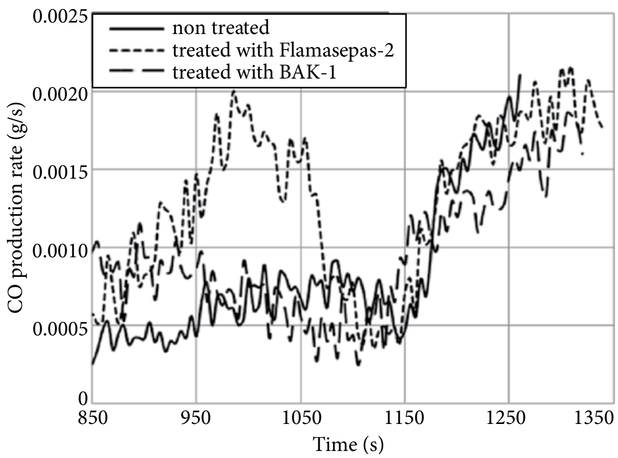

Fig. 9. CO production rate obtained during the last stage of combustion (time interval: 850–1350 s) of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (with piloted ignition)

For comparison, the graphs presenting CO concentration and extinction coefficient obtained during the combustion of the same type of specimens without piloted ignition are given in Figs. 11 and 12.

The combustion process of the studied pine timber has got some local peaks of HRR:

a) the first peak at the initial stage of combustion with piloted ignition (between 40 and 100 s) with the highest value of about 204 kW/m^2 (t = 80 s) for non-impregnated pine timber, 107 kW/m^2 (t = 45s) for timber impregnated with Flamasepas-2 and 61 kW/m^2 for timber impregnated with BAK-1;

b) the second peak at the final stage of combustion with piloted ignition (between 900 and 1200 s) with the highest value of about 161 kW/m^2 (t = 1145 s) for non-impregnated pine timber, 165 kW/m^2 (t = 1000 s) for specimen impregnated with Flamasepas-2 and 146 kW/m^2 (t = 980 s) for specimen impregnated with BAK-1 (see Fig. 4).

The observed peak values taken from the moment of ignition are approximately equal to 14 s for non-impregnated and 11 s for impregnated timber. A rapid increase in HRR occurred at the moment of ignition for all tested specimens. The highest value of HRR slope exceeding 18 kW/(m^{2}s) for non-treated pine timber and the lowest one below 5 kW/(m^{2}s) for specimen treated with BAK-1 have been observed. The rate of HRR increase in the last stage of combustion was significantly lower and did not exceed the value of about 1 kW/(m^{2}s).

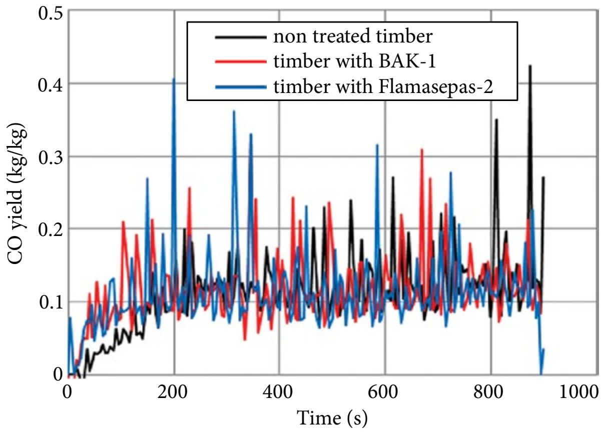

Fig. 11. A peak of CO yield obtained during the combustion of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (without piloted ignition)

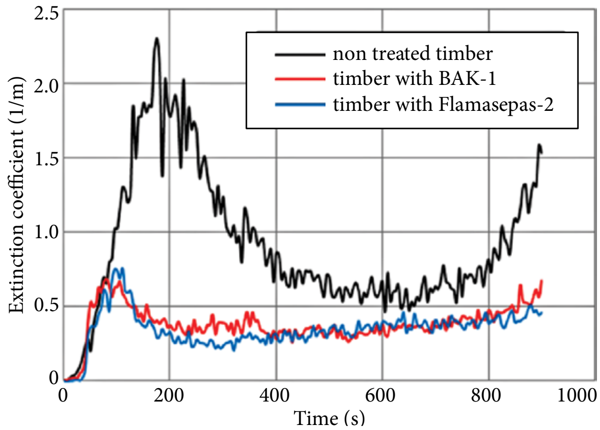

Fig. 12. The extinction coefficient obtained during the combustion of non-treated and treated specimens in the cone calorimeter at the heat flux of 30 kW/m^2 (without piloted ignition)

CO concentration during the combustion process with piloted ignition is characterized by rapid growth in the first stage following approximately 30 s from the start of the experiment, and in the final combustion stage, following approximately 1175 s (see Figs. 6 and 7). Maximum CO concentrations for different specimens at the initial and final combustion stages are given in Table 5. The results show that in the first case, the highest value of about 0.14 kg/kg was obtained for pine timber impregnated with BAK-1 (after 45 s) and the lowest one of about 0.065 kg/kg for pine timber impregnated with Flamasepas-2 (after 60 s). For the remaining non-treated specimen, this value occurred following 50 s and was about 0.09 kg/kg (see Fig. 6 and Table 5). In the final stage of combustion, after 1175 s, one more growth of CO concentration can be observed. This time, the highest value of approx. 0.39 kg/kg (at 1250 s) for timber impregnated with Flamasepas-2 and the lowest value of approx. 0.23 kg/kg (at 1300 s) for timber impregnated with BAK-1 can be noticed. The maximum value of CO concentration for non-impregnated timber was about 0.32 kg/kg at 1255 s.

