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

ΔDelta

FIRE PROTECTION & SAFETY
Scientific Journal

Vol. 16 Iss. 1
July 2022

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Vol. 16 Iss. 1
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Editorial Office of the ΔDelta journal

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Publisher

Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovak Republic, IČO 00397440

Published twice a year

1st Edition – July 2022

EV 3857/09

ISSN (print) 1337-0863

ISSN (online) 2585-9730

Print

Technical University in Zvolen
T. G. Masaryka 24
960 01 Zvolen
Slovak Republic

Content / Obsah

FIRE PROTECTION & SAFETY Scientific Journal
16(1): 7−16, 2022
DOI: 10.17423/delta.2022.16.1.104

Study of Changes of PMMA and PC Flammability Subjected to Aging

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Original Scientific Paper

Received: 20.06.2022; Accepted: 03.07.2022; Published: 31.07.2022

Abstract

Today, plastics are used in every industry, from healthcare to the automotive industry. For their versatile use, it is necessary to deal with their fire-technical characteristics. The aim of the diploma thesis was to determine the effect of aging on the flammability of selected plastics polycarbonate (PC) and polymethylmethacrylate (PMMA), which main use is as a replacement for glass. Testing of plastics was performed according to the international standard STN ISO 1210, namely method A - samples placed in a horizontal position and method B - samples placed in a vertical position. From the point of view of fire-technical characteristics, the linear burning rate and the spontaneous burning time were monitored. In method A, the PC achieved lower flammability because the burning on the tested samples did not exceed the limit of 25 mm compared to PMMA samples, in which the burning of the samples exceeded the limit of 100 mm. In method B, the PC also achieved lower flammability because the samples were extinguished faster compared to PMMA, in which the combustion reached the sample holder. PC has achieved better fire performance and is less flammable than PMMA. The results show that the aging of the samples influenced the flammability of both plastics.

Keywords: fire properties; linear burning rate; polycarbonate; polymethyl methacrylate; spontaneous combustion time.

1 Introduction

Plastics are some of the most important parts of our daily lives. Products made of plastic range from the most sophisticated products such as prosthesis substitutes to auxiliary materials in the kitchen. One of the few reasons for the great popularity of plastics is the wide range of usability both in the home and in industry, due to the huge range of properties that individual plastics have and their ease of processing. The properties of plastics can be adapted to specific requirements by changing their structure, or by mixing them with other types. The first synthetic polymers were discovered in the first half of the 20th century, and Alexander Parkes was one of the discoverers. Nowadays, various materials such as wood, ceramics, glass are replaced by plastics, due to their ease of workability and wide range of usability. In general, plastics as well as products made from them are flammable polymeric materials, so it is important from the point of view of fire protection and safety to deal with their properties.

In the study, we were engaged in the evaluation of polymethyl methacrylate (PMMA) and polycarbonate (PC). Currently, both plastics have significant applications in the chemical, technological, electrical engineering industry. They have a significant presence in construction as various covers, spotlights, boards, roofs, parts, and others.

Polycarbonates belong to the polyesters of carbonic acid and dihydroxy compounds. Those are polyesters of carbonic acid and symmetrical aromatic dihydroxyls of fusion, which contain two phenolic nuclei connected by a bridge, derived from alkyl, or by an atom of oxygen or sulphur. Readily available and in terms of its properties, polycarbonates of 2,2-bis(4-hydroxyphenyl) propane, known by the name of dian or Bisphenol A. [1], are useful. Polycarbonate (PC) was first discovered in 1898 by German scientist Alfred Einborn at the University of Munich. In 1957, linear polycarbonate was patented at Bayer in Uerdingen, Germany, by Hermann Schenll. [2,3]

The PC is classified in class B of reaction to fire, which means that it contributes minimally to the spread of fire. It maintains dimensional stability up to approximately 140 °C and heat-resistant for a short period of time up to approximately 160 °C, and the block begins to deform, causing the material to sag or collapse from anything that holds it in place. It passes into the molten substance when tempered, at a temperature of approximately 220 °C, and the molten substance gradually drips in small quantities. Burning polycarbonate releases a sweetish odour and a yellowish flame coloration. The rate of spread in a fire is very slow, especially when compared to other flammable substances. The PC has an s1 classification, which means that it releases a low amount when burning. But at temperatures of approximately 380 °C, thermal degradation occurs with the formation of thick dark smoke without a special taste and odour. For humans, polycarbonate burning fumes are not physiologically dangerous.

Among other things, the PC is a self-extinguishing polymer and produces a small amount of burning droplets, therefore it receives a d0 rating according to EN 13501-1. However, even these small droplets can contribute to the spread of fire by igniting other objects. [4]

At a temperature of approximately 160 to 170 °C, the molten material is transformed when it begins to drip. This phenomenon can help extinguish a fire if it directly drips onto a source of flame. At the same time, this can detract from the impression when testing the PC, as it can drip onto the burner and stop the test before completing the classification, e. g., with a PC board more than 6 mm thick. For multilayer types, testing is possible to the will of more air and less material for melting. In the combustion products of polycarbonate, with increasing temperature, derivatives of phenols with a small number of elements of aliphatic and aromatic hydrocarbons and aldehydes, phenols, carbon monoxide and carbon dioxide are found. If polycarbonate burns in a room with insufficient burning, Bisphenol A is also found in the combustion products in a certain amount, which in increased quantities can have mutagenic effects on the human body. A burning PC is extinguished mainly with powders, CO_2, or medium and heavy foam. [5,6]

Polymethyl methacrylate is a polymer of methyl methacrylate (MMA) and a polymethracrylic acid ester) from chemical point of view. PMMA is usually synthesized by radical MMA polymerization, and anionic and coordinating polymerizations are also available. PMMA is one of the methacrylic resins, commonly called acrylic resin. PMMA is a transparent thermoplastic and is a widely used polymeric material in the fields of aerospace, engineering, medicine, and architecture, which has shock-, weather-resistant and chemical-resistant properties and is known as a substitute for inorganic glass. Since PMMA is strong, lightweight and has colour versatility, it is used in various applications in optical materials, automotive, electronics, displays and other industries. [1,7] Polymethyl methacrylate (PMMA) was first developed by the German chemist Otto Rohma in 1901. A few decades later, in 1943, Kulzer and Degussa ennobled PMMA into a form of a similar path. Their development led to the formation of cold-hardened PMMA. [8]

PMMA is a readily flammable polymer and begins to melt at around 120°C. The rate of flame on the surface is very low, and the coloration of the flame is blue and yellow. PMMA burnout is even and gradual. During burning, drip does not occur, but burning soft parts of the polymer may fall off. Burning has a sweetish smell. With the thermal degradation of PMMA, many esters are formed, but without the development of combustion products. It belongs to the group of polymers, after which no residues remain and there is no dripping. The substances contained in the combustion products include, first, methyl methacrylate, and others are methyl propinate, methyl acrylate, methyl isobutyrate. Alcohol substances, in particular ethanol and methanol, were also recorded at higher temperatures, as well as ethylene, carbon monoxide, acetylene and carbon dioxide when testing thermal degradation. To extinguish burning polymethyl methacrylate, it is adequate to use a compact or fragmented stream of water or water mist with admixtures of wetting agents. When using water foam, a two-sided reaction of the foam with the formed aldehydes and esters can occur, and such foam can further promote burning. [5,9]

Plastics change their properties over time due to aging.

The aim of the study was to determine the effect of aging on the flammability of PMMA and PC.

2 Material and Methods

The dimensions of the test samples (see Fig. 1 and 2) were laser cut to 125 x 13 x 3 mm. Subsequently, the samples were divided into two sets. One set of samples was stored indoors in a box in a dark place for 18 months, the second set of samples was exposed to weather conditions outdoors for 18 months, the samples were subject to natural aging.

The methodology used to deal with the experimental part of the work was constructed in accordance with STN ISO 1210:1996 [10]. It is an international standard characterizing a laboratory method for comparing fire characteristics in the horizontal (method A) and vertical (method B) position of samples of test plastics that are exposed to the action of a small flame initiator.

The test method is intended to determine the spontaneous flame/glowing time and the length of damage to the test sample. The use of the method shall be applied to lightweight or rigid materials with a specific weight of at least 250 kg/m^3. Testing of samples was in two ways according to the standard.

Method "A" – Determination of the linear burning rate of horizontal samples

For Method "A", marks are made on the samples and then the test device was prepared for the flammability test in a horizontal position. Underneath the sample a foil with filter paper was placed. The burner flame was adjusted so that it reached a length of 20 mm, was at an angle of 45° and touched the sample to a depth of approximately 6 mm. The flame was allowed to act on the sample for 30 s and subsequently delayed or immediately after reaching the marked line in less than 30 s. If the marked line was crossed, the second stopwatch was triggered. If the sample has burned without flame even after the burner has been delayed, the burning time in seconds was recorded. The damaged part of the sample was recorded and calculated according to the procedure in the standard.

Method "B" - determination of the period of spontaneous flame burning or glowing of vertical samples

For method "B", devices have been prepared for the flammability test in the vertical position. Underneath the sample a foil with filter paper was placed. The flame of the burner was adjusted so that it reached a length of 20 mm and was at an angle of 45°. The flame was applied for 10 s to the lower part of the sample at 10 mm below the lower end of the sample. After 10 s, the flame was delayed and at the same time the stopwatch was triggered to monitor the burning time t_1 in seconds.

If the combustion of the sample was interrupted after the flame has been delayed, the burner was replaced under the sample at the same distance and left for 10 s. After 10 s, the flame was delayed again and the burning time t_2 and the glowing time t_3 were monitored. It was also recorded whether part of the sample had fallen off or dripped.

All samples were conditioned for 48 h prior to testing under the ambient laboratory conditions under which the experiment was carried out.

3 Results and Discussion

Fire properties are an important factor in the assumption of determining the fire behaviour of materials. The determination of the spontaneous burning time, the linear burning rate, describe more closely the supposed possibility of burning in real fires. The individual values of PC and PMMA vary, but there is a significant difference in the total time of spontaneous burning and mass loss before and after aging.

3.1 Method "A" results

When applying method "A", the samples were tested in a horizontal position. Demonstration of the combustion process of PMMA and PC samples is shown in Fig. 1-2.

