TECHNICAL UNIVERSITY IN ZVOLEN
FACULTY OF WOOD SCIENCES AND TECHNOLOGY
DEPARTMENT OF FIRE PROTECTION

ΔDelta

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Content

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Comparison of the sensitivity of the FDS computational grid

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Abstract

The main objective of the paper is to assess the sensitivity of the selected CFD fire model as a function of the computational grid density in three separate simulations of a fire in a simple confined space. The selected fire model is the FDS program, which is used to model confined space fires and to track the fluid flow driven by the fire. The density sensitivity of the computational grid is assessed based on the values obtained for heat release rate, heat flux, space temperature, and smoke layer height. From these outputs, graphs of the evolution over time are produced, and finally, the individual outputs of each computational grid are compared and evaluated as a function of the accuracy of the output data and the speed of the simulations. The contribution of the paper is the determination of the optimal cell size of the computational grid concerning the complexity of the simulation duration.

Keywords: FDS; modelling fires; sensitivity of the computational grid

1 Introduction

Today we are experiencing rapid developments in all areas of life, which, in addition to new opportunities and possibilities, also bring with them many risks that need to be eliminated to protect persons and property. In particular, the construction industry has also made great progress in recent times, with ever larger and more complex buildings being constructed and occupied by large numbers of people. A fire in confined spaces is one of the main causes of danger to persons and property in these buildings. To protect against fires, it is necessary to have effective fire prevention measures in place, which also requires sufficient knowledge of the origin and spread of fire, which is conditioned by various parameters. These parameters can limit or intensify the fire and therefore the course of the fire is the subject of long-term research, supported by the development of technologies to ensure the safety of construction objects at risk of fire. This paper aims to create three simple space simulations in the FDS (Fire Dynamics Simulator) program and to assess the selected output data as a function of the computational grid density in the evolution of heat release rate, room temperature, smoke layer height and heat flux recorded from floor to ceiling.

2 Modelling of fires

Among the technology used to assess buildings for fire safety, we include fire models, which, thanks to scientific advances, are coming to the fore and are a common part of fire engineering. According to the STN (Slovak Technical Standard), a fire model is a fire design, based on a limited area of application of specific physical parameters, which is used to design fire safety of buildings, to assess the possibility of evacuation of the building, to create designs for heat dissipation devices with products of combustion, to design the location of fire detectors, to investigate the causes of fire

and its course and to analyze the risk of the building or operation. The distribution of fire models is shown in Fig. 1 [1, 2].

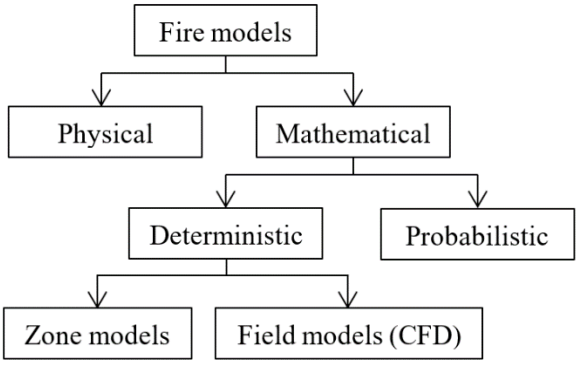

Fig 1. Fire models [3]

CFD (Computational Fluid Dynamics) is a fire model that allows the simulation of fluid motion in space. This type of model is classified as a deterministic fire model, which means that the space in which the fire is modelled is first plotted in the program. These models operate on the principle of a computational grid that divides the space into a large number of small computational cells, with the conservation laws of mass, momentum, energy, and the Navier-Stokes equation applying to each cell [4, 5].

For the use of the program in fire engineering, the program must be flexible and reliable. Flexibility is conditioned by the modernisation of the program depending on the advancement of technology and knowledge in the field. Reliability means the ability to model fires in complex spaces involving a large number of physical parameters. The reliability of the programme also depends on the number of cells contained in the computational grid, the higher the number of cells, the more detailed and accurate the outputs of heat flow, fire and smoke propagation. The CFD fire model is shown in Fig. 2 [5 - 7].

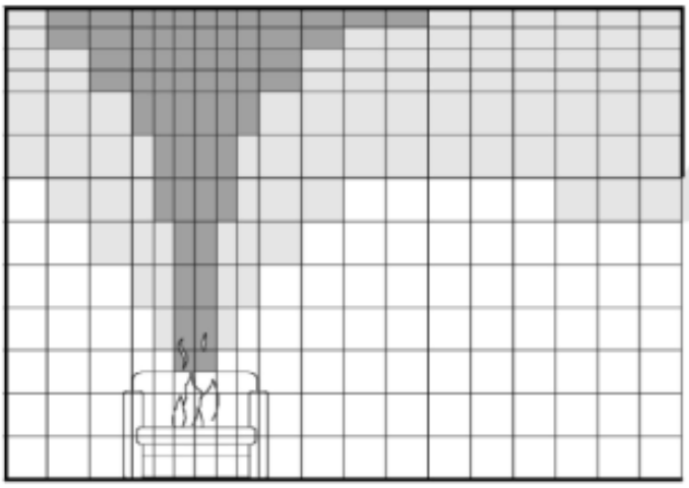

Fig 2. CFD fire model [4]

FDS is one of the most widely used software for the simulation of confined space fires, which is included in CFD models. FDS mainly focuses on the transport of heat and combustion products in a fire compartment with low fluid flow velocities. It is used to simulate thermal radiation, pyrolysis of solid and liquid, flame propagation of low-velocity heat and smoke flow, fire development and fire suppression [6, 8, 9].

FDS works as a set of several subroutines that express quantities and phenomena using mathematical equations, and then apply these calculations to each cell of the computational network

separately. The FDS program also includes the Smokeview program, which is used to visualize the obtained simulation results, which are three-dimensional, and has a colour scale that is used to represent the temperature differences, as shown in Fig. 3 [6, 8, 10].

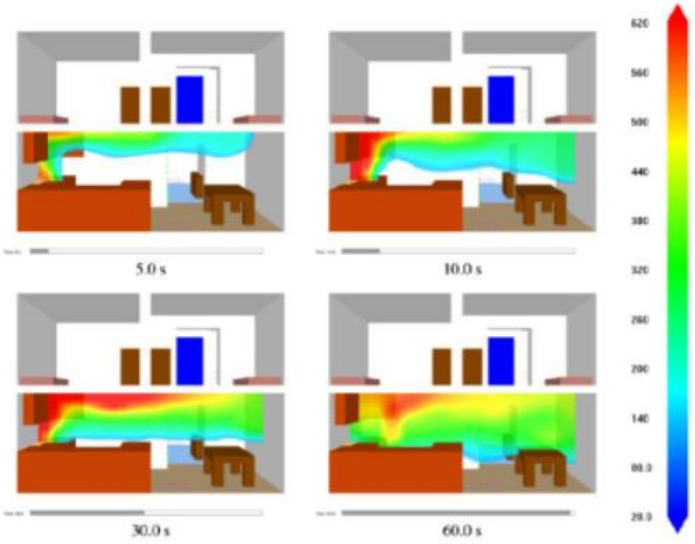

Fig 3. Fire visualisation in Smokeview [11]

3 Material and Methods

For the need to assess the sensitivity of the FDS program to the cell density of the computational grid, it will be necessary to create a simulation room of smaller dimensions with simple space geometry, as more complicated spaces and more complex simulations are very computationally intensive and require longer simulation times, even several days. When considering room dimensions, the dimensions of rooms (e.g. living room) in real life were also taken into account. Based on these factors, the dimensions of the computational grid for each of the three scenarios were chosen to be the same, x (width) = 5 m, y (length) = 4 m, and z height = 3 m, in which the density of cell placement was varied. The cell density of the computational grid was created based on the formula for calculating the optimal grip density D^* [8].

$$D^* = \left(\frac{Q}{\rho_\infty c_\infty T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \quad (1)$$

Where D^* is the optimum grid density
Q is heat released in a fire
ρ is air density
c is the specific heat capacity of the air
T is the thermodynamic ambient air temperature
g is the gravitational acceleration

The values of the input parameters to formula (1) are given in Tab. 1. Those values were selected based on the definition of the simulation space, the size of the fire and the tabulated values according to [12].

Tab. 1 The values of the input parameters

Parameter	Value	Unit
Q	1 000	kW
ρ	1,204	$kg.m^3$
c	1,005	kJ/(kg.K)
T	293	K
g	9,81	$m.s^2$
D*	0,959	m

After calculating the size parameter D* = 0.959 m, the dimensions of the computational grid were determined. According to [8], the rule of thumb of using a suitable parameter to calculate the D* parameter is applied, which is divided by a factor of 5 to 20. Tab. 2 shows the grid sizes for the different scenarios with the conversion value.

Tab. 2 Cell dimensions of computational grids

Type of computational grid	Parameter of calculation	Calculated cell size	Cell size after rounding
Rough (Scenario 3)	5	0,1918 m	0,2 m
Medium (Scenario 2)	10	0,0959 m	0,1 m
Fine (Scenario 1)	20	0,0479 m	0,05 m

Once the simulation grids were created, objects and holes were created to create the simulation space. First, a 20 cm thick wall of concrete material was created. The opening in the wall, representing the door, was 80 cm wide and 2 m high. Next, a seating structure was constructed, which was placed against the back wall of the room, in the centre of the y-axis. The furniture is made of Upholstery material, which consists of Foam (10 cm) and Fabric (0.2 cm). To ventilate the room during the fire simulation, the space to the right of the wall, which is characterized by the Vent command, was used. The simulation room for each of the three scenarios was identical and is shown in Fig. 4.

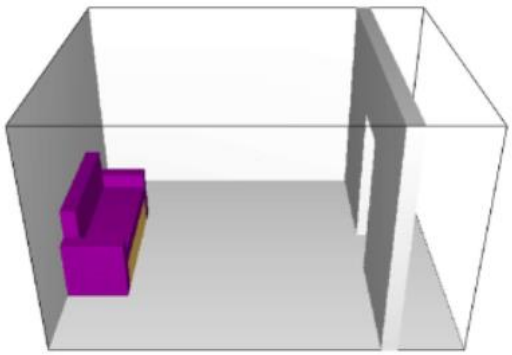

Fig 4. Visualizing the space in Smokeview

The source of initiation in the simulations was defined by the two hot particles of the *Ignitor Particle* commands, which were located in the upper corner of the seating furniture. To define these particles, a new *Ignitor surface* of type *Heater/Cooler* had to be created, which had a constant temperature set to 1 000 °C. Subsequently, a combustion reaction was defined through the substance undergoing thermal decomposition to form products of combustion and heat release. The fuel of the fire was polyurethane, which has a critical temperature of 1 327 °C.

As mentioned earlier, the paper focuses on comparing the outputs of the evolution of *Heat Release Rate*, *Heat Flux*, *Space Temperature* and *Smoke Layer Height* in three simulations. To obtain the outputs of the selected fire parameters, it was necessary to create devices in the FDS to record the results. The simulation length was set to 800 s, given that several variations of simulations were created, and a time of 800 s was the most acceptable given the length of the simulation and the relevance of the results.

4 Results

All the outputs obtained from the simulations were recorded in Microsoft Excel. The first simulation output that can be compared and evaluated is the simulation length. For *Scenario 1* the simulation took 98.5 minutes, for *Scenario 2* it was 8.4 hours and for *Scenario 3* 40 hours.

The first simulation output compared is the *Heat Release Rate*, the evolution plot of which is shown in Fig. 5.