The CO function (see Fig. 8 and 9) indicates that the biggest changes in CO concentrations were obtained for impregnated specimens. For instance, for the sample containing BAK-1, the maximum CO value was about 0.0046 g/s (at t = 45 s), whereas for the non-treated sample this value was slightly higher than 0.001 g/s. At the end of combustion, between 850 s and 1100 s, the highest value of CO for the specimen treated with Flamasepas-2 was observed. A visible increase in CO concentration up to about 0.002 g/s for all tested specimens after t = 1150 s was noticed (see Fig. 9).

Table 5. Maximum values of CO concentration in kg/kg and corresponding times in sec obtained during the initial and combustion final stages of non-treated and treated pine timber (without piloted ignition)

Phase of combustion	Non-treated	Treated with F*	Treated with B**
	time value	time value	time value
Initial	50 0.09	60 0.065	45 0.14
Final	1255 0.32	1250 0.39	1300 0.23

* Flamasepas-2
** BAK-1

Concerning smokiness based on the function of extinction coefficient k (see Figs. 10 and 12) the following can be stated:

a) in the initial stage, the highest degree of smokiness for non-impregnated specimen (k_{max} = 0.47 1/m) and specimen impregnated with Flamasepas-2 (k_{max} = 0.50 1/m) was observed. The application of BAK-1 contributed to reduced smokiness (k_{max} = 0.25 1/m);

b) in the final stage, for specimen impregnated with Flamasepas-2, the highest degree of smokiness with the extinction coefficient of 1.0 1/m was shown, whereas for specimen with BAK-1 this value was 0.46 1/m and for the non-impregnated one – 0.49 1/m. Additionally, with reference to data disclosed in Table 6, the maximum values of coefficient *k* are shown with corresponding times for all three specimens; two combustion stages are presented and a significant shift in time of the following peaks can be seen.

Table 6. Maximum values of extinction coefficient *k* in 1/m and corresponding times obtained during the initial and final combustion stages of non-treated and treated pine timber (without piloted ignition)

Phase of combustion	Non-treated	Treated with F*	Treated with B**
	time value	time value	time value
Initial	65 0.47	40 0.50	35 0.25
Final	1155 0.49	1000 1.00	970 0.46

* Flamasepas-2
** BAK-1

4. Large Scale Tests: Methods, Tested Materials and Results

To confirm the results presented in the previous section in a large scale, fire tests have been performed in a special cabin (2.5×2.5×2.8 m) having two walls made of fire-resistant glass and two - covered with wall ceramic tiles. The compartment had a single doorway, 0.80 m wide and 2.0 m high, centred in the front wall and a controlled horizontal ventilation system mounted under the ceiling. During fire, the doors were closed and the ventilation system was off. Temperatures, CO concentration and optical smoke density were measured during fire tests. 20 K-type thermocouple trees were fixed in the compartment – 5 thermocouples on each tree fixed at the same five different levels - 0.8 m (level 1), 1.5 m (level 2), 2.0 m (level 3), 2.5 m (level 4) and 2.7 m (level 5).

Special measurement heads MG 72 produced by ALTER SA were used for registering CO concentration. Sensors MG 72 are connected with control equipment MSMR-4 that gives the output signal of standard format RS 485. Four sensors were mounted on two aluminium columns at two heights: 2.7 m (important from a ceiling jet point of view) and 1.6 m (important from evacuation conditions point of view). A view of the column with sensors is shown in Fig. 13.

Six sensors of optical smoke density were installed in the cabin and mounted on the aluminium column. The used sensors were designed and made by Cobrabid-Optica Ltd. A general scheme is drawn in Fig 14. A view of the aluminium column with the sensors is shown in Fig. 15. A principle of measurement consists of reducing the ultraviolet or infrared light beam energy which is 930 nm in length and is emitted by a transmitting photodiode generating a power of 50 mW. The light beam is received by the photodiode the surface of which covers 1 cm^2 (larger than the coming beam).