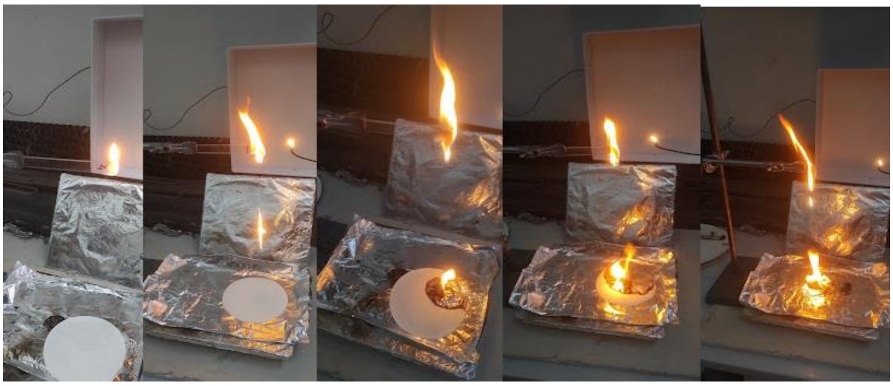

Fig. 1 PMMA burning pattern by Method "A"

Fig. 2 PC burning pattern by method "A"

The PMMA total time of spontaneous burning time is shown in Fig. 3.

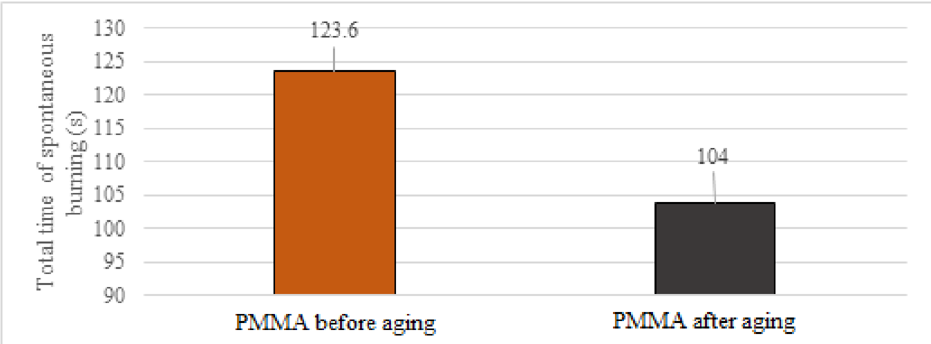

Fig. 1 Total time of spontaneous burning

The total spontaneous burning time shows that PMMA ageing has significantly influenced the comparative characteristics of the samples, with a difference of 19.6 s between PMMA samples before and after ageing. The total spontaneous burning time of the PC could not be determined because the samples did not burn out the 25 mm limit from which the measurement begins.

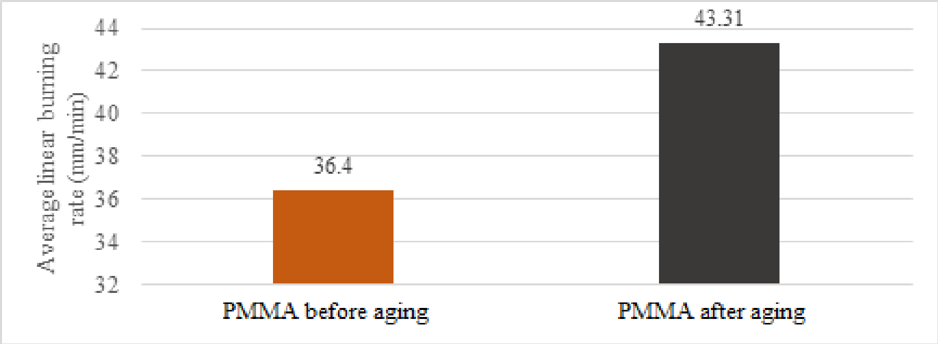

Fig. 4 Average linear burning rate

The graph (Fig. 4) shows that the lowest average linear burning rate was of 36.4 mm/min before ageing and the highest PMMA after ageing was of 43.31 mm/min. The linear burning rate of the PC could not be determined because the 25 mm boundary from which the measurement begins was not burned out for the samples.

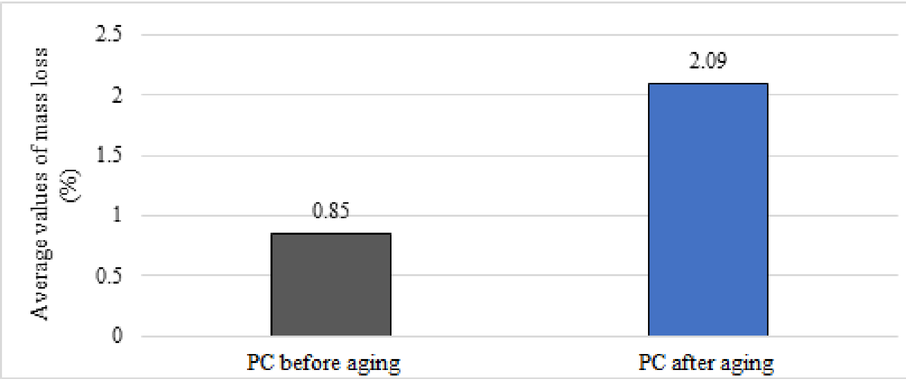

Fig. 5 Average values of mass loss

PC samples (Fig. 5) ahowed a significantly worse effect on the resulting average values of mass loss after aging. The average mass loss of PMMA samples is approximately 67% for both types of aging. However, here we must note that PMMA samples would burn out whole, however, the combustion stopped at the terminal block of the sample holder, therefore the values are removed from the graph. Samples after testing (before and after aging) are shown in Fig. 6.

Fig. 6 PMMA and PC samples after testing with method "A"

3.2 Method "B" results

When applying method "B", the samples were tested in an upright position. A demonstration of the burning process of PMMA and PC samples tested in an upright position is shown in Fig. 7-8.

Fig. 7 PMMA burning pattern by method "B"

Fig. 8 PC burning pattern by method "B"

The total period of spontaneous burning both before and after aging is shown in Fig. 9.

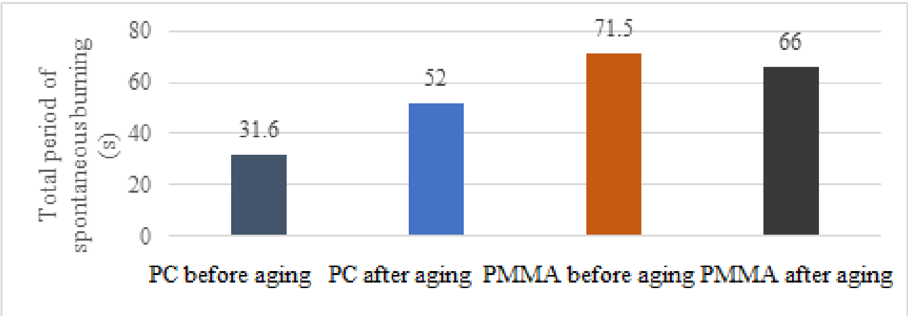

Fig. 2 Total period of spontaneous burning

With the total spontaneous burning time of PC and PMMA, aging has affected both the burning time of both PC and PMMA in a negative direction. As with method "A", the burning of the PC did not reach the upper limit (or sample holder). PC samples burned longer after aging than before aging. The self-extinguishing effect was more pronounced in the sample before aging, which also resulted in less mass loss. PMMA samples burned out after aging in less time than before aging. The mass loss of PC samples is shown in Fig. 10.

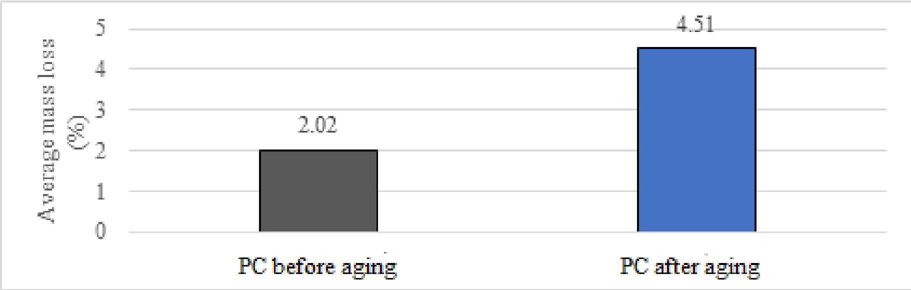

Fig. 3 PC average relative mass loss

For PC samples, aging has a significant impact on mass loss. The difference in mass loss before and after ageing was of 2.49%. The average mass loss of PMMA samples was approximately of 77% for both types of ageing. The same statement applies here as with method "A", that PMMA samples would burn out whole in this case, burning was stopped by the terminal block of the holder. Samples after testing are shown in Fig. 11.

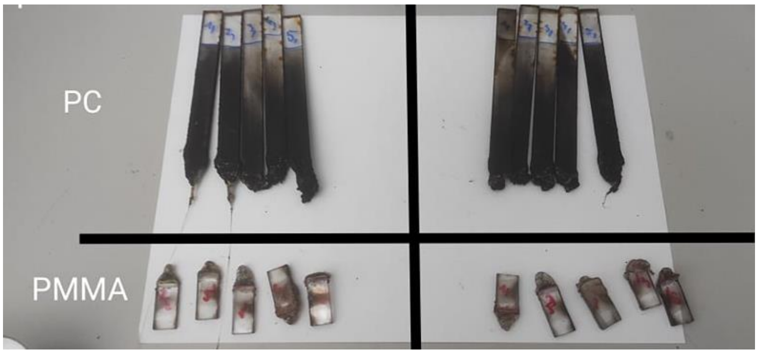

Fig. 4 PC and PMMA samples after testing with method B

In both methods, there is a difference in mass loss for PC samples before and after aging. When applying method "A", the difference in mass loss is 1,24 %, while in method "B" the difference is higher by 2,49 %. The average mass loss for PMMA samples by method "A" and method "B" is 67 % and 77 % respectively. However, for PMMA samples, by both methods, there would be a total burning out of the samples i.e., 100 %, if they were not in the holder which stopped burning.

When comparing the ignition of PC and PMMA samples, we found that PMMA had more negative results, which manifested themselves after just a few seconds, after attaching a flame. There was a sharp ignition, a large flame with the repeatable dripping of the melt, which is immediately ignited after contact with the filter paper.