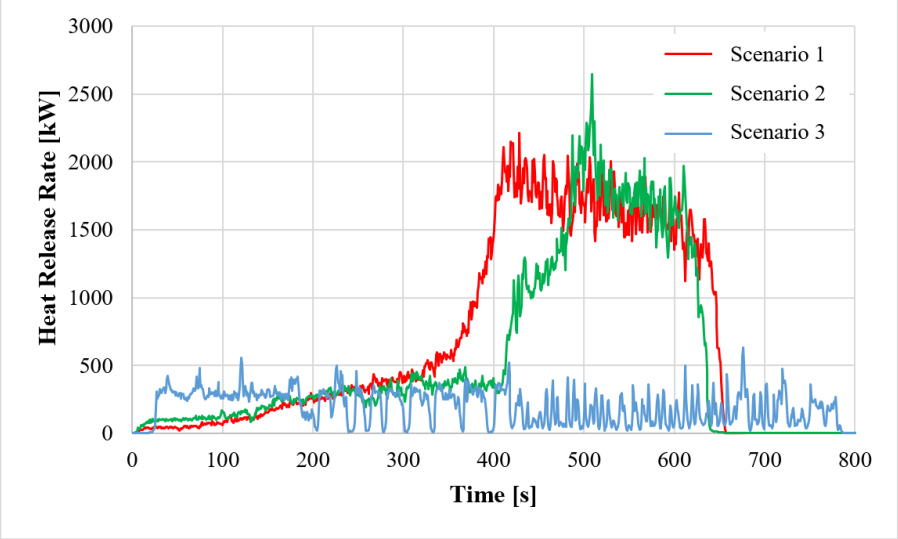

Fig 5. Comparison of Heat Release Rates of different scenarios

From the graph, it can be seen that the values of the *Heat Release Rate* evolution are very similar for *Scenario 1* and *Scenario 2*. First, for both scenarios the *Heat Release Rate* values increase linearly. Later in *Scenario 1*, there is a sharp increase at time 355.2 s, which continues until time 428.8 s, where the curve reaches a local maximum with a value of 2 210.01 kW. In *Scenario 2*, a sharp increase occurs later, at time 408 s, until at time 508.81 s the curve reaches a local maximum with a value of 2 643.25 kW. After reaching the local maximum, both curves start to slowly decrease until the complete cessation of burning, which is at time 676 s in *Scenario 1*, and at time 669.1 s in *Scenario 2*. In *Scenario 3*, the evolution of the *Heat Release Rate* is quite different, the curve fluctuates continuously until the cessation of the fire at 796.05 s. The local maximum in *Scenario 3* is reached at time 676.01 s with a value of 633.66 kW.

Another fire parameter investigated was the *Heat Flux*, the curves of which are shown in Fig. 6.

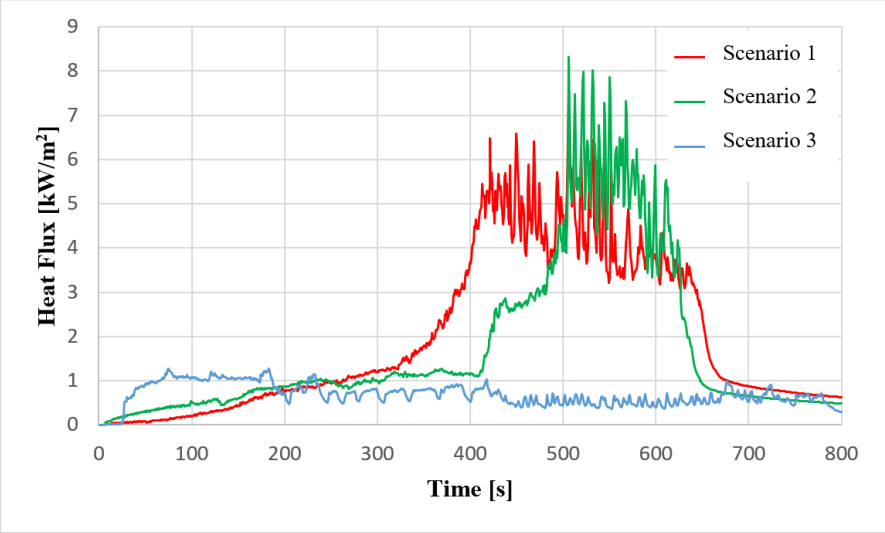

Fig 6. Comparison of Heat Fluxes of individual scenarios

Also for this examined parameter, the values of *Scenario 1* and *Scenario 2* are similar, and *Scenario 3* differs. The *Heat Flux* curves are similar to the *Heat Release Rate* curves. For *Scenario 1*, there is a sharp increase in *Heat Flux* at time 321.6 s, with a maximum value of 7.52 kW/m^2 reached at time 506.4 s, then there is a sharp decrease in *Heat Flux*, and after time 672.8 s this decrease is linear. The curve of *Scenario 2* is very similar, the sharp increase in *Heat Flux* occurs later, at 414.4 s, and the maximum is reached at 506.4 s at 8.31 kW/m^2. After the maximum value is reached, there is a sharp exponential decrease in the *Heat Flux*, and from time 659.22 s onwards a linear decrease until the fire stops. The curve of *Scenario 3* is again quite different with a large number of fluctuations, the maximum value of the *Heat Flux* reached is 1.27 kW/m^2 at time 75.2 s.

To compare the sensitivity of the computational grid, we can also compare the *Space Temperature* which is shown in Fig. 7.

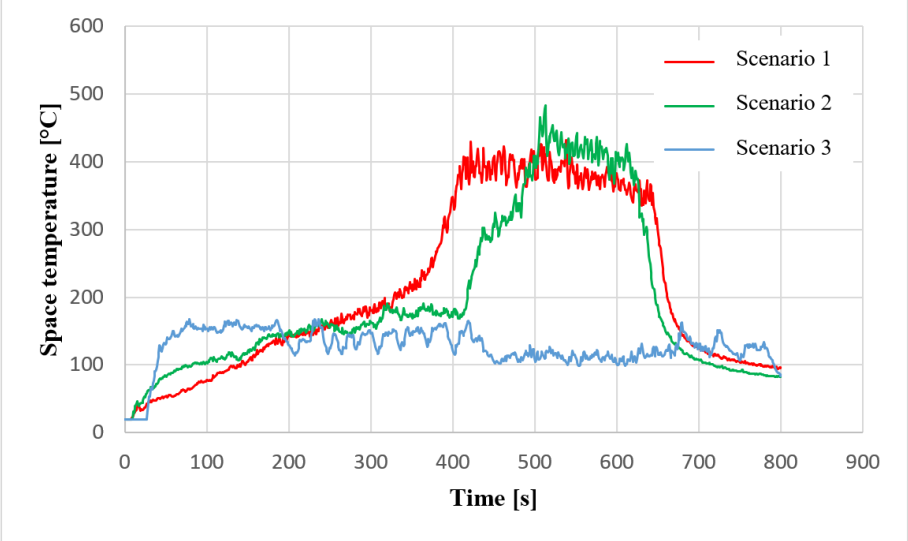

Fig 7. Comparison of Space Temperature in different scenarios

From the evolution of the *Space Temperature* curves, it is evident that they follow the *Heat Flux* curves. Again, the *Scenario 1* and *Scenario 2* curves are very similar, while at the same time quite different from *the Scenario 3* curve. The maximum *Space Temperature* reached among all scenarios is

483 °C, which means that no Flashover has occurred in the simulation space, as the conditions for its occurrence are not met.

The last graph, Pic. 8, shows the evolution of the change of the *Smoke Layer Height* over time.

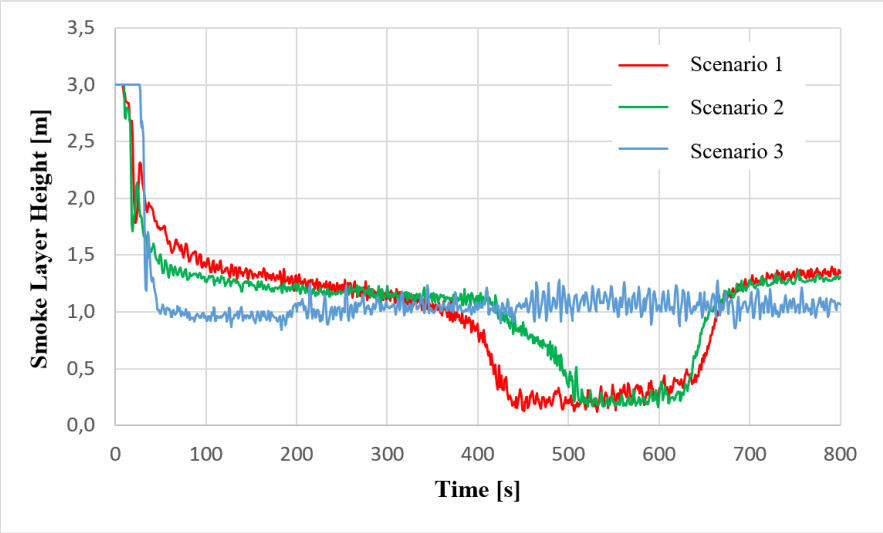

Fig 8. Comparison of Smoke Layer Height in different scenarios

As with the previous parameters, the *Smoke Layer Height* and *Scenario 1* and *Scenario 2* curves are almost identical, but in this case the *Scenario 3* curve is not so different. The ceiling height in the fire room is 3 m. The *Smoke Layer Height* is approximately the same in all three scenarios, until 33 s when there is a gradual divergence. The minimum reached *Smoke Layer Height* for *Scenario 1* is 0.12 m above the floor at time 644 s. For *Scenario 2* it is 0.16 m at time 642 s and for *Scenario 3* it is 0.84 m at time 127 s. At the end of the fire, the curves of *Scenario 1* and *Scenario 2* are almost identical and the *Smoke Layer Height* is rising. *For Scenario 3*, the value of the *Smoke Layer Height* remains approximately the same until the end of the fire.

5 Discussion and conclusions

The above graphs show that the outputs of *Scenario 1* and *Scenario 2* are very similar in all parameters examined. For the *Heat Release Rate*, the maximum values are different mainly in the times of their attainment, namely 428.8 s and 508.81 s. For the *Heat Flux* values, the difference is again observed mainly in the times of their attainment, but the maximum values attained are different only by 0.79 kW/m2. For the *Smoke Layer Height*, the curves are again very similar and differ only in the times of the maximum smoke plume in the space.

It is generally known that computational grids with larger dimensions do produce not very accurate results, but their duration is the shortest of all. Conversely, computational grids with smaller cell sizes achieve very accurate results, but their simulation duration exceeds several days, even weeks, depending on the complexity of the model situation. Based on these findings, and comparing them with the simulations, we see that *Scenario 3*, differs very significantly from *Scenario 1* and *Scenario 2*. The observed results of *Scenario 3* are not even consistent with the generally known fire scenario. The results of *Scenario 1* and *Scenario 2* follow the trend of the generally known fire behaviour. Therefore, it can be said that computational grids with smaller cell sizes are more suitable for fire simulations as their results are more accurate. Considering the duration of the simulations, the most acceptable variant of the computational cell sizes is *Scenario 2*, as its simulation length is not too restrictive, especially if we want to obtain accurate results in a short time. Based on simulations, we can assess that the parameter for the optimum density of the calculating distance D* could range from 10 to 20.

These obtained results show that the cell density of the computational grid has a great influence on the duration of the simulation. Considering the time, it is most advantageous to use a coarser distribution of computational grid cells in the simulations, however, the accuracy of the results, which is best obtained with finely spaced computational grid cells, will pay the price.

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Wood in Building Structures and its Fire Protection

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Abstract

The research is oriented towards the fire protection of wood, mainly with chemical protective agents, which aim at suppressing the various reaction processes in the material that are induced by the thermal loading. One of these substances is HR-Prof, a fire protection agent designed to protect wood, wood products and cellulose. Once applied (by painting, spraying, immersion or vacuum method), this substance allows the natural appearance of wood to be preserved and is suitable to be used both indoors and outdoors. The aim of the experiments carried out was to compare the behaviour of thermally loaded spruce wood after treatment with HR-Prof (2x coating; in the quantity specified by the manufacturer) and untreated. The variables compared were the mass loss of the test samples, the time to ignition, the relative rate of burning and, above all, the effect of the environment (interior, protected exterior and exterior), to which the wood samples were exposed for one month, on the effectiveness of the retardant and the variables evaluated. Summarising the results, it was confirmed that the application of the fire-retardant coating to spruce wood contributed to an increase in its thermal stability (lower mass loss, increase in time to ignition), although with the observation that the final results of the above evaluation criteria were significantly affected by the environment to which the samples were exposed. The samples stored outdoors, where they were directly exposed to the weather, clearly showed the worst results, the samples stored in a sheltered outdoor environment showed a more favourable result and the samples stored indoors were the best in the evaluation. The final conclusion for the practitioner and user is therefore that HR-Prof is clearly preferable for the protection of wood placed in an interior environment, alternatively a systemic protection solution should be chosen, i.e., a combination of this protective agent with a suitable top (anchoring) coating.