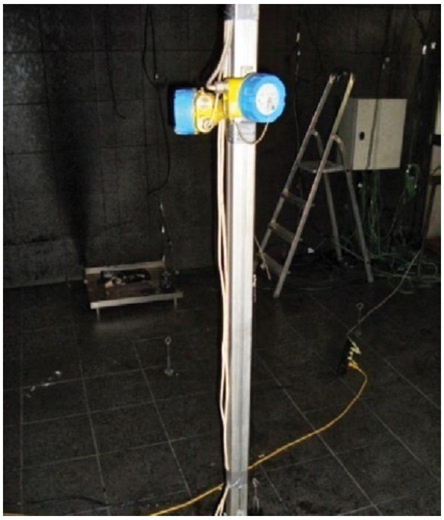

Fig. 13. A view of the aluminium column with mounted sensors MG 72

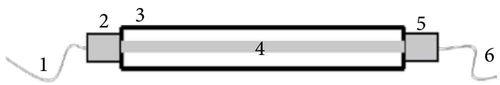

Fig. 14. The scheme of the smoke density sensor: 1 – a cable supplying a transmitting photodiode; 2 – a module with a transmitting photodiode; 3 – a mounting frame; 4 – a beam of ultraviolet or infrared rays emitted by a transmitter in the direction of a receiving photodiode; 5 – a module with a receiving photodiode; 6 – a cable transmitting signals from the receiving photodiode (Gałaj 2008)

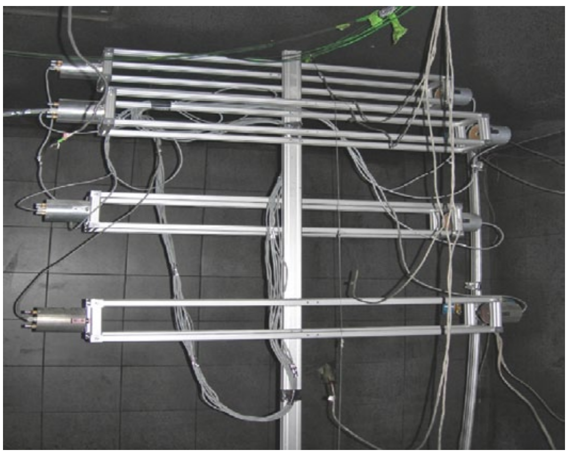

Fig. 15. A view of the column with smoke density sensors

A low output signal obtained from a receiving photodiode is then transformed into the analogue one by a special converter in the range of 0–10 V. The same device is also utilized for power supply to the sensors. The analogue signal is then transmitted to the analogue-digital converter (module ADAM 4017).

Using special module ADAM 4520, the output signals of format RS 485 are converted into format RS 232C, which can be read by a standard serial port of the computer. Then, input data are processed in the computer using special program "Adam View" enabling to display and save data in MS Excel format.

The output digital values obtained from the measuring system correspond to the voltage signals of maximal range 0–10 V. To calculate optical smoke density, the proportion between the intensity of light and voltage was assumed. It seems to be justified because of several reasons. First, smoke density determination, only the quotient of light intensities, not their values, is necessary. Second, a principle of measurement by used smoke density sensors enables to accept this solution.

The equation for optical density D can be written in the form (Gałaj, Bajko 2009):

$$D = \log \frac{U_0}{U}, \qquad (1)$$

where U_0 – voltage signal proportional to light intensity I_0 corresponding to maximum voltage signal measured at the beginning of the test (air without smoke) [V], U – voltage signal proportional to light intensity I corresponding to the current voltage signal measured during the test (air with smoke) [V].

On the basis of value D, more frequently used extinction coefficient was determined according to the following formula:

$$k = \frac{1}{x} \ln\left(\frac{U_0}{U_x}\right), \qquad (2)$$

where x – the distance between a transmitter and a receiver [m].

Visibility Z in accordance with the following relationship was also calculated at $C = 2$ (reflected light objects) and $x = 1$ m.

$$Z = \frac{C \cdot x}{(2.303) \cdot D}, \qquad (3)$$

where C – a constant depending on lighting conditions.

Three combustion processes were performed: first, using non-treated pine timber, second, using timber treated with BAK-1 and the third one using timber treated with Flamasepas-2. Views of specimens with and without timber preservative are shown in Fig. 16.

Three pieces of pine timber, each having the size of 200×200×20 mm, two placed vertically and one put on them horizontally (the impregnated side was inside the structure) were combusted in each experiment. Such structure was put on the steel tray and placed near the wall opposite to the door. The source of ignition was 250 ml of denatured alcohol. Burning samples are shown in Fig. 17.

The cabin was closed just after ignition. When fire parameters stopped increasing (steady stage of combustion), the ventilation system was started. The samples were observed after the experiment and the remains were analyzed (see Fig. 18). All specimens were tested under the same conditions.

The following selected graphs obtained during experiments with fire are presented in the paper:

a) temperature measured by the selected thermocouple located near the fire source at a height of 1.6 m (Fig. 19),
b) CO concentration measured by the sensor located in the centre at a height of 1.6 m (Fig. 20),
c) extinction coefficient at a height of 1.6 m (Fig. 21),
d) visibility range calculated on the basis of the extinction coefficient (Fig. 22).

The following specific parameters of the obtained graphs are included in the tables below:

a) the maximum values and average speed of temperatures during the first stage of combustion (Table 7),
b) the maximum values and average speed of CO concentration during the first stage of combustion as well as the time of the first appearance of carbon monoxide registered by the sensors (Table 8).