By the PC, during the initial contact, there was a slower ignition, and its burning took a shorter time or until the melt drips, however, the filter paper did not ignite. In terms of ignition and the spontaneous spread of flame over the surface, the PC had significantly better results.

The linear burning rate assessment was done only by PMMA when testing using the method "A", while by PC the combustion did not reach the limit of 25 mm of the mark on the samples. The linear burning rate of the PMMA sample before aging showed lower values compared to PMMA after aging, which were exposed to weather conditions.

From the results obtained, we classified samples of PC and PMMA in both types of aging, in accordance with its fire-fighting characteristics, into a suitable class. For both types of aging, we have classified the PC in the FH-1 class. We classified pre-ageing PMMA in class FH-3-36.4 mm/min, and after aging, we classified PMMA in class FH-4-43.31 mm/min.

When using method "B", the total spontaneous burning time of samples in the vertical position was evaluated. From the results obtained, we found that the aging of the material has a significant impact on the total time of spontaneous spread of the flame over the surface, which was shown in impaired results compared to the pre-aging condition.

Finally, based on the results of the PC and PMMA samples, we classified them in a special class according to the standard.

We classified PCs before aging in class FV-1, and PC after aging were classified in 4 class, since according to the standard it is not possible to classify PCs after aging by the "B" method, method "A" is used, according to which a PC is classified in class FH-1 after aging.

We have classified PMMA in 4 classes for both types of aging. According to the standard, PMMA cannot be classified according to method "B", therefore, a classification according to method "A" is used, according to which PMMA before aging is classified in class FH-4-71.6 mm/min and in FH-4-66 mm/min for PMMA after aging.

Audouin et al. [11] used the horizontal ignition and spread of flame test [12] and found that PMMA is easier to ignite than a PC, with the PC first melting and then burning, while by PMMA the melt drops.

According to Wang et al. [13], who dealt with dripping with both types of plastic polymers according to the UL-94 method, PMMA dropped faster than PC, with a PC converting the melt into carbon, while in PMMA it bubbled and gradually solidified.

Chow and Leung [14] found that the heat release rate as well as the total heat released by PMMA is several times greater than that of a PC.

We could not determine the linear burning rate of the PC due to not exceeding the limit of 25 mm. The same results were also released by Weaver [15] according to the ASTM D 635-14 [16] test. While for PMMA samples, we set the linear burning rate before aging at 36.4 mm/min and after aging at 43.31 mm/min.

Beňo [17], who in his work evaluated the fire properties of PC and PMMA material, found that in terms of linear burning rate and spontaneous burning time, PMMA has significantly worse properties compared to PC.

4 Conclusions

Nowadays, plastics are an integral part of human everyday life, including the work life. Plastics, according with their chemical composition, are flammable substances, and it is very important to deal with their behaviour also from a fire safety point of view. The aim of the study was to determine the impact of aging on the flammability of PC and PMMA. Flammability was assessed based on the fire properties as linear burning rate, spontaneous flame burning time and mass loss of sample before and after aging. The testing of the plastics was carried out according to the STN ISO 1210 standard, in which the plastics were evaluated using method "A" and method "B". Applying method "B", we tested three samples of each before and after aging. Applying method "A", five samples were tested before and after aging.

When applied method "A", we found that:

- When burning PC samples, a slight odour was felt and thick black smoke was released,
- PMMA samples showed a sharp, soot-free odour with slight turbulent smoke and regular dripping.
- The average mass loss of PMMA samples in both types of ageing reached 67%, with burning stopping at the holder terminal block.
- PC achieved a higher mean % mass loss after ageing of 2.08%, average % mass loss before ageing was of 0.85%.
- The average linear burning rate of PMMA samples before ageing reached 36.4 mm/min and PMMA after ageing reached 43.31 mm/min.
- For PC burning did not exceed the limit of 25 mm indicated on the sample and therefore it was not possible to determine the linear burning rate.

Next, using method A, we determined the total spontaneous burning time of a set of 3 PMMA samples (for PC the combustion did not reach the limit of 25 mm):

- PMMA before aging reached 123.6 s, while PMMA after aging burned for 104 s.

When applied method "B", we found that:

- When burning PC samples, there was a slight odour and thick black smoke.
- PMMA samples showed a sharp odour, with slight turbulent smoke and regular dripping.
- The burning pattern of PC samples was slow, while for PMMA it was very fast.
- The average mass loss of PMMA samples for both types of ageing were of 77%, with burning stopping at the holder terminal block.
- Average % mass loss of PC samples before aging was of 2.02% and of PC samples after aging was of 4.51%.

Further, using the "B" method, we determined the total time of spontaneous flame burning of PC and PMMA (before and after aging):

- For PMMA, better results we achieved for samples before aging (330 s), and worse for samples after ageing (358 s).
- For PC, better results were achieved for samples before aging (158 s) and worse for samples after aging (289 s).

Based on the results found, we can conclude that aging had an impact on the flammability of plastics. In terms of flammability, PC is more suitable than PMMA to be used in industry.

Besides, the results of the study can be beneficial in other PC and PMMA flammability studies as well as in various fire modelling calculations and can also serve for fire investigation needs.

Acknowledgments

This research was funded by the Slovak Research and Development Agency, grant number APVV-17-0005 (100 %).

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FIRE PROTECTION & SAFETY Scientific Journal
16(1): 17–37, 2022
DOI: 10.17423/delta.2022.16.1.105

Experimental Investigation of Digital Image Analysis Opportunities for Studying the Wildfire Dynamics

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Original scientific paper

Received: 15.07.2022; Accepted: 27.07.2022; Published: 31.07.2022

Abstract

The ongoing climate change and observed impacts on the wildland puts in the foreground the need to study the behaviour of wildfires also in the conditions of Central Europe. This study deals with an investigation of beech forest litter fire behaviour. The main objective of study was the identification and verification of opportunities of digital image analysis application in fire engineering and development of a methodology for automated image processing and derivation of selected parameters necessary for describing fire dynamics from images produced by thermal imaging (infrared band) and optical cameras. There were totally five fire tests provided, while three of them were carried out in a laboratory chamber with the simultaneous use of an optical (video) camera used to record the development of flame burning in time. The other two fire tests were carried out in a laboratory fume hood with simultaneous recording of the fire propagation with the Fluke RSE600 thermal imaging camera from above and with an optical camera from the front. For images pre-processing and processing several software were used. Methodologies were developed to derive selected parameters of fire dynamics, which enable wider and more complex use of knowledge obtained from records from a thermal imaging camera, as well as from classic video camera. The results of the study have their application in science and in practice. From the point of view of application in science, they point to the possibilities and suitability of the application in the work of applied digital technologies for the study of fire behaviour and the automated derivation of its selected parameters. The study provides guidance for conducting similar experiments using digital technologies aimed at studying fire behaviour, too.

Keywords: digital image analysis; fire dynamics, forest litter, wildfire fire

1 Introduction

Protecting the population from the effects of emergencies is one of the key tasks of civil protection in Slovakia. Among such emergencies, specifically natural disasters, belongs also wildfire.

Uncontrollably spreading fires of forest vegetation, grasslands and agricultural crops are a global phenomenon [1,2] that can be linked by expected climatic and meteorological conditions. They often lead to large-scale disasters that result in significant adverse economic, social, and environmental consequences [3-5].

Fire is a complex phenomenon involving many processes (for example, the process of burning, release, and transfer of energy) that occur over a wide range of spatial and temporal scales. The characteristics of the fuel particles and the structure of the fuel itself partly determine the amount of energy that will be released in the process of its combustion and describe the way in which the process of combustion and heat transfer takes place [1,6]. Knowledge of the relevant characteristics of fuel occurring in the wildland, which influence fire behaviour, is essential for informing and supporting the decision-making process of relevant persons, as well as input for a wide range of applications intended for fire management (control) as well as the planning of preventive measures aimed at mitigating the occurrence of large fires [7,8]. These applications can be aimed at assessment of the fire danger and providing fire warnings [9-11], assessing the wildfire risks [12,13], modelling the behaviour of fires occurring in different types of vegetation (e.g. grasslands, forests, bushes), planning tactical procedures for fire elimination, calculation of emissions of combustion products arising during a fire [1] and predicting the effects of a fire from the point of view of several aspects [14,15].

Currently, it is often discussed in professional circles as well as among the lay public that the main cause of the increased frequency of fires in wildland is the ongoing climate change and especially its impacts. However, the latest findings of experts [3] show that the danger of wildfires will increase despite the effects of climate change. Several factors contribute to their increased occurrence, such as the moisture content of fine fuel that occurs on the surface of the ground, but also material of larger dimensions, such as pieces of wood. Sufficiently wet surface of the material can reduce the potential of fire spread and positively influence its flammability. Meteorological factors such as wind speed are also important as they can affect the speed at which a fire could spread once it is ignited. [4] However, a critical factor related mainly to extreme weather (periods of prolonged drought) is the moisture content of coarse woody fuels and other organic matter on the ground. And this will be the most significant problem, especially during periods of long drought.

From the above, it is obvious that there is a need to solve the problem of wildfires and in general to research the dynamics of wildfires even in the conditions of Central Europe, where until now they have not been among the significant and frequently occurring natural disasters. The study presented here, and its results, are a contribution to the solution of this issue precisely at the level of the Central European region, which is characterized by the similarity of its geographical, vegetational and climatic conditions.

The main objective of the study was to identify and verify the suitability of applications of digital image analysis tools in fire engineering, i.e., automated image processing and derivation of selected parameters necessary for describing forest fire behaviour from infrared images recorded by a Fluke RSE600 thermal imaging camera and video (optical) camera during laboratory experiments with beech forest litter in a dry state.

Images obtained from video cameras and infrared (thermal imaging) cameras have been used, especially abroad, for several years to study the spread of forest fire fronts, to determine the height of the flame during a fire, the depth of fuel and the angle of inclination of the flame burning along the fire front [16-19] and even to measure the velocity field in the convection column above the fire front [20,21] and the intensity of radiant heat and flame temperature fields [22]. An experimental method using digital image processing techniques obtained from a combination of optical (video) and infrared cameras was already presented by Martínez-de-Dios et al. [23,24]. The images captured the spreading front of the fire, taken from one or more cameras to obtain the time course of the shape and position of the fire front, the angle of inclination of the flame, the height and width of the fuel base.