Keywords: spruce wood; fire retardant; mass loss; ignition time; relative rate of burning

1 Introduction

Wood is an organic material, classified as a natural lignocellulosic polymer. Due to its good technical, aesthetic, and other advantageous properties, it has been known and used as a building material by human ancestors for centuries. However, its main disadvantage is that it requires constant maintenance - it is susceptible to damage by abiotic and biological agents and is flammable. The resistance of different types of wood to deterioration by abiotic agents (water, sun, oxygen, etc.) and biological agents (fungi, bacteria, insects) is referred to as the natural durability of wood. It depends on the species of wood, its structure and the susceptibility of the basic components - organic polymers (cellulose, hemicelluloses and lignin) - to these agents. Damage to the organic polymers of wood also plays an important role in the degradation processes to which wood is subjected at higher temperatures, either by direct exposure to flame or by other high-temperature activation sources. Polymers are split and flammable gases are formed. These react with oxygen at a sufficiently high temperature in various thermo-oxidation reactions of an exothermic nature, carbon oxides and water are formed, and a considerable amount of energy is released [1]. In terms of reaction to fire, according to EN 13501-1 (2019) [2], wood is usually classified as Class D, which means that it can contribute significantly to the development of a fire in a building.

Therefore, the care of this material is an essential requirement for the unlimited use of wood in building structures.

The continuous improvement of methods and tools for acquiring knowledge of the structure and properties of wood has gradually expanded, and is still expanding, the knowledge of ways of increasing its resistance to the above-mentioned damages. For construction timber, various methods of protection are being implemented in practice, which can be suitably combined. According to Reinprecht and Štefko et al. [1, 3], this is mainly a combination of structural, chemical, physical and fire protection measures, depending on the anticipated threat. Structural protection is based on the optimization of the exposure conditions of the wood and the use of more durable species. Physical protection consists, for example, in sterilising the wood with heat or UV radiation, while chemical protection uses substances with different directional effects (biocidal, UV-sorbing, fire-resistant, etc.). Intensive research to increase the resistance and durability of wood is also currently being carried out in the application of nanoparticles. According to Kubovsky et al. [4] allow to increase its photostability, resistance to wood-destroying fungi, insects, but also to fire. Also, the results of Reinprecht and Vidholdova [5] as well as Boonstra and Tjeerdsma [6] confirmed that the biological resistance of wood is significantly increased by its thermal modification.

Although there are currently various ways of increasing the fire safety of wood (dry and wet technologies), one of the most widely used is the treatment with coatings (fire retardants). These are substances suppressing various reaction processes in the material induced by the thermal loading [7]. Using them, it is possible to implement high-quality and cost-optimized solutions depending on the required fire resistance of the structural element. Many of them allow to preserve the original appearance of the wood and can be applied directly in production or at the place of use.

The mechanism of action of these substances varies. They reduce the flammability of materials by physical or chemical means, but most often the synergistic effect of both is used. They either prevent oxygen from reaching the surface of the wood, or thermally insulate the wood substance from the heat source, or dilute the flammable gases produced during the thermal decomposition of the wood or prevent the oxidation of the carbon in the charcoal layer to carbon dioxide.

In practice, mainly water-based systems are used, either as concentrated solutions of suitable inorganic salts (ammonium phosphates, ammonium sulphates, ammonium chlorides, etc.) or as water-based dispersions of suitable polymers with the addition of retarding and foam-forming components ('intumescent coatings'). Combinations of nitrogenous substances with phosphorus compounds are particularly preferred. The phosphorus-containing compounds undergo dehydration and carbonisation to form protective carbon layers, the presence of nitrogen helps to absorb heat and produce non-decomposition of the polymers. The synergistic effect of nitrogen and phosphorus on the suppression of the combustion process has been confirmed also by Bogdanova et al. [8]. Similarly, Grzeskowiak [9] states that an increase in the number of nitrogen atoms in the formulation provides a higher efficiency of the flame retardant. The nanomaterials are nowadays perspective in the field of flame retardant protection. For example, the retardant effects of phosphorus in various combinations are being investigated, e.g., phosphorus-modified wheat starch [10], phosphorylated cellulose nanofibers [11], phosphorus-modified lignin nanoparticles [12]. Research is also focusing on the use of titanium dioxide and zinc oxide [13], also silica [14,15], or a combination of the two has been applied. In their work, the authors [16] highlight the retarding effect of sodium silicate in combination with expandable graphite particles.

2 Material and Methods

The research is focused on wood fire protection. It focuses primarily on the protection by chemical coatings, as documented by the experimental results presented in the following sections of this paper. In particular, the evaluation of the thermal resistance of retardant-treated spruce wood with HR-Prof, under the thermal loading by radiant heat source.

The HR-Prof retardant is a manufacturer's product for both interior and exterior use. This was the reason for its selection for the treatment of the test wood samples.

The aim of the experiments carried out was to evaluate whether the environment (interior, protected exterior and exterior) to which the treated spruce timber was exposed would affect the effectiveness of the retardant used and thus the resistance of the spruce timber under fire conditions.

The results of the evaluated groups of treated samples were compared with the results of the evaluated groups of chemically untreated samples.

2.1 Preparation of samples

Wood samples of Norway spruce (*Picea abies L.*) with dimensions of 50 x 40 x 10 mm were used for the experiments. The samples were divided into three groups consisting of 10 pieces each, cleaned and stripped of sharp edges. For each group evaluated, half of the samples were surface treated with the retardant HR-Prof, the other half remained untreated (control samples). The coating was carried out using a brush in two layers (24 h apart), using the following application rate: 0.6 g/1 sample/1 layer (this is the calculated amount according to the manufacturer's recommendations). The samples thus prepared were placed in a metal frame fitted with a grid (Fig. 1).

Fig 1. Storage of test samples: (1) adjustable metal stand; (2) metal frame with mesh for placing test samples; (3) test samples (untreated and treated with HR-Prof).

The first group of test samples prepared this way was stored in an outdoor unprotected environment (outdoors), the second group in an outdoor protected environment (under shelter) and the third group in an indoor (laboratory) environment. After one month, samples from each environment were collected and stored in a desiccator for acclimatization and comparability of results. The moisture content of all samples after removal from the desiccator was 6%. Subsequently, the samples were tested.

HR-Prof [17] - is the trade name of a substance intended for fire protection of wood and cellulose products (e.g., wooden trusses, coffered ceilings, wooden floors, tiles, etc.). It is a water-based solution of ferric phosphate, citric acid, and special additives. The preparation has a high ability to diffuse into the structure of the material, the treated material has a self-extinguishing character. It provides an increase in fire resistance of the protected structure by 10 min.

2.2 Method of testing

The wood samples were loaded with a radiant heat source. This is a non-standard test method (Fig. 2) which allows continuous recording of the change in mass of the test material, time to ignition and evaluation of the measured results by means of a computer program during the thermal loading with the radiant heat source.

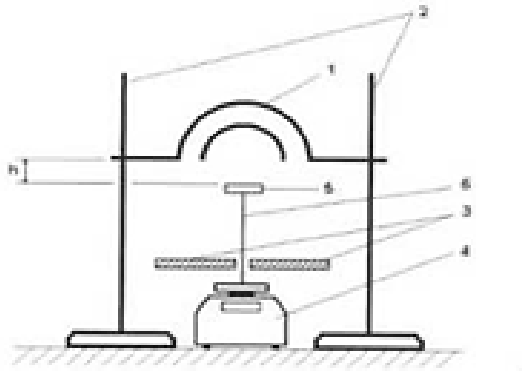

Fig 2. Scheme of the test equipment: (1) infrared radiation source with a power of 1 kW; (2) metal supporting frame; (3) scales protection plates; (4) electronic scales; (5) test sample; (6) stand for placing the test sample.

The total duration of the test is 10 min (time representing approximately the first phase of the development of a standard structural fire). From the measured values, the relative mass loss and the relative rate of burning are calculated according to the following equations:

$$\delta_m(\tau) = \frac{m(\tau_0)-m(\tau)}{m(\tau_0)} * 100 \qquad (\%) \qquad (1)$$

$$v_r = \frac{[\delta_m(\tau)-\delta_m(\tau+\Delta\tau)]}{\Delta\tau} \qquad (\%/s) \qquad (2)$$

Where:

$\delta_m(\tau)$ - relative mass loss over time (τ) (%);
v_r - the relative rate of burning(%/s);
$m(\tau_0)$ - original mass of the sample (g);
m(τ) - mass of the sample at time (τ) (g);
$\delta_m(\tau + \tau\Delta)$ - relative mass loss over time ($\tau + \Delta\tau$) (%);
$\Delta\tau$ - time interval at which the masses are recorded (s).

3 Results and Discussion

The results of the completed experiments are presented in tables (Tab.1-2) and graphs (Fig. 3-9). In summary, it is an evaluation of the effect of fire-retardant treatment on the thermal resistance of spruce wood and an evaluation of the effect of the environment to which this material was exposed (interior, protected exterior and exterior) on the effectiveness of the applied protective substance HR-Prof. The evaluation criteria were the mass loss, the ignition time and the relative rate of the material burning for the specified test time of 600 s, under the action of radiant heat. These evaluation criteria were used for all evaluated groups, i.e., for both retardant-treated and untreated ("control") spruce wood samples. The results are presented as average values of five measurements.

Tab. 1 Final values of mass loss and time to ignition of untreated and retardant-treated spruce wood samples.

Environment	**Untreated samples**		**Treated samples**	
	Mass loss (%)	Ignition time (s)	Mass loss (%)	Ignition time (s)
Interior	68	95	48	155
Protected exterior	85	61	71	92
Exterior	90	37	89	37

Tab. 2 Values characterizing the burning rate and time of maximum burning rate of untreated and retardant-treated spruce wood samples.

Environment	Untreated samples		Treated samples	
	Maximum rate of burning (%/s)	Time of achieving the maximum rate of burning (s)	Maximum rate of burning (%/s)	Time of achieving the maximum rate of burning (s)
Interior	0.23	150	0.10	150
Protected exterior	0.28	70	0.20	110
Exterior	0.39	70	0.41	60

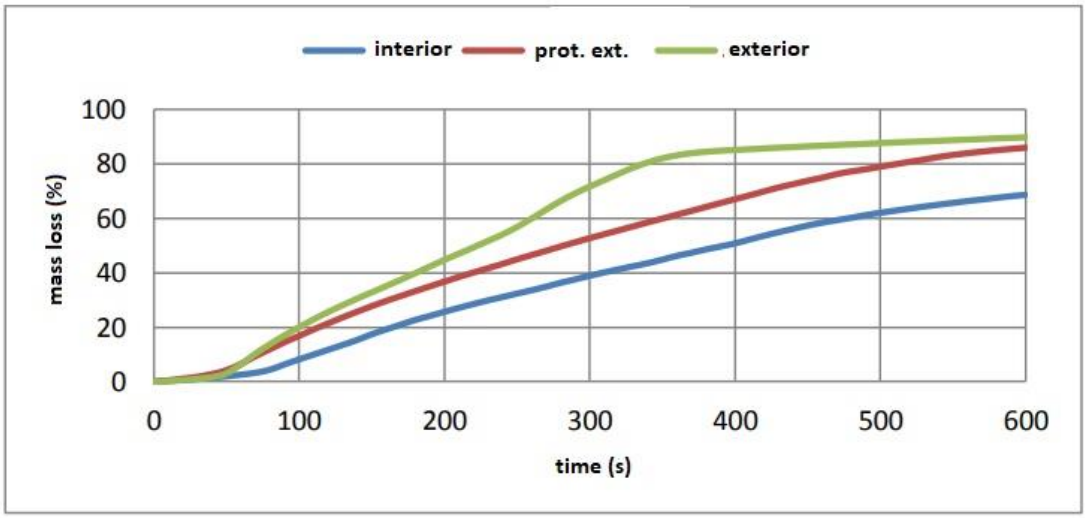

Fig 3. Effect of environment on mass loss of untreated spruce samples.