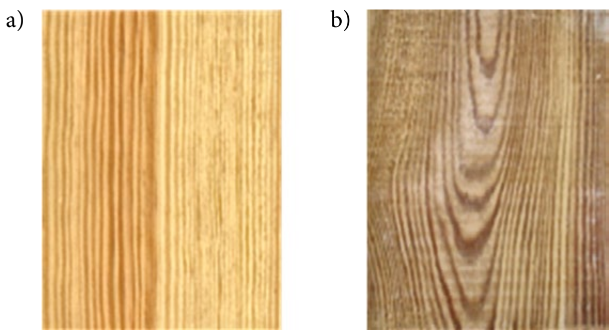

Fig. 16. A view of timber specimens: a – without preservative; b – with preservative

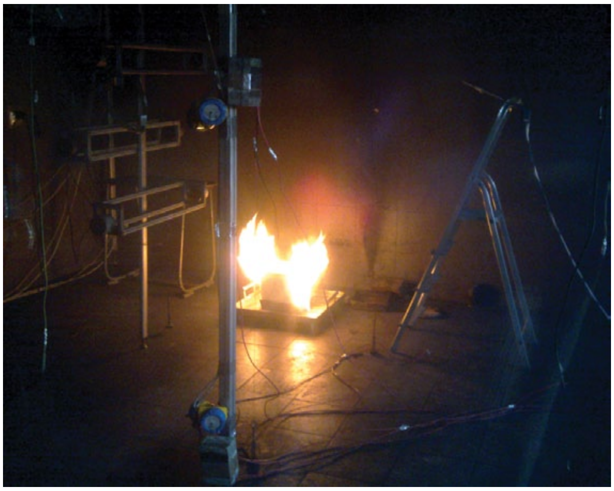

Fig. 17. A view of burning pine timber

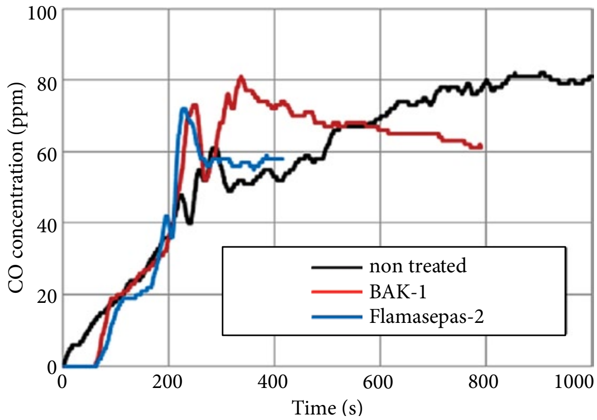

Fig. 20. CO concentration during the combustion of non-treated and impregnated pine timbers measured by the sensor in the centre of the compartment at a height of 1.6 m

Fig. 18. A view of the remains after combustion (treated timber – on the top, non-treated – on the bottom)

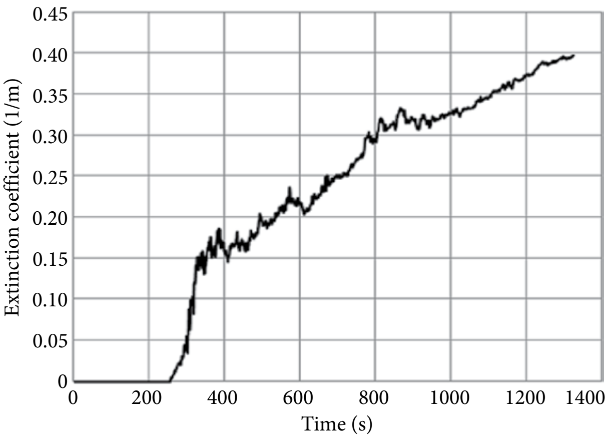

Fig. 21. The extinction coefficient during the combustion of non-treated pine timbers measured by the sensor located at a height of 1.6 m (for treated pine timbers, the extinction coefficient was equal to zero during the experiment)

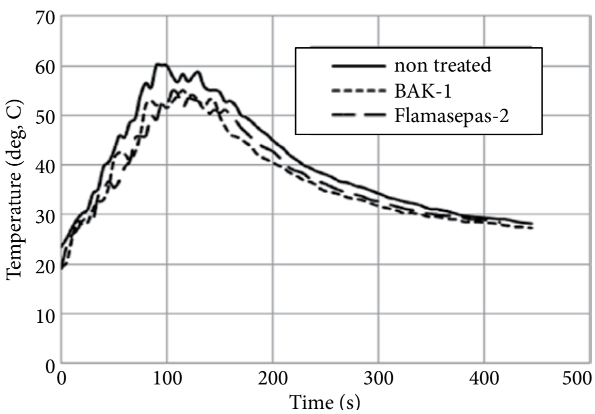

Fig. 19. Temperature during the combustion of non-treated and impregnated pine timbers measured by the thermocouple 18,3 located near the fire source at a height of 1.6 m