2 Material and Methods

The material that was investigated was the forest litter collected in the beech forest (stand no. 551, located on the territory of the University Forestry Enterprise of the Technical University in Zvolen) on August 17, 2021. This stand was characterized by the following woody vegetation: European beech 95%, Silver fir 2%, European larch 2% and Sessile oak 1%. The age of the stand was of 60 years.

The sampled beech litter was dried to a dry state in the MEMMERT air dryer before the fire tests were carried out, and in this state, it was also used in individual experiments, in the amount of 100 g for each test. The duration of each experiment was set to 10 min. While the following data were also recorded during the test: end of flame burning, end of glowing and smouldering.

Laboratory fire tests (5 tests totally) were carried out using the available research infrastructure of the Combustion Laboratory, which is managed by the Department of Fire Protection. The fire tests were carried out in two phases. In the first phase, three fire tests were carried out in the laboratory chamber, together with providing video recordings of the flames.

In the second phase, two fire tests were carried out using not only a video camera, but also a thermal imaging camera. These were carried out in the MERCI G laboratory hood. Here we consider it necessary to emphasize that the implementation of the fire tests served exclusively the purpose of obtaining a basic set of data, i.e., images that were the basis for the processing of image analyses and the development of methodologies for automated image processing and the derivation of selected parameters of fire dynamics.

The experiments were performed using a circular test dish with a diameter of 50 cm and a height of 3 cm. During the experiments, the mass loss of the fuel was recorded at intervals of 10 s. RADWAG WLC R2 precision scales were used for this purpose. Thermocouples (T1 – T5) connected to an autonomous measuring station ALMEMO®710 by AHLBORN and a Fluke RSE600 thermal imaging camera providing a sequence of images with a temporal resolution of 8.6 frames per 1 s and a spatial resolution of 640 x 480 pixels were used to record the course of temperatures during the fire.

The GoPro4 video camera was used to create videos of the fire tests. These records were used in a later phase to derive selected flame parameters applying digital image analysis tools.

From the provided laboratory fire tests, data on the course of temperatures recorded by individual thermocouples (T1-T5) were obtained and further analysed.

Using the RADWAG precision scales, the mass loss of the samples was recorded during the 10-min lasting fire tests. These were processed into graphs. From these data, we also calculated the relative mass loss (1) and the relative mass burning rate (2) in time:

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

$$v_r = \frac{\delta_m(\tau) - \delta_m(\tau + \Delta\tau)}{\Delta\tau} \cdot 100 \qquad (\%\cdot s^{-1}) \qquad (2)$$

Where:

$\delta_m(\tau)$ – relative mass loss in time (%)
v_r – relative rate of burning ($\%\cdot s^{-1}$)
$\Delta\tau$ – time interval in which the weights are recorded (s)
$\delta_m(\tau + \Delta\tau)$ – relative mass loss in time (%)

Data on the surface temperature of the fuel at the positions of the thermocouples, which recorded the temperature inside the fuel, were processed from the records obtained by the thermal imaging camera. Subsequently, these temperatures were compared with each other, and the results were analysed and discussed.

The course of temperatures on the surface of the fuel was also recorded and analysed on other profiles, both within the entire surface of the test dish and on specified profiles across the test dish.

From the thermal imaging records, video records and observations, the duration of the flame burning and the time of the glowing (smouldering) of the fuel were obtained. These times were compared to each other. Conclusions were drawn from the results of the comparison.

Data on the mean, average and maximum height of the flame during the fire tests were derived from the data acquired by the video camera. These were derived from images for each 5 s interval.

To calculate the flame height (L_f), it was first necessary to define the mean flame height (m). This is best to determine by averaging the visible height of the flame as a function of time. This is the height at which the flame appears in half of the time (equation 3).

Equation (3) considers the height of continuous (L_{fk}) and pulsating flame (L_{fp}) in half of the flame burning time.

$$L_f = \frac{L_{fk}+L_{fp}}{2} \qquad \text{(m)} \qquad (3)$$

We calculated the average flame height as the average of all flame heights recorded at 5 s intervals during flame burning.

The maximum flame height we determined based on the highest flame height value from the flame height values recorded at 5 s intervals during the flame burning.

Using the data from the fire tests carried out in laboratory fume hood, we calculated the density of the radiated heat flux (mm) according to the formula (4) for each pixel of the image (Wien's displacement law):

$$\lambda_{max} = \frac{b}{T} \qquad (4)$$

Where:

λ_{max} – wavelength at which, at temperature (T), the radiation intensity is maximum
b – universal constant 2.898 (mm·K)
T – thermodynamic temperature on surface of the material (°C)

In the Idrisi TerrSet environment, input images were processed applying image analysis tools (Idrisi Image Processing), i.e., images obtained every 5 s from video recordings and representing the course of fire tests in a specific time. Those further underwent thresholding and reclassification. As a result, we got 2D flame shapes outlines, which were further used for flame heights calculation.

The rate of burning was calculated based on the mass loss of the sample recorded during the experiments at 10 s intervals.

3 Results and Discussion

In this chapter, we present the results of fire tests, the results of image analysis processing aimed at deriving selected parameters of fire dynamics.

3.1 Temperature course in a fire

In this subsection, we present the results of the fire tests namely, temperature curves obtained from data from individual thermocouples (T1 – middle of the bowl, T2 – western edge of the bowl, T3 – northern edge of the bowl, T4 – eastern edge of the bowl, T5 – southern edge of the bowl) located inside the layer of beech litter and also the course of temperatures measured on the surface of the test sample using a Fluke RSE600 thermal imaging camera. The results presented here were obtained during the laboratory fire tests and from processing of the thermal imaging images (in the SmartView R&D software) and of video recordings.

3.1.1 Temperature course – data from the thermocouples

Thermocouples T1-T5 were in the middle of the fuel complex placed on a circular test dish with a height of 3 cm and a diameter of 50 cm. Thermocouple T1 was in the centre of the test dish and the other thermocouples were located 2 cm far from the dish edge.

Fig. 1-3 show the results for the fire tests carried out in the laboratory chamber.

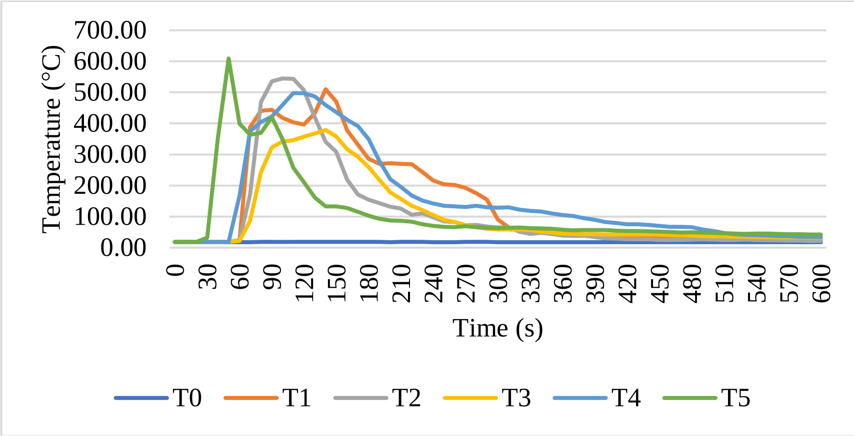

Fig. 1 Temperature course during fire test 1 (chamber) recorded by thermocouples T1-T5

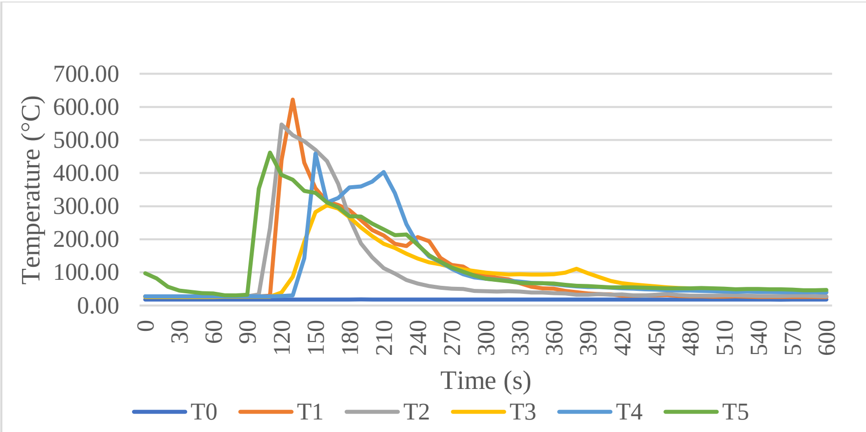

Fig. 2 Temperature course during fire test 2 (chamber) recorded by thermocouples T1-T5

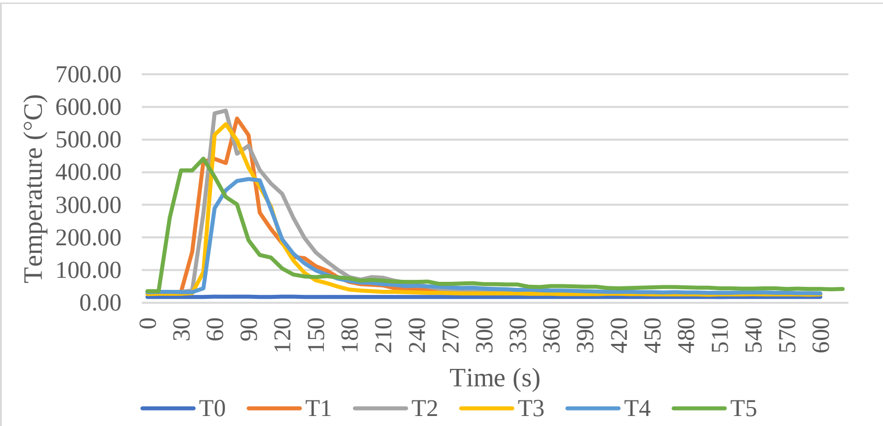

Fig. 3 Temperature course during fire test 2 (chamber) recorded by thermocouples T1-T5

From the course of the provided fire tests, it is obvious that the different course of temperatures in the individual experiments. Combustion was initiated by igniting the fuel in the centre of the test dish (thermocouple T1). Thermocouple T0 recorded the temperature of the surrounding environment. In Tab. 1, we present the maximum temperature values reached on thermocouples T1-T5 during all three tests carried out in the laboratory chamber.