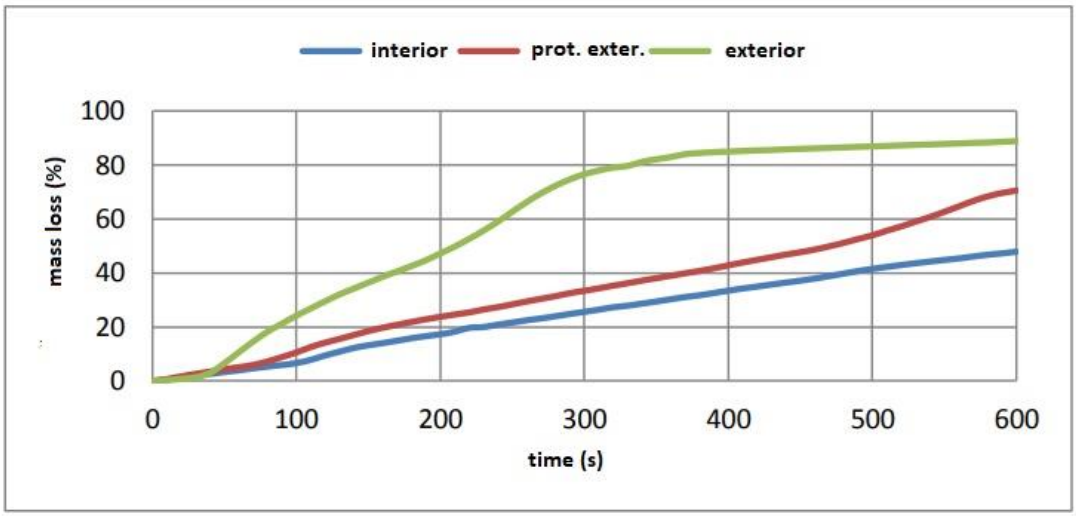

Fig 4. Effect of the environment on the mass loss of spruce samples with application of the retardant HR-Prof.

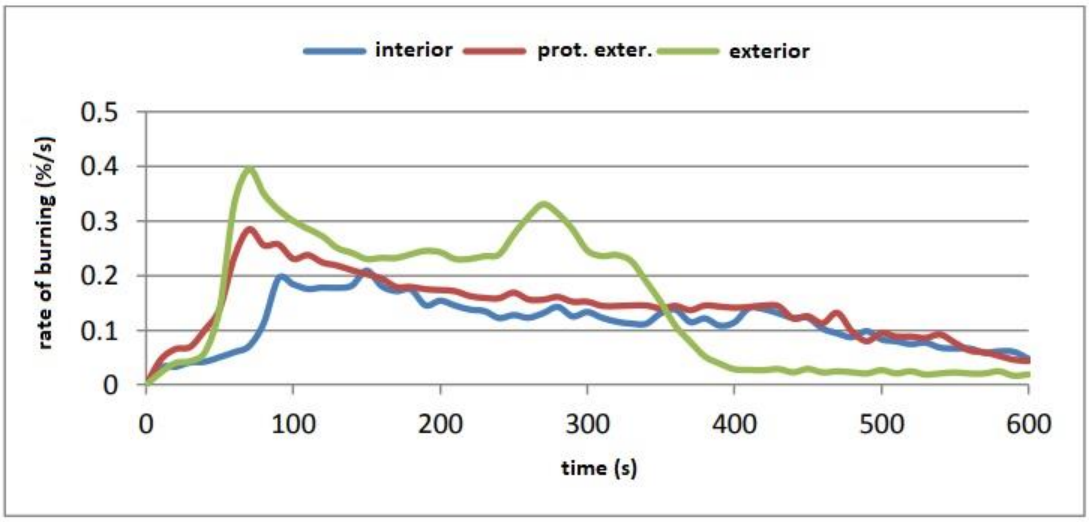

Fig 5. Effect of the environment on the rate of burning of untreated spruce samples.

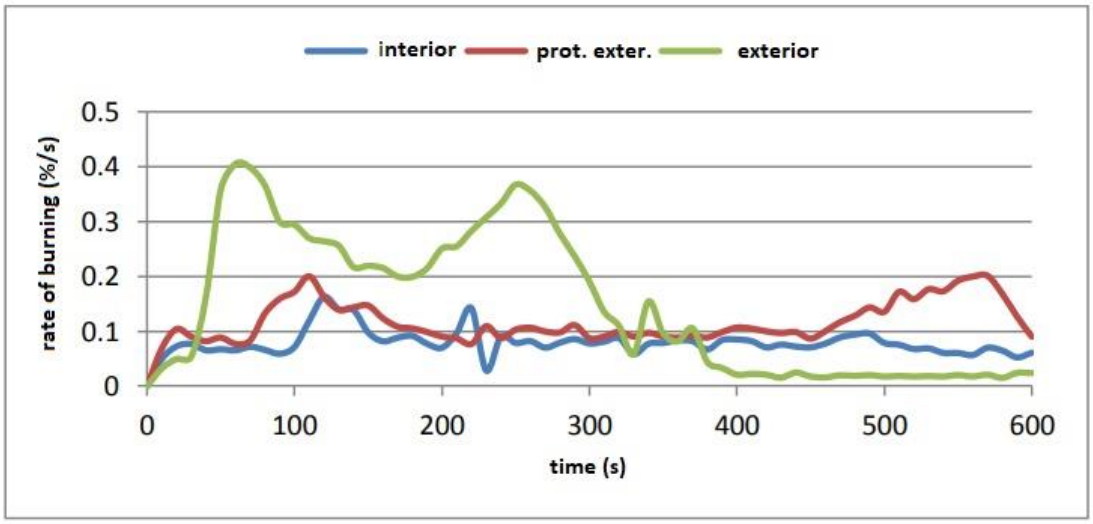

Fig 6. Effect of the environment on the rate of burning of spruce samples with application of the retardant HR-Prof.

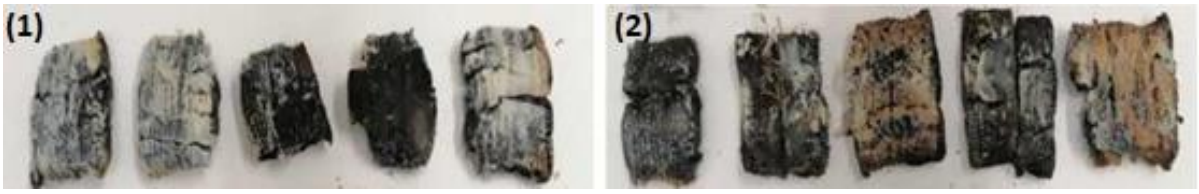

Fig 7. Spruce wood samples after the test (stored in an unprotected exterior): (1) untreated spruce samples; (2) spruce samples with HR-Prof application.

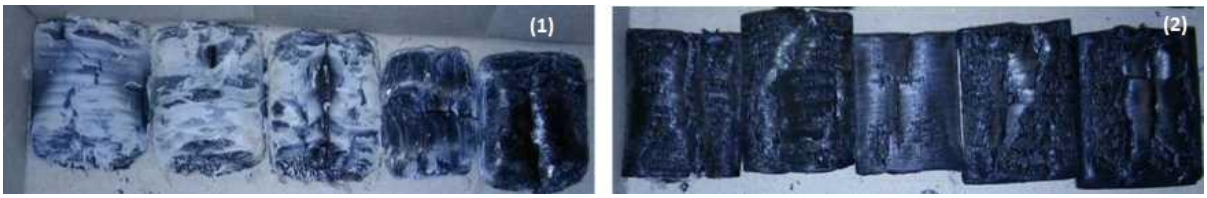

Fig 8. Spruce wood samples after the test (stored in a protected exterior): (1) untreated spruce samples; (2) spruce samples with HR-Prof application.

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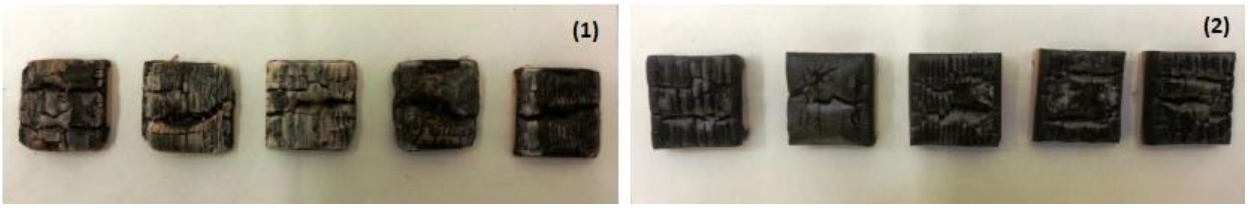

Fig 9. Spruce wood samples after the test (stored in an interior): (1) untreated spruce samples; (2) spruce samples with HR-Prof application.

The evaluation documented in Tab. 1 and 2 and Figs. 3 to 9 showed that the environment to which the spruce wood was exposed, both untreated and retardant treated, had a significant influence on the change in its properties. The external environment (exterior) and the change in weathering have been shown to contribute to a more significant deterioration in its fire properties. Samples taken from this environment (although they were then conditioned to exclude the influence of humidity) degraded after subsequent thermal loading in the presence of flame. Their surface ignition occurred shortly after being placed in the thermal loading environment (on average at 37 s) and they lost on average 90 % of their original mass during the time of testing. An interesting finding of this first group evaluated is that even retardation treatment of the samples did not ensure an improvement in their properties. Comparing the curves in Figs. 3 and 4 and from Tab. 1, the mass loss of the treated samples is only 1 % lower compared to the untreated samples, and that they started to burn at the same time as the untreated samples. From this it can be concluded that the retardant used was washed out of the material by alternating conditions in the outdoor environment (direct exposure to sun and rain).

The above statement can be used to compare the results of the first group evaluated with the other two, namely the group of samples that were stored in an outdoor but protected environment and the group of samples that were stored indoors. The results show a gradual improvement in the properties - lower mass loss and higher ignition time of the untreated and especially retardant treated samples. In Figs. 3 and 4 it can be observed that, compared to the first group evaluated, storing the samples in a protected outdoor environment provided a mass loss reduction of 5 % for the untreated samples and 18 % for the treated samples. An even greater reduction can be observed for the samples stored in an indoor environment (indoors). Here, the mass loss was reduced by 22 % for untreated samples and by up to 41 % for treated samples.

The protected environment (compared to the unprotected one) also had a positive effect on the ignition rate of the tested samples. Placing the samples in a protected outdoor environment provided an increase in ignition time by 24 s for untreated samples and 55 s for treated samples. An even higher increase was observed for samples stored in an indoor environment. Here, the ignition time increased by 58 s for untreated samples and by up to 118 s for treated samples.

The effect of the environment on the effectiveness of the retardant HR-Prof and the thermal resistance of the treated spruce wood was also observed in the evaluation in terms of the rate of burning. Based on the results presented in Tab. 2 and Figs. 5 and 6, it can again be stated that the samples that were exposed to the external environment recorded the worst results. They reached the maximum rate of burning in the shortest time (about 1 min). This applies to both untreated and treated samples. On the contrary, for the samples stored indoors, the maximum rate of burning was measured about 1% of a minute later compared to the first group evaluated.

The reported changes of the different groups of tested samples are also captured by the photo-documentation obtained after the end of the thermal loading (Figs. 7 to 9). The resulting visual appearance of the samples also confirms that both the effect of the protective agent and the environment to which the material has been exposed have a significant influence on the change in properties. The application of the protective agent HR-Prof promoted the formation of a charred layer on the surface of the tested wood material (its protective function is also highlighted by [18, 19, 20]), which significantly contributed to its compactness and, finally, to a lower weight loss. However, also in this case, this is true only for the samples of the second and third groups evaluated (Figs. 8, 9). The unfavourable influence of the exterior is documented in Fig. 7, where one can already see a considerable destruction of the material after thermal loading and very little or no difference between the untreated and treated samples.