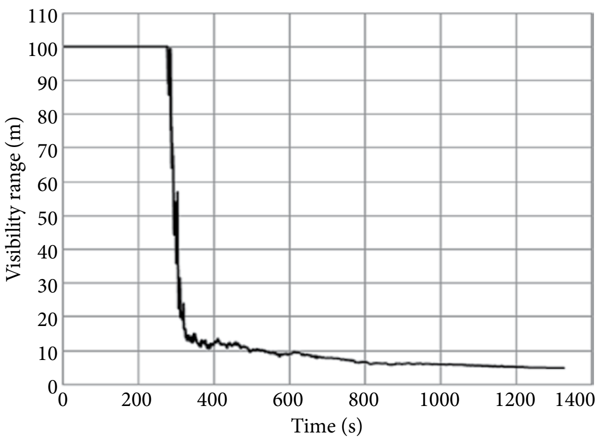

Fig. 22. Visibility range during the combustion of non-treated pine timbers measured by the sensor located at a height of 1.6 m (for treated pine timbers, visibility was equal to zero during the experiment)

Table 7. The maximum values and average speed of growth in temperature during the first stage of combustion

Material	Maximum values [deg C]	Average speed [deg C/s]
Pine timber	58.8	0.39
BAK-1	55.0	0.37
Flamasepas-2	54.9	0.37

Table 8. The maximum values and average speed of growth in CO concentration during the first stage of combustion and time for the first appearance of carbon monoxide

Material	Maximum values [ppm]	Average speed [ppm/s]	Time of appearance [s]
Pine timber	82	0.22	0
BAK-1	81	0.48	61
Flamasepas-2	72	0.62	63

Conclusions arising from the analysis of the results of the fire test have been formulated and are listed in the next chapter.

5. Conclusions

After analyzing the results obtained using the cone calorimeter and full scale fire, the following general conclusions can be formulated:

1. The treatment of pine timber with fire retardant causes a significant reduction in the time of specimen ignition in the case of piloted ignition only. Ignition time for timber treated with Flamasepas-2 (31 s) and BAK-1 (46 s) are evidently less than that for non-treated timber (74 s). This surprising property was confirmed in many experiments. The tests carried out by other scientists in Lithuania showed that the opposite situation might occur in the case of combustion without piloted ignition.

   The presented studies have confirmed the above displayed information, since in case of three studied specimens, during the tests without ignition stimulus, ignition did not occur during 15 minutes. Considering the above results, it can be concluded that the use of tested additives can bring unexpected results in some circumstances.
2. The impregnation of pine timber with Flamasepas-2 and BAK-1 significantly reduces (almost twice) the rate of the heat released in the initial combustion period (first 100 s) crucial for the safety of people evacuation. It reflects the rate of temperature increase in the compartment, which is much slower in the case of pine timber treated with fire retardant. In the final combustion stage (over 800 s), differences are insignificant and do not exceed 25 kW/ m^2.
3. The treatment of pine timber with fire retardant does not reduce the maximum value of CO concentration (in case of ignition with flame); moreover, it can even increase its value in the initial stage of combustion, as was observed in case of BAK-1 (difference was about 0.05 kg/kg compared to non-impregnated specimen). The treatment of specimen with Flamasepas-2 reflected lower maximum concentration making approx. 0.025 kg/kg. After 70 s, the observed values of CO rapidly decreased for all studied specimens and stabilized at the level of 0.02 kg/kg. After 1200 s, CO concentrations increased repeatedly with the maximum value for this stage obtained for specimen treated with Flamasepas-2 (about 0.39 kg/kg) and with the lowest value for specimen treated with BAK-1 (about 0.23 kg/kg).
4. In the initial combustion stage, the highest CO emission rate was observed for specimen impregnated with BAK-1 (the maximum value of 0.0045 g/s) and the lowest one for non-impregnated specimen (the maximum value of about 0.0011 g/s). The maximum emission rate for specimen with Flamasepas-2 was about 0.0028 g/s. The above data indicate an unfavourable influence of impregnation on the flammable properties of pine timber.
5. The application of fire retardant has an impact on smokiness (extinction coefficient) in the initial combustion stage, which is crucial for evacuation actions as well as for the final combustion stage. BAK-1 has proven to be the most suitable. Its treatment reduced smokiness twice in the first minutes of specimen combustion compared to non-impregnated pine timber. The influence of Flamasepas-2 was not significant; however, it also caused a reduction in the extinction coefficient for approx. 0.2 *l*/m. On the other hand, due to shorter ignition time, smokiness appeared faster in the case of impregnated wood compared to the non-impregnated one. In the final combustion stage, the highest degree of smokiness (twice as high as in the initial combustion stage) along with the extinction coefficient of about 1.0 *l*/m for specimen treated with Flamasepas-2 was observed.