Tab. 1 Maximum temperature values reached by thermocouples – fire tests in the chamber

Fire test /Thermocouple	1		2		3	
	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)
T1 (C)	510.0	140	622.0	130	564.3	80
T2 (W)	549.6	100	546.8	120	588.7	70
T3 (N)	378.7	140	302.7	160	547.0	70
T4 (E)	497.6	110	402.9	210	379.0	90
T5 (S)	420.2	90	461.9	110	441.5	50

*Note: W – west direction; N – north direction; E – east direction; S – south direction; C – centre.

From the results shown in Tab. 1, it is possible to deduce that the heating of the fuel occurred gradually, depending on the direction in which the fire front progressed and where the fire controlled by the available fuel later occurred (maximum temperatures reached during further burning of the fuel). Since the ignition of the fuel always occurred in the centre of the test dish, it is obvious, for example in fire test 1, that the fire front moved from the centre of the test dish first towards the West (T2) and towards the East (T4), i.e., especially in the horizontal direction, slower in the vertical direction. In the case of fire test 2, the front of the fire moved faster especially towards the West (T2) and South (T5). In the case of fire test 3, it spread fastest in the Western (T2) and Northern (T3) directions.

Next, we present the results for the fire tests carried out in the laboratory fume hood (Figures 4 and 5). The obtained results were validated based on knowledge obtained from the study of thermal (infrared) imaging records.

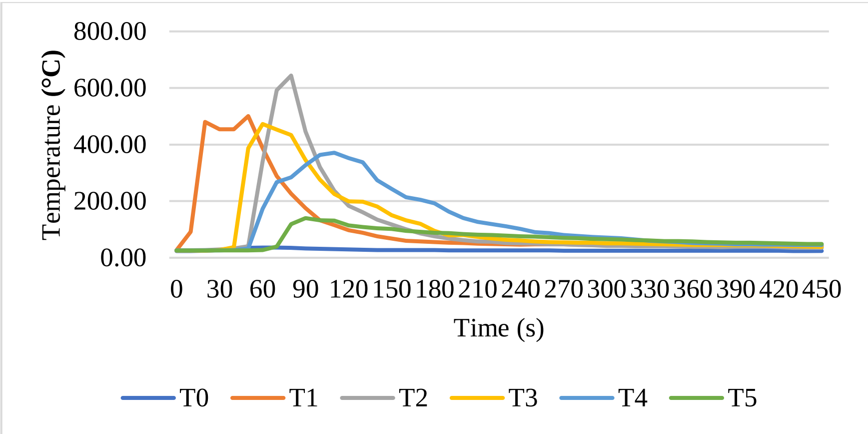

Fig. 4 Temperature course during fire test 1 (fume hood) recorded by thermocouples T1-T5

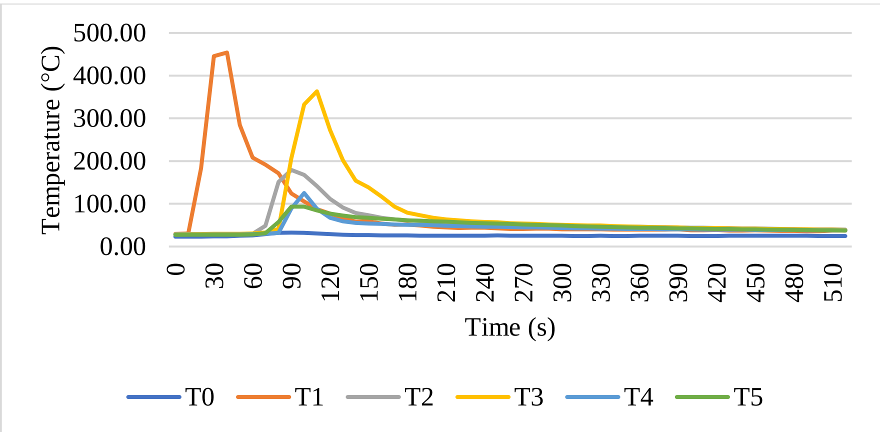

Fig. 5 Temperature course during fire test 2 (fume hood) recorded by thermocouples T1-T5

Like the case of the fire tests carried out in the laboratory chamber, significant differences during both experiments were also seen in the case of the tests carried out in the laboratory fume hood. In Tab. 2 we present the maximum temperature values reached on thermocouples T1-T5 during both tests.

Tab. 2 Maximum temperature values reached by thermocouples – fire tests in the fume hood

Fire test /Thermocouple	1		2	
	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)
T1 (C)	500.7	50	454.1	40
T2 (W)	644.0	80	179.3	90
T3 (N)	472.7	60	363.3	110
T4 (E)	371.1	110	125.3	100
T5 (S)	140.1	90	93.4	90

From the results presented in Table 3, we deduce that due to the above-mentioned principle of evaluating the results, in the case of fire test 1, the fire front moved first towards the Western and Northern edges of the dish. In the case of fire test 2, the fire front moved first towards the Northern (upper) edge.

Images from a thermal imaging camera were used to validate the findings presented here. The results of the analysis of thermal imaging images pointed to the following facts. In fire test 1, the fire front moved fastest to the North, or Northwest, where it reached the Northern edge of the test dish (T3) already in time of 43 s (Fig. 6).

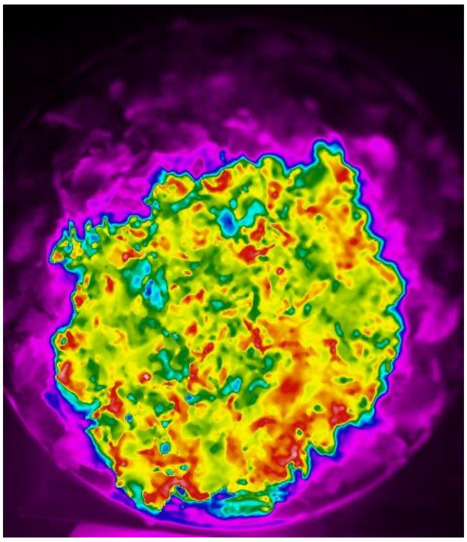

Fig. 6 Fire front reached edge of the test dish – fire test 1

Subsequently, the fire front reached the Western edge of the test dish at 56 s, the Eastern edge at 65 s, and the Southern edge of the dish at 67 s from the start of the fire test. Also, for this reason, considering the amount and structure of available fuel storage, the highest combustion temperatures were later reached at those positions.

In the case of fire test 2, the assumption about the spread of the fire front was not confirmed. Based on the results of the digital image analysis of the infrared images, the fire front moved significantly towards the Northern edge of the test dish at the beginning (Figure 7), but later it spread mainly towards the Southern edge, which reached at time of 61 s. The western edge of the test dish was reached at time of 64 s from the beginning of the fire test.

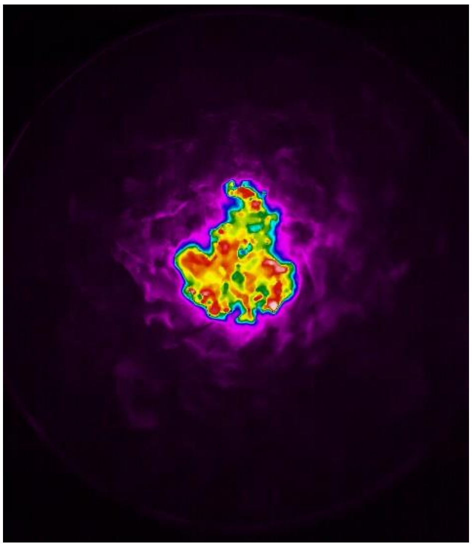

Fig. 7 Fire front movement at the beginning of fire test 2 (time 20 s)

The fire front reached the Eastern edge of the test dish in 73 s and the Northern edge in up to 146 s, while on the surface of the test dish there was also an area of unburned fuel (Figure 8).

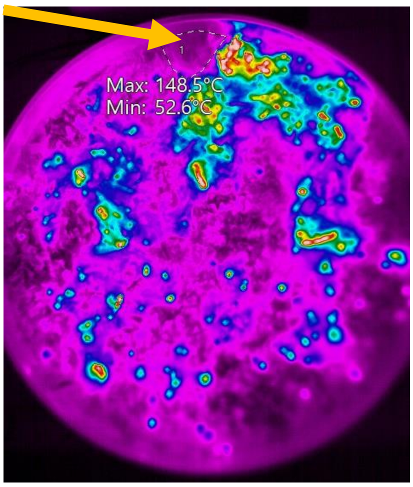

Fig. 8 Position of unburned area in fire test 2

3.1.2 Temperature course – data from the thermal imaging camera

The temperature course on the surface of the test sample was recorded for the position of the individual thermocouples, the entire test dish and subsequently on the individual profile lines. To determine the temperature of the surface of the test sample, recordings from a Fluke RSE600 thermal imaging camera were used, which were processed in the SmartView R&D software. Therefore, the temperatures were determined only within the framework of 2 fire tests carried out in the fume hood.

The thermal imaging camera records individual images at an interval of 0.1 s. In Fig. 9 and 10, we present the values in this interval, therefore we express the time units in the format h:min:s, not in seconds (s).

First, we present the results of the temperature course measured on the surface of the test sample detected at the positions of thermocouples T1-T5.