4 Conclusions

Wood is a renewable raw material, which finds its application in modern wood construction as a construction element. However, different areas of application require different product systems for its protection. In this paper, one such method has been presented. The article presents the results of experiments that can be used in practice for the use of wood in areas with increased requirements for fire protection.

The results confirm that the application of the tested retardant HR-Prof on the surface of spruce wood contributed to an increase in its thermal stability. However, its effect was largely influenced by the environment to which the test samples were exposed. The outdoor environment (exterior) proved to be the most unfavourable environment affecting the effectiveness of the substance, even though the manufacturer states that it can be used in this environment as well. A more favourable result was found when the substance was used in a protected outdoor environment, i.e., an environment without direct exposure to weathering (sun, rain, frost).

Clearly the most suitable environment for the use of HR-Prof was found to be indoors. The recommendation to the consumer is therefore that the substance is clearly more suitable for the protection of wood placed in an indoor environment. Alternatively, a system solution can be chosen, i.e., a suitable combination of both fire protection and top protective coating.

Acknowledgments

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Retardant treated and untreated upholstery PUR foams comparison based on the thermal analysis and cone calorimetry results

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Abstract

The materials used in the composition of the upholstered furniture are composed of flammable organic materials which may contribute in the case of a fire to its development. In the paper, there are introduced the results of thermal and cone calorimetry analyses and fire hazard assessment for upholstery polyurethane (PUR) foams, which make up a substantial part of the upholstered furniture composition. Among the PUR foams tested belonged soft foam types as KF 5560, DEFLAMO KF 4545 – with reduced flammability, high-elastic V 4010, high-elastic VF 6020 with reduced flammability and standard N 5063. For the evaluation of PUR foams, we chose the thermal analysis methods - thermogravimetry and differential scanning calorimetry, according to STN EN ISO 11358 and STN EN ISO 11357-1, and cone calorimetry method (ISO 5660). The results showed the effect of retardation on the assessment parameters. The samples with retardation treatment achieved better thermal stability than samples without retardation treatment. The lowest standard thermal stability the standard N 5063 PUR5 foam sample achieved. In the differential scanning calorimetry analyses, all the samples showed significant exothermic effect. As the most hazardous in terms of amount of heat released was determined the N 5063 PUR5 foam, which released the largest amount of heat (4,199.9 J g^{-1}) at temperature of 322.4 °C. In the second decomposition stage, in temperature range of 449 – 595 °C, it released heat of 3 099.2 J g^{-1}. The cone calorimetry results showed that from heat release rate (HRR) peak point of view the least fire hazardous was KF 4545 PUR2 foam (363.90 kW m^{-2}), followed by KF 5560 PUR1 foam (390.01 kW m^{-2}), VF 6020 PUR4 foam (417.29 kW m^{-2}), N 5063 PUR5 foam (417.49 kW m^{-2}), and the most fire hazardous was V 4010 PUR3 foam (683.07 kW m^{-2}). Those results were also confirmed by time to ignition, time to HRR peak and total heat release values.

Keywords: PUR foam; thermal analysis; thermogravimetry; differential scanning calorimetry; cone calorimetry

1 Introduction

Combustible insulation materials, such as the commonly used wood and wood-based materials, foams of polyurethane (PU/PUR), polystyrene (PS) and polyisocyanurate (PIR); and constitutes represent potential fire hazards for life and health of residents. Their flammability and fire risk have drawn increasing attention from both scientific and industrial communities. For the residence fire, bedding and upholstered furniture are the first item ignited in roughly 19% of fatal fires [1]. In a white

paper launched at the EU parliament in 2014, entitled “Europe is playing with fire”, Fire Safe Europe called on the European Commission to act to improve fire safety in buildings [2].

When talking about the of fire protection in buildings, the optimal level depends on a large extent on the amount and type of flammable materials and substances that occur in them. As mentioned above, flammable materials, which are relatively common in building sites, include polymeric materials (e.g. wood, wood-based materials, plastics (including polyurethane foams), and linen and upholstery fabrics). Some polymers, especially porous polymers with a large specific surface area, such as polyurethane foam [3-5], fabrics [6-9], and wood [10], burn easily, releasing a large amount of heat, flame and smoke in association with generation of many droplets during the burning process, and thereby threatening people’s lives and property. A progressive approach to reduce the flammability of polymers is to apply the flame retardants.

Recent trends in flame retardancy of polyurethane foams (PUR) and, in general of polymers, have been deeply influenced by regulation requirements and by the concept of "sustainable development" which implies that the fire retardants should present a low impact on human health and environment during the whole life cycle of the polymer; it concerns then also the toxicity and the density of smoke developed during burning of the materials. Therefore, the reduction of the amounts of brominated compounds used in flame retardancy formulations is one of the main aims of the research in this field, although this reduction is not very easy because of their very high effectiveness [11].

Recently, Modesti et al. [11] reviewed and discussed novel halogen-free flame-retardant systems for polyurethane foams. They studied the charring compounds which may lead to the development of different char morphologies: compact, intumescent and "glassy-like" char layers. The advantages and disadvantages of each system on fire behaviour and thermal stability of polyurethane foams was analysed. Attention was put on possible synergistic effects arising from suitable mixing of them. In the flame retardants analyses, there were involved the phosphorus-based compounds (phosphates, elementary phosphorous and novel hypophosphites), intumescent systems (for example expandable graphite) as well as glass precursors like borates, alumino-silicates and glass modifiers. The recent interest in nanocomposites, potential application and benefits of layered silicates on fire behaviour and thermal stability of PUR foams was also reported.

To test the fire and thermal properties of PUR foams several standardized and progressive analytical methods are deployed. Yang and Nelson [12] used cone calorimetry to test the newly developed flame retardants of PUR foams. Hu and Wang [13] applied cone calorimetry (CC), thermogravimetric analyses (TGA) and scanning electron microscopy (SEM) to study the effect of the additives on the physical mechanical property, fire behaviour and thermal stability of PUR, PIR (polyisocyanurate) foams. Chen and Jiao [14] studied smoke suppression properties and synergistic flame-retardant effect on thermoplastic polyurethane (TPU) composites using the smoke density test (SDT), cone calorimeter (CC), scanning electron microscopy (SEM) and thermogravimetric analysis (TGA). The influence of carbon fillers on the thermal properties of polyurethane foams studied Ciecierska et al. [15]. For the study, they used thermogravimetry analysis (TGA) combined with infrared (IR) measurements. Gao et al. [16] investigated the improved mechanical property, thermal performance, flame retardancy and fibre behaviour of lignin based rigid polyurethane foam nanocomposites using Fourier transform infrared (FTIR) spectroscopy, site exclusion chromatography (SEC), thermogravimetric analysis, differential scanning calorimetry (DSC), limiting oxygen index (LOI) testing and cone calorimetry. Liu et al. [17] studied the thermal stability and pyrolytic gases of a series of flame retarded PIR – PUR foams using the thermogravimetry (TG) and thermogravimetry combined with Fourier transform infrared spectroscopy (TG-FTIR) methods. Besides, they used also Py-GC-MS analyses to study the toxicity of PIR-PUR foams combustion products. Cone calorimetry was applied to determine the heat release rate (HRR). To study the form of combustion products, the scanning electron microscopy (SEM) was used. Thermogravimetric analysis (TGA) combined with FTIR (TG-FTIR), LOI testing, smoke density rating (SDR), cone calorimetry and X-ray photoelectron spectroscopy was used to study smoke and toxicity suppression properties of ferrites on flame-retardant polyurethane-polyisocyanurate foams [18]. Liu et al. [19] also studied the catalysis of boron phosphate on the thermal stability and char forming in flame retarded PUR-PIR foams using the cone calorimetry, thermogravimetric analysis, microscale combustion calorimetry and TG-FTIR-MS methods. Xu et al. [20] conducted two scale tests, microscale

and bench scale to analyse the flammability of a flexible polyurethane foam. Microscale tests included simultaneous thermal analysis coupled to Fourier transform infrared spectroscopy (TG-FTIR) and microscale combustion calorimetry (MCC). Using these methods, they obtained data on evolved gas components, heat release rate per unit mass, total heat release, derived heat release capacity and minimum ignition temperature. Bench scale tests were performed on cone calorimeter to obtain data on peak heat release rate per unit are, effective heat of combustion, minimum incident heat flux for ignition and total heat release per unit area of different incident heat fluxes.

In this paper, there are introduced the methods, procedures and results used to determine the thermal properties of selected types of flame retardant treated and untreated upholstery foams. To determine the thermal properties of the PUR foams the TG/DTG, DSC and CC calorimetry analyses were performed.

2 Material and Methods

The objective of the experiment was to study the differences in fire and thermal properties of selected retardant treated and untreated upholstery PUR foams and to assess the fire based on the thermal analysis and cone calorimetry results.

2.1 PUR foam samples

Among the PUR foams tested belonged soft foam types KF 5560 (PUR1), DEFLAMO KF 4545 (PUR 2) - with reduced flammability, high-elastic V 4010 (PUR3), high-elastic VF 6020 (PUR4) with reduced flammability and standard N 5063 (PUR5).

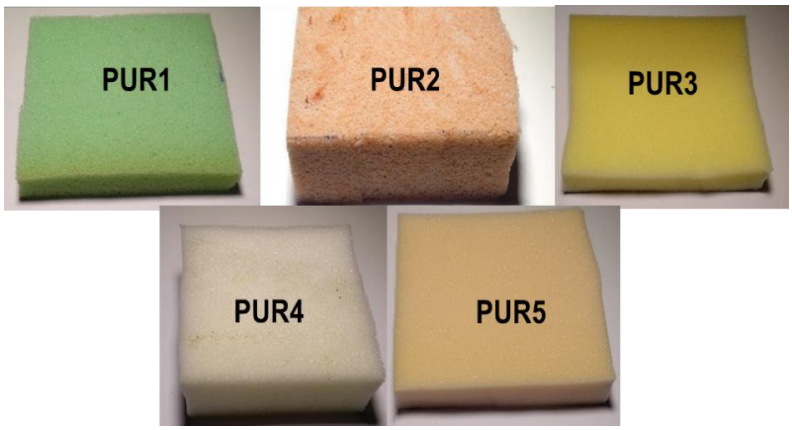

Fig 1. Samples of PUR foams used for testing

In Figure 1, there are introduced the samples used in the analyses. Table1 presents the basic parameters of tested PUR foams.

Tab. 1 Basic parameters of tested PUR foams

Sample	Foam type	Resistance to compression (kPa)	Density (kg m^{-3})	Note
PUR1 – KF 5560	Comfort	6.0	55	Flame-retardant treated
PUR2 – DEFLAMO KF 4545	Comfort	4.5	45	Flame-retardant treated
PUR3 – V 4010	Viscoelastic	1.0	40	Untreated
PUR4 – VF 6020	Viscoelastic	2.0	60	Flame retardant treated
PUR5 – N 5063	Normal	6.3	50	Untreated

2.2 Methodology

To study the fire and thermal properties of PUR foams, we used the thermal analysis methods – thermogravimetry (TG) and differential scanning calorimetry (DSC), according to STN EN ISO 11358 [21] and STN EN ISO 11357-1 [22], and cone calorimetry method according to ISO 5660 [23].
All the tests were provided in the Accredited Laboratory of the Fire Research Institute of the Ministry of Interior of the Slovak Republic.

In the thermogravimetric analysis (TG / DTG), all samples were tested on a Mettler TA 3000 thermal analyser with the processor TC 10A, and TG 50 thermogravimetric scales, at an air flow rate of 200 ml min^{-1}, heating rate of 10 °C min^{-1} and under standard test room conditions. The STEP program was used for the measurement of mass loss step changes. The type of temperature sensor Pt100 was used in the heater body of thermogravimetric scales. As a test sample holder, the Mettler MET-24123 corundum (Al_2O_3) crucible was used. Each sample was conditioned for at least 24 hours prior to testing under standard test room conditions. The temperature recording interval was of 35 up to 700 °C. For temperature calibration, materials with given Curie temperatures were used: Isatherm (144.5 °C), Nickel (357.0 °C) and Trafoperm (748.0 °C). During the analysis, the percent mass loss and carbon residue of a test sample was recorded while the samples were being heated at above specified rates in an appropriate environment.