6. The application of fire retardant has no significant impact on the temperatures in the compartment. The only difference consists in a slightly higher maximum value and average increase rate during the fire development stage for non-impregnated timber. Difference makes about 4°C and 0.02 °C/s respectively, without regard to the type of fire retardant.
7. The maximum value of carbon oxide concentration is slightly lower (approx. 10 ppm) (full scale experiments) for timber treated with Flamasepas-2 fire retardant comparing to non-impregnated timber and makes about 72 ppm. In case of BAK-1 fire retardant, maximum concentrations were almost the same and made 82 ppm. In addition, for non-impregnated timber, a constant increase in CO concentration up to 80 ppm have been observed while in other cases, the values have oscillated, and after a shorter time (about 260 s) for Flamasepas-2 and longer (about 480 s) for BAK-1, CO values have stabilized at 60 ppm (about 20 ppm lower than non-impregnated timber).
8. The average increase rate of CO values in the first stage of fire is significantly higher for timber treated with fire retardant (0.48 ppm/s for BAK-1 and 0.62 ppm/s for Flamasepas-2) rather than for non-impregnated one (0.22 ppm/s). However, the time of CO detection in case of non-impregnated timber is almost instantaneous while in case of timber treated with fire retardants, it took approx. 1 minute, which enables safety evacuation of people from the compartment (full scale experiments).
9. After 252 s from the start of fire, a rapid increase in the extinction coefficient reflecting smokiness degree in the compartment can be observed only in case of non-impregnated timber. Between 250 and 320 s, a rapid decrease in visibility up to the safety level of approx. 5 m have occurred. During the whole test on impregnated timber, the extinction coefficient was at zero level, which indicates no smoke in the compartment (full scale experiments).

Taking into account the results obtained from both experiments with the combustion of non-treated pine timber specimens treated with two different fire retardants, including Flamasepas-2 and BAK-1, it can be concluded that impregnation influences the combustion process decreasing (see conclusion 2) the rate of heat release and increasing CO emission (in case with piloted ignition). Generally, lower concentrations have been observed for specimens impregnated with Flamasepas-2. Concerning only CO concentrations, the results are not that unequivocal, since treatment with BAK-1 can increase its concentration in the initial stage of combustion. However, taking into account the results obtained during timber combustion in full scale tests, especially CO values and visibility ranges, it can be stated that the use of fire retardants increases human safety by delayed toxic CO occurrence, its lower concentrations and a lack of smoke if compared to non-impregnated timber. Although the obtained fire parameters in all combustion cases in full scale do not pose any real danger for people, since they do not exceed limit values (60°C in case of temperature, 100 ppm in case of CO concentration and 5 m in case of visibility range), considering a limited amount of flammable material, it can be expected that the values will be exceeded when a larger amount is used. However, the curves of fire parameters should remain the same. Taking into account all obtained results, the following general conclusion can be made: both studied fire retardants partly fulfil their tasks while Flamasepas-2 shows slightly better performance than BAK-1 from the human safety point of view.

In order to choose suitable fire retardant and reducing an unfavourable impact of combustion on human during potential internal fire, each situation should be analysed independently, considering the smokiness and generation of toxic combustion products.

References

Abraitis, D.; Stankevičius, V. 2007. Heat conductivity modelling in ceramics and fire – resistant, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 1: 2–6. Ed. by Skibniewski, M. J.; Vainiūnas, P.; Zavadskas, E. K. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika.

Abramowicz, M.; Kowalski, R. 2007. Residual mechanical material properties for the reassessment of reinforced concrete structures after fire, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 3: 1147–1151. Ed. by Skibniewski, M. J.; Vainiūnas, P.; Zavadskas, E. K. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika.

Airbus Industry document ABD0031, 7–4, *Toxicity*.

Arvidson, M.; Axelsson, J.; Hertzberg, T. 2008. *Large-scale Fire Tests in a Passenger Cabin*. SP Testing Research Institute of Sweden. Boras.

Bednarek, Z.; Kaliszuk-Wietecka, A. 2007. Analysis of the fire-protection impregnation influence on wood strength, *Journal of Civil Engineering and Management* 13(2): 79–85. doi:10.1080/13923730.2007.9636423

Bednarek, Z.; Kamocka, R. 2006. The heating rate impact on parameters characteristic of steel behaviour under fire conditions, *Journal of Civil Engineering and Management* 12(4): 269–275. doi:10.1080/13923730.2006.9636403

Bednarek, Z.; Ogrodnik, P. 2007. Testing steel – concrete bond in fire conditions, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 3: 1152–1158. Ed. by Skibniewski, M. J.; Vainiūnas, P.; Zavadskas, E. K. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika.

Blonqvist, P.; Persson, H. 2008. *Self-heating in storages of wood pellets*. World Bioenergy 2008. Jonkopi.

Brushlinsky, N. N.; Hall, J. R.; Sokolov, S. V.; Wagner, P. 2009. *World fire statistics 14*. CTIF International association of fire and rescue services. 580 p.

Buhanan, A. H. 2002. *Structural design for fire safety*. Wiltshire: John Wiley and Sons, LTD. 421 p. ISBN 0-471-88993-8.

Chung, Kyung-soo; Park, Su-hee; Choi, Sung-mo. 2007. Fire resistance of concrete filled square steel tube columns subjected to eccentric axial load, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 2: 500–505. Ed. by Skibniewski, M. J.; Vainiūnas, P.; Zavadskas, E. K. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika.

EN 13501:2007+A1:2010. Fire classification of construction products and building elements.