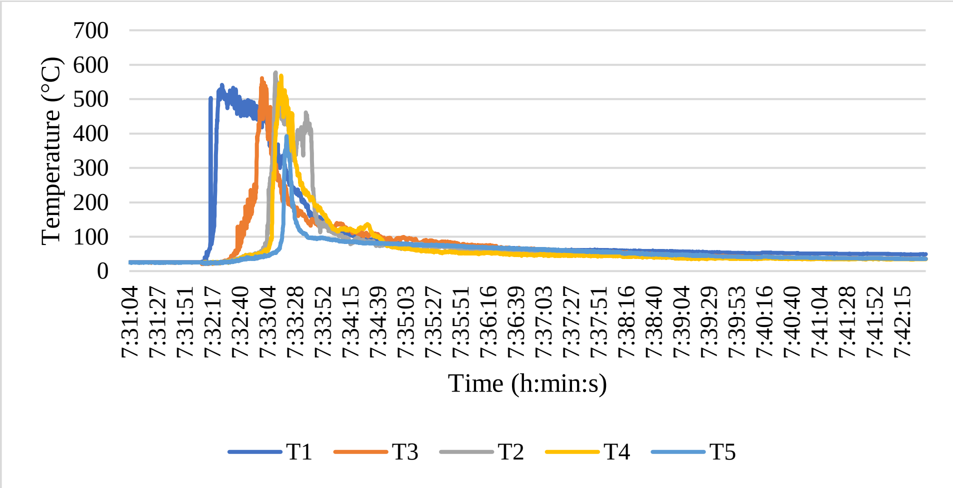

Fig. 9 Temperature course during fire test 1 recorded by thermocouples T1-T5

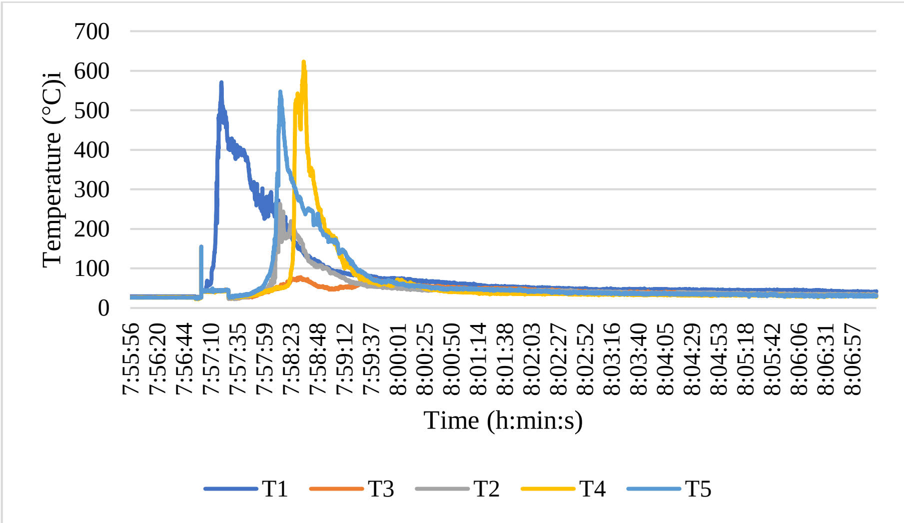

Fig. 10 Temperature course during fire test 2 recorded by thermocouples T1-T5

During the fire test, the maximum and average temperatures reached during the burning of beech litter were recorded on individual thermocouples. In Tab. 3 we provide an overview of these data, which are supplemented with the time in which this value was reached. At the same time, we also present outputs from the SmartView R&D program, i.e., images from the thermal imaging camera, capturing the surface of the test dish and the course of the temperature of the sample during the fire at the pre-defined times, calculated from the start of the fire test.

Tab. 3 Maximum and average temperatures recorded by thermocouples during the fire test carried out in the fume hood

Fire test /Thermocouple	1		2	
	T MAX (°C)	Time (s)	T MAX (°C)	Time
T1 (C)	541.7	13	571.0	7
T2 (W)	578.0	59	264.2	58
T3 (N)	560.9	48	78.4	80
T4 (E)	568.6	64	622.5	82
T5 (S)	392.3	69	547.4	61

Next, we present thermal images recorded at time of 13 s (Figure 11), 48 s (Figure 12), 59 s (Figure 13), 64 s (Figure 14) and 69 s (Figure 15) from the start of the fire test. These show the propagation of the fire during the fire test 1.

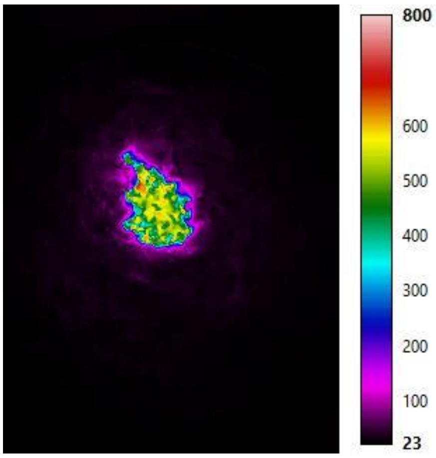

Fig. 11 Fire propagation during the fire test 1 – time of 13 s

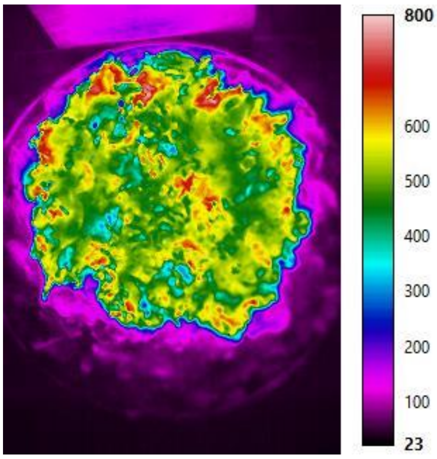

Fig. 12 Fire propagation during the fire test 1 – time of 48 s

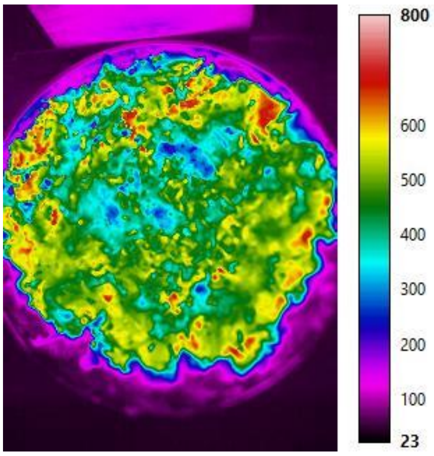

Fig. 13 Fire propagation during the fire test 1 – time of 59 s

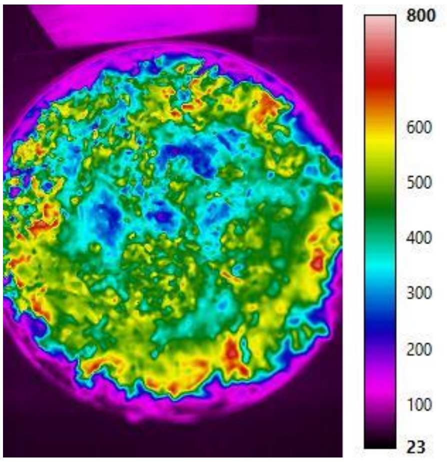

Fig. 14 Fire propagation during the fire test 1 – time of 64 s

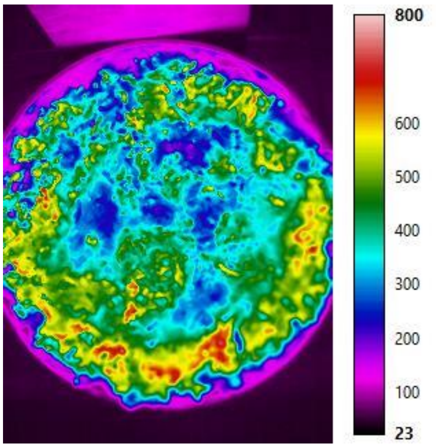

Fig. 15 Fire propagation during the fire test 1 – time of 69 s

The course of temperatures during fire test 1 calculated for the area of the entire test dish is presented in Figure 16.

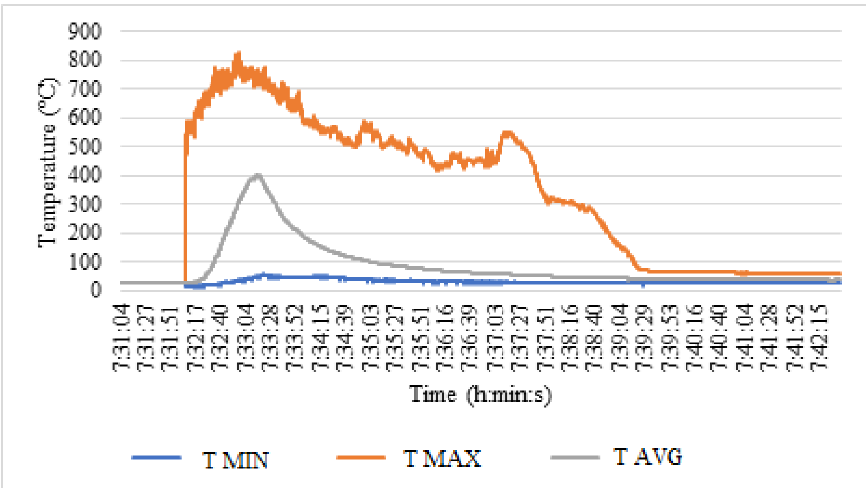

Fig. 16 Temperature course within the area of the test dish during fire test 1

During the fire test 1, the maximum temperature value of 770.6 °C was recorded at 21 s from the start of the fire test. At this time, the highest average temperature during the test was also recorded, namely 179.7 °C. At the time of the end of the test, there were no more spots on the surface of the test dish leading to re-ignition of the fire in case of a sudden supply of air.

The temperature during burning was automatically detected on profiles (4 profiles - eight cardinal points) created in the SmartView R&D software based on temperature information stored in infrared images acquired by the FLUKE thermal imaging camera.

3.1.3 Comparison of temperature course inside and on the surface of the fuel sample

The comparison of the temperature course on the surface and inside the fuel during the fire test was possible when providing the fire tests in the laboratory fume hood, together with using the FLUKE RSE600 thermal imaging camera.

We consider it necessary to draw attention to the fact that the performed study present ways of using progressive recording techniques and digital image analysis of images to derive important fire parameters that serve to understand fire dynamics. The objective of the study was not the analysis of the behaviour of forest litter during a fire itself. This would require the implementation of a sufficient number of fire tests, e.g., for the purpose of deriving dependencies between parameters. The results presented here also correspond to this fact.

Figures 17-22 show the results of the fire test 1 and data recorded by the thermocouples T1-T5.