Using the differential scanning calorimetry (DSC), the difference between the heat flux (energy) supplied to the test sample and the reference sample as a function of temperature was measured, while the test and reference samples being exposed to the selected temperature program. All the samples were tested on a Mettler TA 3000 thermal analyser, with the processor TC 10A completed with measurement cell DSC 20, at air flow rate of 50 ml min-1 and at heating rate of 10 °C min^{-1}.

With the DSC method, the changes in the reaction enthalpy of individual samples of PU foams were measured. Within the given temperature range, the reaction heat was determined, and the maximum heat generation rate was characterized by the maximum exothermic peak temperature on the thermo-analytic curve at a temperature range of 35 – 600 °C. There were also obtained the quantitative results such as: maximum peak temperature (T_{MAX}), i.e. maximum deviation temperature of the curve from the baseline; temperature interval, i.e. the interval, in which the individual exothermic / endothermic effects and the amount of heat released from the sample were recorded.

In the thermogravimetric analysis, there was studied the thermal stability of the sample and in the differential scanning calorimetry the change of enthalpy. The evaluation criteria for the thermal analysis were mass loss, carbon residue, initial and final temperatures, enthalpy change, and the amount of heat released. The weight of the samples in the thermal analyses was of 10 ± 2 mg.

To determine the ignition time, peak heat release rate, peak heat release rate time, the effective combustion heat and the total heat released, the cone calorimetry (dual calorimeter) method was used. To test the PUR foam which are thermally thin a special holder was made from stainless steel 9.1 cm × 9.1 cm × 0.3 cm which was placed into the main holder supplied with cone calorimeter. The holder was isolated from its bottom by 5 mm thick layer of kaowool. The samples were wrapped into aluminium foil and isolated from the bottom of the holder by 5 mm layer of kaowool. The centre of the samples was situated 6 cm from the lowest part of the cone heater. The temperature on the regulator of the cone radiator was set at 680 °C which corresponds to the heat flux density of 25 kW m^{-2}. The thickness of PUR foam samples was of 20 mm (PUR1, PUR4 and PUR5) and of 45 mm (PUR2 and PUR3). The samples were spark ignited. The heat release rate was calibrated by burning of the methane standard. The reproducibility of burning experiments as it concerns the ignition time, heat release rate, mass loss and total smoke production under conditions of piloted ignition was good provided that the holders with sample were initially conditioned to the room temperature.

3 Results and Discussion

In the following three five subchapters the results of thermal, LOI and cone calorimetry analyses are introduced.

3.1. TG/DTG analysis results

The TG curve of the PUR1 sample showed a four-stage thermal degradation process. The first stage of thermal degradation took place in the temperature range of 100 – 275 °C with the mass loss of 17.15 %. In the second stage of the thermal degradation, the highest mass loss, i.e. the mass loss peak (T_{MAX}), was found at temperature of 323 °C. The thermal degradation process in this stage occurred in the temperature range of 275 – 430 °C and the mass loss was of 64.78 %. The third stage occurred in the temperature range of 430 – 620 °C with the mass loss of 14.90 %. In the fourth stage the mass loss was of 2.03 % and took place in the temperature range of 620 – 671 °C. The carbon residue of PUR1 sample was of 1.14 %.

The PUR2 sample was subjected to thermal degradation process in three stages. The first stage was found in the temperature range 110 – 262 °C and the mass loss was of 14.4 %. The second stage of thermal degradation took place in the temperature range of 262 – 367 °C, with the highest mass loss (63.79 %) found at temperature of 304.3 °C. The third stage of degradation process was found in the temperature range of 367 – 620 °C and the mass loss was of 20.60 %. The remaining carbon residue of the PUR2 sample was of 0.30 %.

The course of the TG curve of the PUR3 sample represents a four-stage thermal degradation process. Thermal degradation of the PUR3 sample began in the temperature of 133 °C and terminated at temperature of 694 °C. The first stage was found in the temperature range of 133 – 265 °C. The mass loss was of 8.34 % in this stage. The second stage with highest mass loss (68.71 %) was found in the temperature range of 265 – 350 °C. The temperature at which the maximum mass loss occurred was 323 °C. The third stage of thermal degradation process took place in the temperature range of 350 – 420 °C and was represented by the mass loss of 15.09 %. In the fourth stage, in the temperature range of 420 – 694 °C, the mass loss of the sample was of 6.67 %. The remaining carbon residue of PUR3 sample was of 0.46 %.

The TG curve of the PUR4 sample was like PUR3 sample due to the four-stage thermal degradation process. The first stage of thermal degradation took place in the temperature range of 119 – 231 °C and represented the mass loss of 9.65 %. The second stage was found in the temperature range of 231 – 280 °C and the mass loss of the sample was of 12.23 %. In the third stage of thermal degradation process, in the temperature range of 280 – 400 °C, the maximum mass loss of 69.62 % was found at temperature of 333.7 °C. The fourth stage occurred in the temperature range of 400 – 570 °C and it was characterised by the lowest mass loss (7.52 %). The remaining carbon residue of PUR4 sample was of 0.35 %.

The course of TG curve of the PUR5 sample was like PUR1, PUR3, and PUR4 samples due to the four-stage thermal degradation process. The first stage was found in the temperature range of 100 – 291 °C with the mass loss of 38.21 %, which represents the highest mass loss in comparison to the other stages. The maximum mass loss occurred at temperature of 272.3 °C. The second stage occurred in the temperature range of 291 – 326 °C and the mass loss was of 18.39 %. The third stage of thermal degradation took place in the temperature range of 326 – 429 °C with the mass loss of 28.99 %. The fourth stage was found in the temperatures range 429 – 694 °C and the mass loss was of 13.78 %. The remaining carbon residue was of 0.25%.

Applying the thermogravimetric method, we have obtained important data on the course of thermal degradation of each sample tested. The resulting values for the PUR foams are introduced in Table 2.

Tab. 2 Summarized thermogravimetry analyses results

Sample	T_I / ˚C	T_{MAX} / ˚C)	T_F / ˚C	T_F - T_I / ˚C)	*RR C600* / %
PUR1	100	323.0	671	571	1.14
PUR2	110	304.3	620	510	0.30
PUR3	133	323.0	694	561	0.46
PUR4	119	333.7	570	451	0.35
PUR5	100	272.3	694	594	0.25
Average	112 ± 14	311.3 ± 24	650 ± 54	537 ± 57	0.50 ± 0.37

* Note: T_I – initial temperature; T_{MAX} – temperature at which mass loss peak was achieved; T_F – final temperature; *RR* – resistant residue.

According to the results achieved, we can state that the initial thermal degradation process started at temperature of 113 °C. At this temperature, the TG curves begin to point out a slight mass loss. The maximum mass loss occurred in the second stage of thermal degradation process, except the samples PUR4 and PUR5, where, in the case of PUR 4 sample, it was found in the third stage and in the case of PUR5 sample already in the first stage of thermal degradation process. The temperatures at which the maximum mass loss was achieved were close or within the temperature range of 304.3 – 333.7 °C, except the PUR5 sample, where the maximum mass loss was achieved at temperature of 272.3 °C.

3.2 DSC analysis results

From the PUR foam fire hazard point of view, it is important to determine the temperature interval, when the thermal degradation reactions have an exothermic effect. For this purpose, the differential scanning calorimetry was used.

In the DSC analysis of the PUR1 sample we found two stages of thermal degradation process. The sample showed the exothermic effects. The first stage of thermal degradation took place in the temperature range of 254 – 451 °C, where the amount of heat released was of 3,315.4 J g^{-1}. The second stage began at 451 °C and was not completed. From the DSC curve, it was evident that the amount of heat released increased and the sample was not completely decomposed.

The DSC analysis of the PUR3 sample confirmed the two-stage thermal degradation process, although the second stage differed significantly from the first stage in the amount of heat released. Thermal degradation process was not completed in this case. The first stage of thermal decomposition process took place in the temperature range of 243 – 450 °C, where the heat release was of 3,877.8 J g^{-1}. At temperature of 322.3 °C, there was a sharp rise in the heat release value, which peaked at temperature of 342.7 °C. In the second stage, in the temperature range of 450 – 595 °C, the heat release was of 1,818.2 J g^{-1}. The total amount of heat released by the PUR3 sample was of 5,696 J g^{-1}.

According to DSC results, we can state that the thermal degradation process of the PUR4 sample had two stages. From a temperature of c.a. 340 °C up to the temperature of 595 °C, the heat release values were very similar. The first signs of thermal degradation, according to the DSC curve, occurred at temperature of 214 °C, and at temperature of c.a. 340 °C, there was recorded a higher release of heat from the sample. The total heat released from the sample was of 7,393 J g^{-1}. Also, in this case, the thermal degradation process was not completed.

DSC analyses results of the PUR2 and PUR5 samples were comparable. They varied with temperature intervals and the amount of heat released. Both samples as well as the other PUR samples (PUR1, PUR3 and PUR4) did not undergo complete thermal degradation process. In the case of PUR2 sample, the highest amount of heat released was at temperature of 591.5 °C. During the incomplete thermal degradation process, the PUR2 sample released 6,537.6 J g^{-1} of heat. The PUR5 sample released the highest amount of heat (4,199.9 J g^{-1}) at temperature of 322.4 °C. In the second thermal degradation stage, in the temperature range of 449 – 595 °C, the PUR5 sample released 3 099.2 J g^{-1} of heat.

In the DSC analysis of the PUR foams samples, we obtained quantitative results on the course of their thermal degradation process. Those results, i.e. comparison of initial and final temperatures, enthalpy change values, and the amount of heat released values are introduced in Table 3.

Tab. 3 Summarized DSC analyses results

Sample	T_I / ˚C	T_F / ˚C	T_{MAX} / ˚C	Heat released /J g^{-1}	Enthalpy change peak 1 / J g^{-1}	Enthalpy change peak 2 /J g^{-1}
PUR1	254	595	349.3	6,514.7	3,315	3,199
PUR2	259	595	591.5	6,537.6	3,179	3,359
PUR3	243	595	342.7	5,696.0	3,878	1,818
PUR4	214	595	380.3	7,393.0	4,070	3,323
PUR5	244	595	322.4	7,299.1	4,200	3,099
Average	243 ± 17	595	397 ± 110	6,688.1 ± 691	3,728 ± 457	2,860 ± 700

From the results is clear that the initial temperatures of the samples were comparable. The PUR1 and PUR2 samples showed the existence of a retardation treatment because the samples had a higher initial temperature. The reason of only one value of final temperatures for all samples was the fact that thermal degradation process was not completed since the maximum temperature of the measuring apparatus was reached during the testing.

The DEFLAMO retardant treated PUR2 sample released the highest amount of heat at temperature of nearly 600 °C. The lowest amount of heat PUR3 sample released.

3.3 Cone calorimetry results

From the cone calorimetry we obtained the information on ignition time, peak heat release rate, peak heat release rate time, the effective combustion heat (EHC) and the total heat released (THR).

The HRR curves are illustrated in Figure 2 and the summarized results of cone calorimetry analyses are introduced in Table 4.