Gałaj, J. 2007. Computer tests of fire in multi-storey building for different flammable materials, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 3: 1174–1177. Ed. by Skibniewski, M. J.; Vainiūnas, P.; Zavadskas, E. K. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika.

Gałaj, J. 2008. Comparison of the changes in temperature and carbon monoxide and dioxide concentrations in the unventilated compartment during fire with polyurethane foam or pine wood, in *SGSP Scientific Papers*, vol. 36: 41–60. Warsaw.

Gałaj, J.; Bajko, G. 2009. Investigation of smoke density and visibility in unventilated compartment during full-scale fire tests with polyurethane foam and pine wood, in *Proceedings of the 18-th symposium "Fire Protection 2009"*, 09–10 September 2009, Ostrava.

Gann, R. G. 2004. Sublethal Effects of Fire Smoke *Fire Technology* 40: 95–104. doi:10.1023/B:FIRE.0000016898.88522.79

Gu, J. W.; Zhang, G. C.; Dong, S. L.; Zhang, Q. Y.; Kong, J. 2007. Study on preparation and fire-retardant mechanism analysis of intumescent flame-retardant coatings, *Surface and Coatings Technology* 201: 7835–7841. doi:10.1016/j.surfcoat.2007.03.020

Hammarstrom, R.; Axellson, J. 2008. *Bus Fire Safety*. SP Testing Research Institute of Sweden. Boras.

Hansen, A. S. 2002. Prediction of Heat Release in the Single Burning Item Test, *Fire and Materials* 26: 87–97. doi:10.1002/fam.789

Harada, T. 2001. Time to ignition, heat release rate and fire endurance time of wood in cone calorimeter test, *Fire and Materials* 25: 161–167. doi:10.1002/fam.766

Hertzberg, T.; Tuovinen, H.; Blomqvist, P. 2005. *Measurement and Simulation of Fire Smoke*. SP Swedish Testing and Research Institute. Boras.

IMO. 1998. IMO FTP Code Resolution MSC 61(67), Chapter 1, Annex 1, Part 2.

Just, A.; Tera, T. 2010. Variability of Charring Along the Wooden Wall Studs, *Engineering Structures and Technologies* 2(4): 119–128. Vilnius: Technika. doi:10.3846/skt.2010.16

Karpovič, Z. 2009a. Antipireniniais tirpalais impregnuotos medienos užsiliepsnojimo priklausomybė nuo medienos tankio, *Mokslas – Lietuvos ateitis* [Science – future of Lithuania] 1(5): 30–33. doi:10.3846/185

Karpovič, Z. 2009b. Lietuvoje sertifikuotų antipireninių tirpalų efektyvumo tyrimas, in *The Conference „Statybinės konstrukcijos"* [Building Constructions]. Ed. by Šapalas, A.; Valivonis, J.; Juknevičius, L. February 6, 2009, Vilnius, Lithuania. Vilnius: Technika, 67–72.

Karpovič, Z.; Šukys, R. 2009. Pušies medienos ir kamštinio ąžuolo pavojingumas smilkimo metu, *Sveikatos mokslai* [Health Sciences] 3: 2425–2429.

Kolbrecki, A. 2000. *Toksyczność i dymotwórczość wyrobów budowlanych*. Katowice. 300 p.

Konecki, M. 2007. *Wpływ szybkości wydzielania ciepła I emisji dymu na rozwój pożaru w układzie pomieszczeń*. Warsaw. 258 p.

Konecki, M.; Półka, M. 2009. Simple fire model for comparative studies of critical conditions during combustion of chosen polymer materials, *Journal of Civil Engineering and Management* 15(3): 247–257. doi:10.3846/1392-3730.2009.15.247-257

Lewin, M. 2005. Unsolved problems and unanswered questions in flame retardante of polymers, *Polymers Degradation Stability* 88: 9–13.

Ozkaya, K.; Cemil Ilce, A.; Burdurlu, E.; Aslan, S. 2007. The effect of potassium karbonate, borax and wolmanit on the burning characteristics of oriented strandboard (OSB), *Construction and Building Materials* 21: 1457–1462. doi:10.1016/j.conbuildmat.2006.07.001

Peacock, R. D.; Averill, J. D.; Reneke, P. A.; Jones, W. W. 2004. Characteristics of Fire Scenarios in Which Sublethal Effects of Smoke are Important, *Fire Technology* 40: 127–147. doi:10.1023/B:FIRE.0000016840.14947.61

Persson, H.; Blonqvist, P. 2007. *Fire and fire extinguishment in silos*. Interflam 07. Interscience Communications Ltd, London.

Półka, M. 2008. The influence of flame retardant additives on fire properties of epoxy materials, *Journal of Civil Engineering and Management* 14(1): 45–48. doi:10.3846/1392-3730.2008.14.45-48

Robinson, J. E.; Hull, T. R.; Lebek, K.; Stec, A. A.; Galea, E. R.; Mahalindham, A.; Jia, F.; Patel, M. K.; Persson, H. 2007. *Assessment of the impact of computed and measured fire environments on building evacuation using bench and real scale data. Interflame 07*. Interscience Communications Ltd, London.