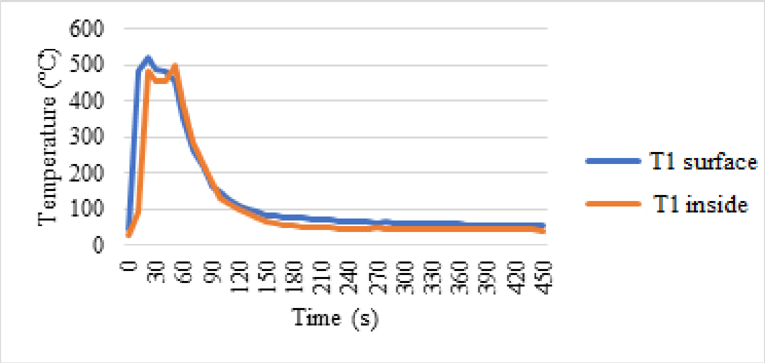

Fig. 17 Temperatures course comparison on the surface and inside the fuel - fire test 1 (hood), T2

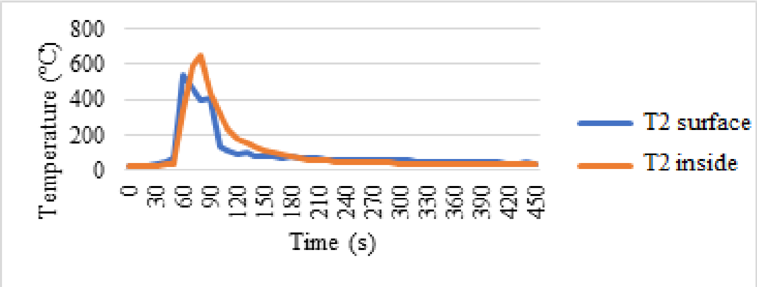

Fig. 18 Temperatures course comparison on the surface and inside the fuel - fire test 1 (hood), T2

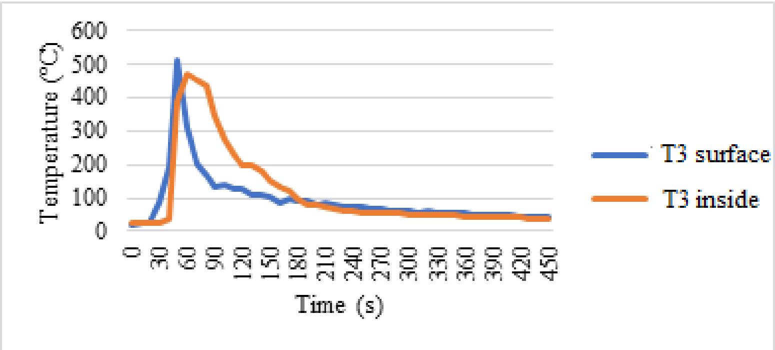

Fig. 19 Temperatures course comparison on the surface and inside the fuel – fire test 1 (hood), T3

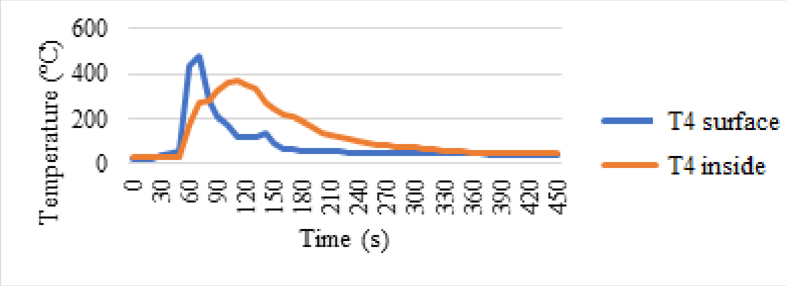

Fig. 20 Temperatures course comparison on the surface and inside the fuel – fire test 1 (hood), T4

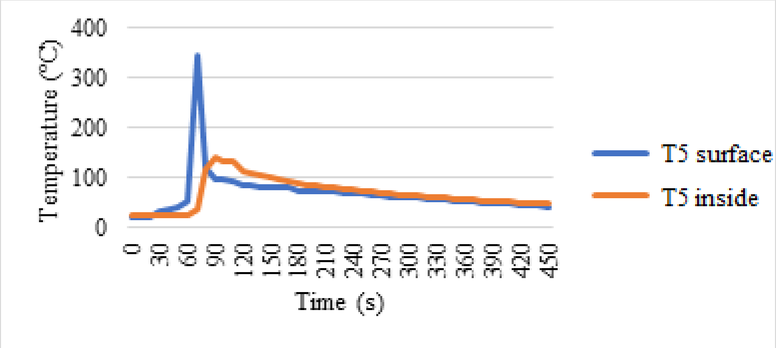

Fig. 21 Temperatures course comparison on the surface and inside the fuel – fire test 1 (hood), T5

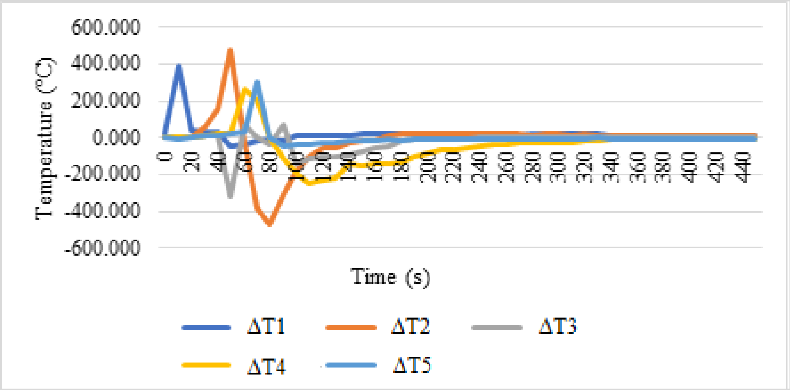

Fig. 22 Temperatures course comparison on the surface and inside the fuel – fire test 1 (hood), T1-T5

As seen from Fig. 22, the significant differences between the temperatures recorded by the thermocouples and the temperatures recorded by the thermal imaging camera were in the flame burning phase. The minimum (T MIN), maximum (T MAX) and average (T AVG) values of temperature differences at the position of individual thermocouples during fire tests are provided by Tab. 4.

Tab. 4 Values of temperature differences at the position of individual thermocouples during the fire test 1

Fire test /Thermocouple	1			2		
	Δ T MAX (°C)	Δ T MIN (°C)	Δ T AVG (°C)	Δ T MAX (°C)	Δ T MIN (°C)	Δ T AVG (°C)
T1 (C)	389.7	-45.0	24.7	452.7	-184.2	19.9
T2 (W)	473.8	-473.1	-11.3	157.0	-67.1	-2.4
T3 (N)	72.1	-319.7	-22.6	34.8	-316.4	-29.7
T4 (E)	258.4	-250.0	-42.2	437.9	-8.9	20.6
T5 (S)	305.3	-43.7	1.7	402.8	-8.4	27.1

3.2 Duration of flame burning and glowing/smouldering

The study of combustion during fire tests was divided into flame and flameless combustion phases. From the measured values and calculations, we determined 3 phases of combustion. While the flame burning phase itself took place in two sub-phases, i.e., phases of fire development and steady burning. Flameless combustion took place in the last phase called decay. While the highest mass loss, relative burning rate, highest temperatures and flame height were observed right during the flame burning. The rate of the flame burning allowed the fire to spread around the entire perimeter of the test dish. During flameless combustion, the values were stabilized and without significant changes until the end of the experiment. The transition from flameless combustion to flameless combustion was accompanied by smoke, which could be observed visually.

The duration of flame burning was detected from video images analysis. In Tab. 5 and 6, we present data on the duration of flame and flameless (smouldering/incandescence) burning (also as a percentage of the entire duration of the fire test, i.e., 600 s) for fire tests carried out in the laboratory chamber and for fire tests carried out in the laboratory fume hood. The burning was initiated by the flame of a match.

Tab. 5 Flame burning duration

Fire test	Flame burning duration (s)	Flame burning duration (%)
Chamber1	132	22
Chamber2	169	28
Chamber3	154	26
Hood1	176	29
Hood2	217	36
Average Chamber	152	25
Average Hood	166	28

Tab. 6 Glowing/smouldering duration

Fire test	Glowing/smouldering duration (s)	Glowing/smouldering duration (%)
Chamber1	328	55
Chamber2	271	45
Chamber3	296	49
Hood1	265	44
Hood2	min. 383	min. 64
Average Chamber	298	50

As seen from the results shown in Tab. 5 and Tab. 6, there are obvious differences in fire behaviour between the individual tests. The reason for this is mainly the fact that forest litter is not a homogeneous material in its structure, like e. g. wood. The behaviour of the fire in this case is mostly influenced by its distribution on the surface and the overall structure of the fuel. Even with the greatest effort to create test samples that will be similar. This will create a problem because such samples cannot be prepared with this type of material. However, this does not mean that it is not necessary to investigate them, on the contrary, we need to create an extensive set of data based on several fire tests and then try to derive dependencies between the parameters affecting the behaviour (dynamics) of the fire.

3.3 Flame height

In terms of flame height, several parameters were monitored. The maximum, mean and average flame height values were derived from the video data extracted for 5 s intervals of flame burning. Results are presented in Tab. 7 and Tab. 8.

Tab. 7 Average and maximum flame height

Fire test	Average flame height (m)	Maximum flame height (m)
Chamber1	0.24	0.52
Chamber2	0.20	0.72
Chamber3	0.16	0.50
Hood1	0.16	0.45
Hood2	0.08	0.21

Further, there are introduced results for mean flame height (Tab. 8).

Tab. 8 Mean height of the flame according to equation (3)

Fire test	Mean height of the flame (m)	Time (s)
Chamber1	0.16	65
Chamber2	0.02	85
Chamber3	0.04	80
Hood1	0.01	90
Hood2	0.03	110

Using the results of fire tests carried out in the fume hood, we created an algorithm that enables the automated calculation of the density of the radiated heat flux (equation 4) for the entire area of the test dish.

Here we only present the results for the maximum temperature values recorded in both fire tests.

In the case of fire test 1, the highest temperature, 770.6 °C, was recorded by the thermal imaging camera at time of 21 s from the start of the fire test. After substituting this temperature into equation (8), we obtained the value of the wavelength of the maximum radiation intensity at the level of 0.0038 mm = 3.8 μm (mid-wave infrared radiation – MWIR).

A higher maximum temperature value was reached during the fire test 2 (797.6 °C), within 65 s from the start of the test. In this case, the wavelength value of the maximum radiation intensity was calculated to be 0.0036 mm = 3.6 μm (MWIR).