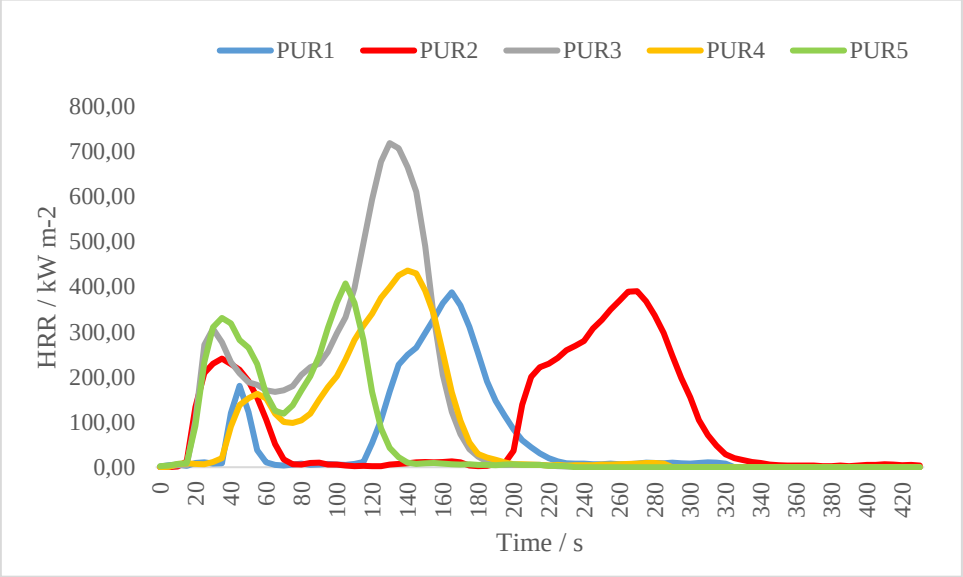

Fig 2. HRR curves of PUR foams

As shown in Figure 1, all the PUR foam samples were ignited at lower incident heat fluxes. All of them showed two-stage course of thermal degradation process, which was also described by Pitts (2014) [24], Ezinwa et al. [25], Lefebvre et al. [26] and Xu et al. [20].

Tab. 4 Summarized cone calorimetry results

Sample	Weight / g	Time / s	EHC / MJ kg^{-1}	Peak HRR / kW m^{-2}	Peak HRR time / s	THR / MJ m^{-2}
PUR1	8.00	20-37 100-207	28.50	390.01	165	24.10
PUR2	15.50	5-57 166-305	24.50	363.90	270	39.79
PUR3	14.70	4-163	28.60	683.07	130	51.13
PUR4	11.00	19-176	25.50	417.29	140	32.80
PUR5	7.90	5-123	31.90	417.49	105	27.02
Average	11.42 ± 3.59	–	27.80 ± 2.92	454.35 ± 129.80	162 ± 64.10	35.00 ± 3.59

According to data introduced in Table 4, we can state that the longest time to ignition showed the samples PUR1 and PUR4. Both were treated by flame retardant. We expected similar behaviour by sample PUR2, which was also treated with flame retardant but it had comparable time to ignition values like the non-treated PUR foam samples. The maximum value of HRR was recorded by the PUR 5

sample, representing the normal type of PUR foam without any flame-retardant treatment. The lowest value of HRR was recorded by PUR2 sample, which also reached its HRR peak latest (after 270 s). From the THR point of view, we can stet that the maximum amount of heat released the PUR3 (V 4010) sample.

4 Conclusions

Thermal analysis and cone calorimetry still belong among the progressive analytical methods to study the fire and thermal properties of materials. In this study we investigated the fire and thermal parameters of five PUR foams commonly used in furniture of residencies as well as in industry. Based on the results of TG / DTG, DSC and cone calorimetry we stated the fire hazard rating of all the tested PUR foams.

The results pointed out the effect of retardation on the assessment parameters. The samples with retardation treatment achieved better thermal stability than samples without retardation treatment. The thermal (TG / DTG, DSC) analyses results pointed out the flame retardant non-treated standard N 5063 PUR foam to be the most fire hazardous due to the its lowest thermal stability. The cone calorimetry results confirmed its fire hazard, although the most fire hazardous from ignition time and HRR peak values was found the flame retardant non-treated V 4010 PUR foam sample. N 5063 PUR foam followed the V 4010 in the order of fire hazard.

Results of this study are immediately applicable in the fire safety practice, as an input parameter for modelling of compartment fires as for design of new PUR foam products with higher resistance to fire.

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The Impact of the Heat Flux Density on Separation Distances from Flammable Surfaces of Exterior Walls

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Case study

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Abstract

The paper deals with the topic of determining the density of heat flow from combustible surface treatments of exterior walls, such as combustible insulation systems, combustible cladding of facades and from all-wood constructions of exterior walls. Heat flow density is an important indicator in determining the fire resistance rating of exterior walls and in determining safe separation distances. The article describes the ways in which exterior walls can be classified in terms of fire resistance. One of these methods is a numerical calculation (of the surface amount of released heat and heat flow density), which will be applied to various types of combustible surfaces of the perimeter walls of wooden buildings. The results showed that the numerical calculation is a suitable method for determining the classification of fire resistance rating of exterior walls with combustible coating. The Czech legislation defines the criteria for this classification better.

Keywords: flammable surface treatment; released heat per area; thermal flux density; Heat Release Rate; partly fire open area; fire separation distance

1 Introduction

At the present time, fire safety of the building is placing an emphasis on determining the fire separation distances from the exterior walls, which have an external surface treatment made of combustible materials in the form of wooden cladding or insulation made of plastic or wood fiber materials. This approach is relevant, especially for the frame or prefabricated panel timber buildings, which are often covered with wooden or other combustible cladding on the outside and for all-wood log wooden buildings or wooden buildings made of CLT panels. The listed combustible materials release a surface amount of heat in the event of a fire, which must be taken into account when determining the fire resistance of exterior walls and subsequently when calculating the fire separation distances in accordance with valid standards. In practice, this means that the distances determined in this way can be significantly increased, especially for wooden buildings, which is undesirable in view of the decreasing size of land plots for wooden buildings. Therefore, it is necessary to look for methods to determine the separation distances more precisely so that the distances are adequate and at the same time safe for neighboring buildings.

1.1 Fire closedness and fire openness of exterior walls

Fire-resistive-rated structures are those that are closed to the spread of fire. The term fire closedness is not defined by STN 92 0201-4/Z3 [1], but we can say that a fire-closed structure is one that has fire resistance and that prevents the spread of fire for a certain time. Fire-open structures are those that are

vulnerable to the effects of fire, i.e., they do not have the required fire resistance. The concept of fire-open area is defined in STN 92 0201-4/Z3 [1], while two types of fire-open areas are defined as follows:

Completely fire-open area (CFOA) is the area of:
a) an exterior wall that does not provide for the stability of the building or its part, which does not meet the requirement for fire resistance according to STN 92 0201-2 [2];
b) an exterior wall of a one-story building that does not meet the requirement for fire resistance according to STN 92 0201-2 [2];
c) an opening in the exterior wall or an opening in the exterior wall filled with a filling that does not meet the requirements for fire resistance according to STN 92 0201-2 [2] which is, therefore, considered fore-open.
Partially fire-open area (PFOA) is the area of an exterior wall or its part that meets the requirement for fire resistance, but its outer side has a flammable surface, and it is able to release more than 100 $MJ.m^{-2}$ of heat from 1 m^2 during a fire.

This definition suggests that, in the case of a partially fire-open area, it is necessary to consider not only combustible construction products and components that are added from the outside to the construction of the exterior wall, but also combustible surfaces; if the entire exterior wall is made of combustible material, e.g., in case of a wooden log wall or a CLT exterior wall.

The size of the fire-hazardous space depends on the classification of the fire openness of the exterior wall. Whether it is a wall with a fire-closed or fire-open area can be determined in several ways [3]:
1. By calculation:
    - numerical calculation (amount of released heat, heat flux density),
    - mathematical model, e.g., CFD (Computational Fluid Dynamics) model;
2. By test:
    - fire resistance test,
    - test of the reaction-to-fire of facades,
    - conical calorimetry.

1.2 Released heat per area

Numerical calculation is rather often used method for determination of fire openness of the surface by the amount of released heat from the combustible mass. The classification depends in this case on area weight and calorific value of used materials.

The released heat per area *Q* from the combustible materials of outer surface of the exterior walls can be determined according to the following equation [1]:

$$Q = \Sigma M_i \cdot H_i \quad (1)$$

where:
Q - released heat (MJ/m^2),
M_i – area weight of the flammable material *i* placed on the outer surface of the exterior wall (kg/m^2),
H_i – calorific value of flammable material i on the outer surface of the exterior wall (MJ/kg) according to STN 73 0824 [4],
j – the number of types of flammable materials.

1.3 Heat flux density

Heat flux density, called also heat flux density per area, is a heat flux which is transferred by the unit area perpendicular to the direction of heat transfer. The SI unit of thermal flux density is W/m^2.

According to STN 92 0201-4/Z3 [1], the fire hazardous space, surrounded by a defined separation distance, is safe towards the neighbouring buildings when the thermal flux density on its boundary stays below q = 18,5 kW/m^2.

A lot of countries state thermal flux density value more strictly, e.g., England 12.5 kW/m^2, Sweden 15 kW/m^2 resulting in bigger separation distances. Namely, in Sweden, the separation distances are determined according to the Swedish procedure to architectural design

(Boverket's building regulations). The buildings must be placed at least 4.0 m from the boundary or at minimum 8.0 m from other buildings at the neighbouring lot. In case the separation distances are not met, it must be proven that potential fire shall not spread between the buildings [5].

Thermal flux density per area is determined according to [1] from the respective time of fire duration τ_e, or calculated fire load p_v, and from the gas temperature which is expressed by a standard time-temperature curve T_N for the respective duration of fire:

$$q = (T_N + 273)^4 \cdot 5{,}67 \cdot 10^{-11} \quad (2)$$

$$T_N = 20 + 345 \log (8t + 1) \quad (3)$$

where:
q – thermal fluc density per area (kW/m^2),
T_N – standard gas temperature in the burning space (°C),
t – respective fire duration τ_e or calculated fire load $p_{v,}$ (kg/m^2).

1.4 Fire openness of structural elements abroad

According to ČSN 73 0802 [6], the boundaries between fire-opened and fire-closed areas of exterior walls are determined by the threshold values of the amount of released heat Q and the area density of the heat flow I according to Tab. 1.

Tab. 1 Threshold values of heat flux density I and the amount of released heat Q [6]

Fire-closedness definition	I (kW/m^2)	Q (MJ/m^2)
Fire-closed area	$I \leq 15$	$Q \leq 150$
Partially fire-open area	$15 > I \leq 60$	$150 > Q \leq 350$
Completely fire-open area	$I > 60$	$Q > 350$

For exterior walls of type DP1 (D1) or DP2 (D2) both of the above-mentioned criteria (I and Q) can be applied, for walls of type DP3 only calculation of heat flow density I or fire test can be used.

According to Article 8.4.5 ČSN 73 0802 [6] for structural parts (structural elements) of type DP1 (D1) and DP2 (D2) are classified as fire-closed areas. The exception is in cases where the outer surface of products of fire-reaction class E or F with released heat $Q > 150$ MJ/m^2. The wall is then considered as a partially fire-open area. The type of structural part (structural element) has an influence on the classification of the fire openness of exterior walls according to the regulations of the Czech Republic. Constructions DP1 and DP2 (as long as no combustible material is added to their outer surface) can be classified as fire-closed surface by virtue of their definition (no heat is released from them). Constructions of type DP3 are mostly classified as fire-open areas. An important factor in these constructions is fire resistance. This means that even a structural part of the DP3 type can be classified as a fire-closed area, as long as its fire resistance is ensured by an effective fire coating on the outer side of the wall [3].

However, the technical standard in the Slovak Republic [1] does not state threshold values of the heat flux density per area and the amount of released heat to specify fire openness. Only the threshold amount of released heat is determined to include an exterior wall with an outer combustible surface into a partially fire-open area (Q > 100 MJ/m^2), which must be taken into account when calculating separation distances. However, this does not take into account the type and thickness of the combustible surface of the perimeter wall; it only classifies the combustible surface as a partially fire-open surface (PFOA), whereby the distance from the exterior wall remains the same, regardless of the type and thickness of the combustible material (see Table 2).