Stec, A.; Hull, R. 2010. *Fire toxity*. Woodhead publishing limited. 688 p.

Šukys, R.; Karpovič, Z. 2010. Research on toxicity of pine timber treated and non-treated with fire retardants, in *The 10th International Conference "Modern Building Materials,* *Structures and Techniques"*. Vilnius, Lithuania. Vilnius: Technika, 1306–1313.

Tewarson, A. 2002. *SFPE Handbook of fire protectio engineering*. 3-rd edition. NFPA, Quincy, MA.

Tuovinen, H. 2002. *CO Formation from soot and CO_2 in the hot gas layer*. SP Swedish National testing and research institute. Boras.

Zavalis, R.; Šneideris, A. 2010. The Effect of High Temperature on Reinforced Concrete Structures, *Statybinės konstrukcijos ir technologijos* [Engineering Structures and Technologies] 2(1): 12–21. doi:10.3846/skt.2010.02

Žurauskienė, R.; Nagrockienė, D. 2007. Influence of the burning parameters to the properties of ceramic bodies, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 1: 209–217. Ed. by Skibniewski, M. J.; Vainiūnas, P.; Zavadskas, E. K. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika.

IMPREGNAVIMO POVEIKIO PUŠIES MEDIENOS DEGUMUI TYRIMAI TAIKANT KŪGINĮ KALORIMETRĄ IR NATŪRINIŲ TYRIMŲ METODĄ

J. Gałaj, Z. Karpovič, W. Jaskółowski

Santrauka. Gaisrinė sauga – vienas pagrindinių reikalavimų, kurį privalo atitikti pastatai. Gaisrinės saugos užtikrinimas svarbus ir pastato gyventojams, naudotojams, klientams, žiūrovams, ir gelbėtojams, vykdantiems gelbėjimo darbus. Vertinant termokinetinius dydžius, susijusius su dūmais ir nuodingais degimo produktais, taikomi degimo produktų vertinimo tyrimo metodai. Šie metodai skirstomi į natūrinius, geriausiai pakartojančius gaisro parametrus, ir mažų bandinių, kuriuose šis pakartojimas gerokai mažesnis. Straipsnyje pristatyti antipireninių tirpalų BAK-1 ir Flamasepas-2, gaminamų Lietuvoje ir naudojamų medienai impregnuoti, poveikio gaisro parametrams tyrimai. Tyrimai atlikti naudojant kūginį kalorimetrą (mažų bandinių tyrimai) uždaroje patalpoje su įrengta matavimo įranga (natūriniai tyrimai). Tyrimai parodė, kad antipireniniai tirpalai sumažina šilumos išskyrimo greitį (HRR). Atvirkštinė situacija susidaro vertinant laiką iki užsiliepsnojimo, CO išsiskyrimą ir dūmingumą. Šie antipireniniais tirpalais impregnuotos medienos gaisro parametrai, palyginti su neimpregnuota mediena, pablogėja (trumpėja laikas iki užsiliepsnojimo, padidėja CO išsiskyrimas ir dūmingumas). Šie rezultatai gauti naudojant papildomą šaltinį, uždegantį bandinio paviršių. Atliekant tyrimus, kuriuose šis šaltinis nebuvo naudotas, gauti priešingi rezultatai. Nė vienas iš tiriamų impregnuotų bandinių neužsiliepsnojo, o tyrimai buvo nutraukiami praėjus 15 min., CO išsiskyrimas ir dūmingumas buvo didesnis neimpregnuotos medienos. Tai patvirtinta natūriniais tyrimais, kurių metu nustatyta, kad pušies medienos impregnavimas neturi didelės įtakos temperatūros pokyčiams kilus gaisrui patalpoje.

Reikšminiai žodžiai: pušies mediena, antipireninis tirpalas, impregnavimas, gaisras, toksiškumas, šilumos šaltinis, degimo produktas, anglies monoksidas.

Jerzy GAŁAJ. PhD, the Head of the Hydromechanics and Fire Water Supply Institute of the Fire Technique Department of Fire Safety Engineering Faculty at the Main School of Fire Service, Warsaw, Slowackiego Str. 52/54, 01-629, Poland. Starting from 1995 - a member of the Polish Society of Theoretical and Applied Mechanics and the member of the Society of Fire Protection Engineers. Publications: over 50 scientific publications. Research interests: fire modelling, combustion of timber wood and polymers, extinguishing systems. Recently, has been particularly interested in the development of hybrid fire models.

Zbignev KARPOVIČ. MA, a doctoral student, at the Department of Labour Safety and Fire Protection, Vilnius Gediminas Technical University (VGTU). Publications: 7 scientific publications. Research interests: protective features of fire retardants, fire safety of impregnated timber.

Waldemar JASKÓŁOWSKI. PhD, the Head of Combustion and Fire Theory Department at The Main School of Fire Service, Warsaw, Slowackiego Str. 52/54, 01-629. Publications: over 30 scientific publications. Research interests: reducing the flammability of wood and wooden materials, fire properties of composite materials.