Tab. 2 Determination of separation distance depending on various combustible surfaces of the exterior wall according to STN [7]

	Flammable surface	Thickness (m)	Density (kg/m^3)	Area weight (kg/m^2)	Standard calorific value H (MJ/kg) STN73 0824	Heat per area Q (MJ/m$^{2)}$	PFOA	$Spo_2 \cdot k_{10}$ (m^2)	p_o (%)	d (m)
1	Facade EPS 70 F	0.15	17	2.55	39	99.45 ≈100	yes	22.27	46.89	8.1
	STEICO Protect	0.06	265	15.9	18	286.2	yes	22.27	46.89	8.1
	Wood cladding (spruce)	0.022	460	10.12	17	172.04	yes	22.27	46.89	8.1
2	Log house wall	0.2	420	84	17	1428	yes	22.27	46.89	8.1
3	CLT wall	0.08	470	37.6	17	639.2	yes	22.27	46.89	8.1

2 Material and Methods

In order to determine the fire openness of the considered exterior wall more accurately, we will proceed according to the methodology of Czech standards. The separation distance for the same materials considered in Tab. 2 shall be determined, while the facade cladding materials EPS 70 F, STEICO Protect - wood fiber board and wood (spruce) cladding will be applied from the outside of the column structure of the perimeter wall of type D2, and the log wall and the wall made of CLT panels are made of solely spruce wood, that means it is structural elements of type D3. There are two window openings measuring 1.10 × 1.25 m in the considered exterior wall. The dimensions of the perimeter wall are 12.41 × 4.3 m and it is a single-family house building, which forms one fire compartment.

According to Czech legislation, the calculation of the amount of released heat according to equation (1) can only be used for structural elements of type D1 and D2. This calculation cannot be used for structures of type D3 because we cannot neglect the combustible load-bearing structure in the calculation. For structural elements of type D3, the heat flux density calculation or fire test [3] is used.

Calculation of heat flux density can be used for all types of structural elements D1, D2, D3. We can use the following simplified equation [3] to determine the fire resistance of exterior walls:

$$I = \varepsilon \cdot \sigma \cdot (T_N + 273)^4 \quad (4)$$

where:
I – heat flux density (kW/m^2),
ε – emissivity with the estimated value $\varepsilon = 1.0$ (-),
σ – Stefan-Boltzmann constant equal to the value of $5.67 \cdot 10^{-8}$ W/m$^2 \cdot$K^4,
T_N – temperature of the burning surface (°C).

The gas temperature value is variable. The formula of the external fire curve or the hydrocarbon curve (for flammable gases and vapours) is inserted into the equation. All the mentioned curves depend on the duration of the fire.

In the case of timber structures made of structural elements of type D3, it is also possible to use a more effective assessment of the fire openness, or closedness of the exterior walls depending on the

calorific value and burning rate. This method is used, for example, in software for fire CFD simulations [3]:

$$I = \frac{\upsilon \cdot H}{60} \tag{5}$$

where:
I – heat flux density (kW/m^2),
υ – burning rate (kg/m^2·min),
H – calorific value of the flammable material on the outer surface of the exterior wall (MJ/kg).

When calculating, it is possible to take into account the fact that a larger part of the total released heat is usually released in the form of air flow and combustion products, and a smaller part by heat radiation, heat transfer through conduction is neglected. From the safety point of view, it is possible to consider a value of the radiation equal to 50 % of the total released heat. In mathematical models, the radiation is assumed to be even smaller [3].

2.1 Methodology of calculation of heat flux density for chosen flammable materials on the outer side of the exterior wall

In order to take into account the type and thickness of the material from the outer side of the considered exterior walls (post-frame construction D2 construction, log construction D3 and CLT panel construction D3), according to relation (5), the heat flux density I is calculated for each type of combustible surface material. As mentioned before, this calculation can be used for all types of structural elements D1, D2, D3. The input data for the calculation are listed in Tab. 3. The calculation results are shown in Tab. 4. The burning rate of individual combustible materials is determined according to Annex C, Tab. C2 of STN 92 0201-1 [8]. The calorific value of these materials is determined according to STN 73 0824 [4].

Tab. 3 Input data for the calculation

Item No.	Combustible surface	Thickness (m)	Density ς (kg/m^3)	Surface weight M_i (kg/m$^{2)}$	Standard calorific value H (MJ/kg) STN 73 0824	Heat per area Q (MJ/m^2)	Burning rate υ (kg/m^2·min)
1	Facade EPS 70 F	0.15	17	2.55	39	99.5	1.50
	STEICO Protect	0.06	265	15.9	18	286.2	0.22
	Wooden cladding (spruce)	0.022	460	10.12	17	172.04	0.45
2	Log house wall	0.2	420	84	17	1428	0.45
3	CLT wall	0.08	470	37.6	17	639.2	0.45

2.2 Methodology of separation distance calculation

The separation distance shall be calculated according to the technical standard [1] and [9]. First, the separation distance from the completely fire-open areas shall be determined for the specified reference exterior wall construction.

The total fire-open area S_{po} is determined from the ratio of heat flux density according to individual areas of the equation:

$$S_{po} = S_{po1} + k_{10} \cdot S_{po2} + k_{11} \cdot S_{po3} \quad (m^2) \tag{6}$$

where:
S_{po1} – completely fire-open area (m^2),
S_{po2} – partially fire-open area (m^2),
S_{po3} – fire-open area of roof cover (m^2),
k_{10} – coefficient of partlially fire-open area (-),
k_{11} – coefficient of fire-open area of roof cover (-).

Coefficients k_{10}, k_{11} are determined according to Tab. 2 STN 920201-4 [9]. Further, the percentage of fire-open area p_o and the total area of exterior wall according to the equation:

$$p_o = \frac{S_{po}}{S_p} \cdot 100 \leq 100 \ (\%) \tag{7}$$

where:
p_o – percent of fire-open areas (%).
S_{po} – total fire-open area (m^2),
S_p – area of exterior wall (m^2).

The separation distance d (m) is deteremined according to Tab. 3 STN 92 0201-4 [9] depending on the length and height of the exterior wall l and h_u and percent of fire-open areas p_o and fire risk by calculated fire load p_v. According to Tab. K1 STN 92 0201-1 [8], the fire risk value for the construction of a family house is p_v = 50 kg/m^2. In case of a combustible structural assembly of the building, the calculated fire load in the fire section must be increased by 25 kg/m^2 in accordance with [1]. To determine the separation distance, we will, therefore, consider the value p_v = 75 kg/m^2.

3 Results and Discussion

Part 1.4 mentions that both criteria I and Q can be used to assess the fire openness (closedness) for exterior walls of type D1 or D2. As for walls of type D3, only the calculation of heat flow density I can be used. For post-frame exterior wall of type D2 with combustible cladding materials (EPS, STEICO, wooden cladding) are the values of the amount of heat per area Q already calculated (see Tab. 2 and Table 3) according to Tereňová (2021) [7]. To classify the post-frame exterior wall from the point of view of fire openness (closedness), Tab. 1 according to ČSN 73 0802 [6] was used. For log and CLT exterior wall type D3, the heat flux density I was calculated according to relation (5), while a 50 % radiation share according to [3] was taken into account and was classified also according to Tab. 1. The separation distance was determined for all types of combustible surfaces according to the methodology given in part 2. 2. The results of the calculations are shown in Tab. 4.

Tab. 4 Calculation results according to the Czech Technical Standard (ČSN)

Number	Combustible surface	Heat per Area Q (MJ/m^2)	Heat flux density I (kW/m^2)	Fire openness of exterior wall	Percentage of fire open area p_o (%)	Separation distance d (m)
1	Facade EPS 70 F	99.5	-	Partially fire-closed area	5.15	2.7
	STEICO Protect	286.2	-	Partially fire-open area	46.89	8.1

Continuation of Tab. 4

1	Wooden cladding (spruce)	172.04	-	Partially fire-open area	46.89	8.1
2	Log house wall	-	63.75	Completely fire-open area	100	11.4
3	CLT wall	-	63.75	Completely fire-open area	100	11.4

When the results of determined fire openness (closedness) and separation distance according to Czech legislation (Table 4) and Slovak legislation (Table 2) are compared, significant differences can be seen. With a combustible EPS surface, the exterior wall was classified as a fire-closed area according to Tab. 4 and thus the separation distance changed from the value of 8.1 m to 2.7 m as it was determined only from the size of openings in the exterior wall. With a greater thickness of EPS insulation, an increase in the amount of released heat Q can be assumed which would classify the exterior wall as a partially fire-exposed area.

The results for the combustible surface of the exterior wall cladded with STEICO Protect wood fiber board. Wooden cladding remained unchanged after comparison with Tab. 2 as the amount of released heat Q in both cases exceeded the value of 150 MJ/m^2 which meets the conditions for inclusion in a partially fire-exposed area according to STN and ČSN.

In the case of a log wall and a wall made of CLT panels, the value of the calculated heat flow density I (Tab. 4) exceeded 60 KW/m^2 and placed the structures in a completely fire-open area whereby the separation distance increased to a value of 11.4 m.

Based on the results, the following conclusion can be drawn, the type of structural element has an impact on the results of the evaluation of the fire openness of exterior walls with a combustible surface. Whether the given structure of type D1 or D2 will be classified as a closed or partially open area depends on the value of the amount of released heat Q, mainly on the type and thickness of the combustible surface. However, it is questionable what value of Q should be taken as a threshold; whether 100 MJ/m^2 according to STN or 150 MJ/m^2 according to ČSN.

The results confirmed that in the case of all-wood D3 constructions, it is appropriate to base the determination of the fire openness (closedness) of the exterior walls on the value of the heat flow density I. This is evidenced by the high calculated values of released heat Q = 1428 MJ/m^2 for the log wall and Q = 639.2 MJ/m^2 for a wall made of CLT panels (see Tab. 2) which are considerably higher than in other cases. Therefore, the established separation distance of 11.4 m according to ČSN is adequate.

Similar results were achieved by Pokorný (2014) [3] who numerically evaluated a log cabin with a massive wooden exterior wall which accounted for the required fire resistance. He considered the speed of wood burning v = 0.45 kg/m^2·min and the calorific value of coniferous wood H = 17 MJ/kg with a 50 % radiation share, he calculated the heat flux density I = 63.8 KW/m^2 which classified the solid wooden exterior wall as a completely fire-open area. This result complies with our calculations (see Tab. 4).

Pokorný (2014) [3] also evaluated a building with the exterior wall of type D2 construction with wooden cladding thickness 20 mm, density 500 kg/m^3, calorific value 17 MJ/kg. Based on the given input data, he calculated the amount of released heat Q = 170 MJ/m^2 and the exterior wall was classified as a partially fire-open area. The result is identical to the result in Tab. 4.

To evaluate the degree of fire openness, it is possible to use a small-scale test with a conical calorimeter. Based on tests performed at the Technical Institute of Fire Protection in Prague (TUPO), presented by Kašová (2017) [10], samples of fiber board plastered with cement plaster (as designed for D3 type construction with fire resistance) showed heat release rate greater than 15 kW/m^2 and less than 60 kW/m^2. Therefore, the composition was classified as a partially fire-open area. In our case, the

STEICO fiber board was classified in the same way. Heat Release Rate is currently one of the most important fire engineering characteristics. The heat release rate does not only indicate the total amount of heat released, but it also expresses its time performance during the development of the fire. Therefore, it is not completely suitable for determining fire openness [10, 11].

Kašová (2017) [10] presents the results of a non-standardized large-scale test, during which construction D1 with combustible OSB cladding in which there was a window opening was tested. During the test, the fire was set according to the standard temperature curve inside the furnace to which the fire scenario of an external fire in the lintel was added. By numerically calculating the amount of released heat, the tested wall was classified as a partially fire-open area. The determination of fire openness (closedness) on the basis of the proposed non-standardized large-scale test turned out to be not very suitable because the classification of fire openness (closedness) is determined using the heat flux density on the burning surface. There is currently no procedure for measuring this parameter. At the same time, the methodology for testing this parameter has not been established yet.

4 Conclusions

According to the obtained results using numerical calculations, it was shown that it is a suitable way of determining the fire openness (closedness) of exterior walls with a combustible surface. The criteria for this classification are defined more precisely in the Czech legislation. Slovak legislation lacks threshold values of heat flux density I and the amount of released heat Q. The results of calculations of fire openness of the assessed exterior walls with a combustible surface according to ČSN and STN were different. Bigger separation distances were detected by Czech legislation. It would be appropriate to supplement the obtained calculation results with the results of mathematical modelling. However, the test methodology is still not clear.

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