Next, we present the result of the automated determination of the wavelength of the maximum radiation intensity in the form of a time profile of the density of the radiated heat flux calculated for the centre of the test dish (position T1).

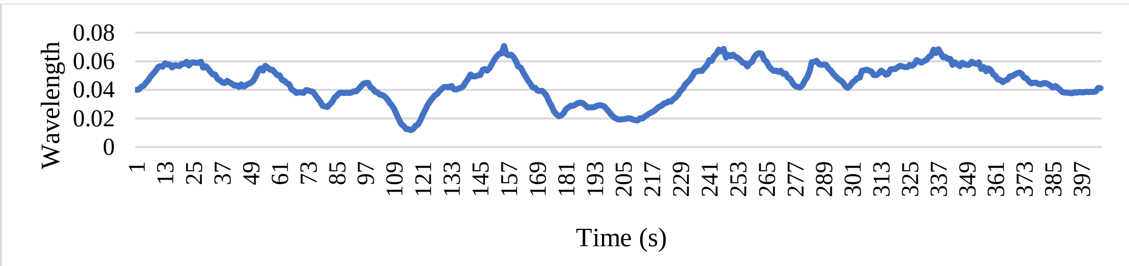

Fig. 23 Density of radiated heat flux in time in the centre of the dish (position T1)

These values are extracted from the generated image, where each pixel contains a wavelength value calculated according to formula (4). After converting the values from mm to μm and classifying (reclassifying) the wavelength values into the appropriate category, we obtain information about the type of infrared radiation and its spatial distribution on the surface of the sample (material).

3.4. Burning rate

From the point of view of calculating the burning rate, we focused on determining the relative mass burning rate and surface burning rate of fuel recorded on surface of the test dish.

3.4.1 Relative mass burning rate

We have expressed the mass burning rate based on the mass loss data, which was recorded during the tests with accurate scales from the RADWAG company. The fire test lasted a total of 600 s = 10 min.

In Figure 24 we present the results of mass loss for fire tests carried out in a laboratory chamber.

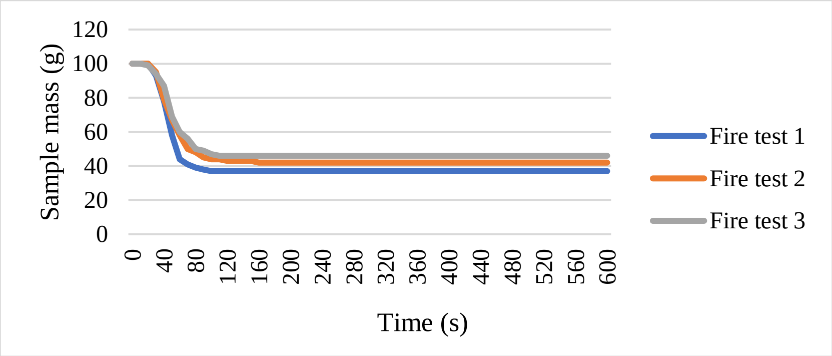

Fig. 24 Mass loss of samples during fire tests carried out in the chamber

Fig. 25 gives a view of the relative mass rate of burning of the samples during the implementation of fire tests in the laboratory chamber. We calculated this according to formula (2).

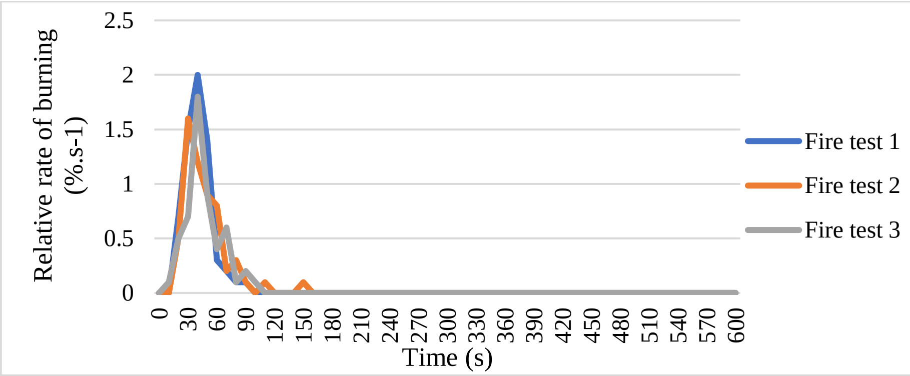

Fig. 25 Relative mass burning rate of samples during fire tests in the chamber

In Fig. 26, we introduce the results according to the mass loss of samples during fire tests provided in laboratory fume hood.

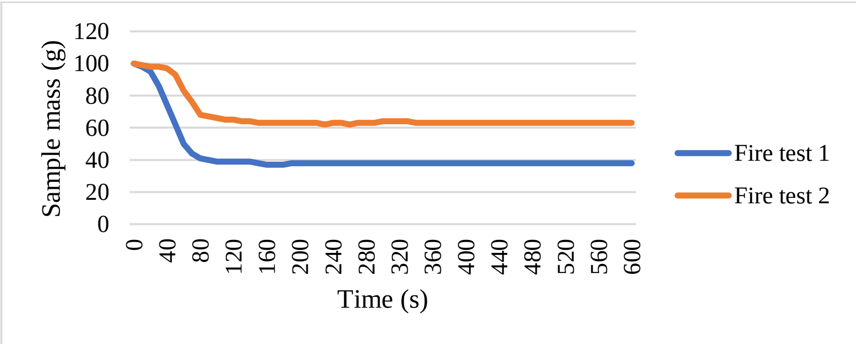

Fig. 26 Mass loss of samples during fire tests carried out in the fume hood

Fig. 27 provides an overview of the relative mass rate of burning of samples during fire tests in a laboratory fume hood.

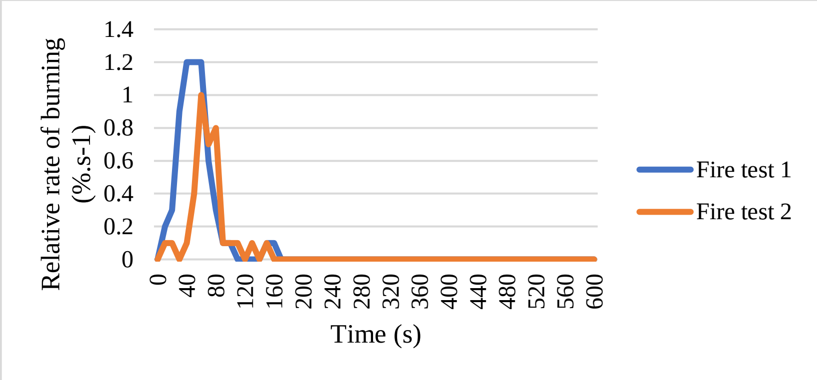

Fig. 27 Relative mass burning rate of samples during fire tests in the fume hood

3.4.2 Surface burning rate

The calculation of the surface burning rate was preceded by analyses aimed at determining the increase in the burning area (burning area with a temperature above 400 °C) within the test dish over time (time interval of 1 s). Here we present the results for fire test 1 (Fig. 28). At the same time, we also present the result regarding the extent of the fire area on which the temperature above 400°C was reached during the fire (Fig. 29).

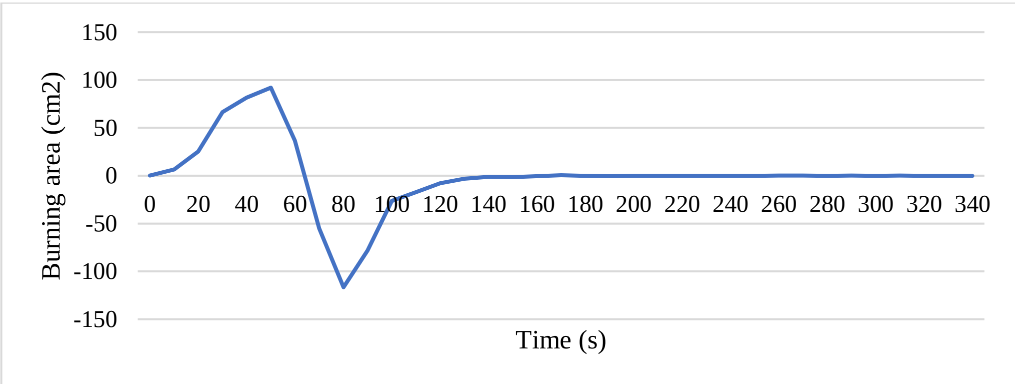

Fig. 28 Fire test 1 – Increase in burning area over time

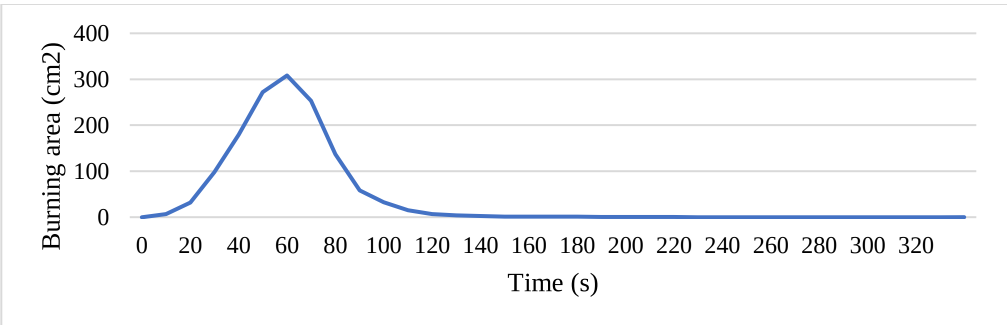

Fig. 29 Fire test 1 – Total burned area over time

From Fig. 27 and 28, it is obvious that the highest increase in the burning area is precisely in the phase of flame (steady) burning. While the maximum increase in the burning area was recorded in 50 s after the start of the fire test and represented a value of 92 cm^2. In the time 60 s after the start of the test, the largest burning area was reached, namely 308 cm^2.

The surface burning rate was calculated based on the algorithm developed in the Python programming language. In this subsection, we present the results of the image analysis for fire test 1, the images of which were also used for the development of an algorithm for the automated calculation of the area burning rate of the sample in 600 s.

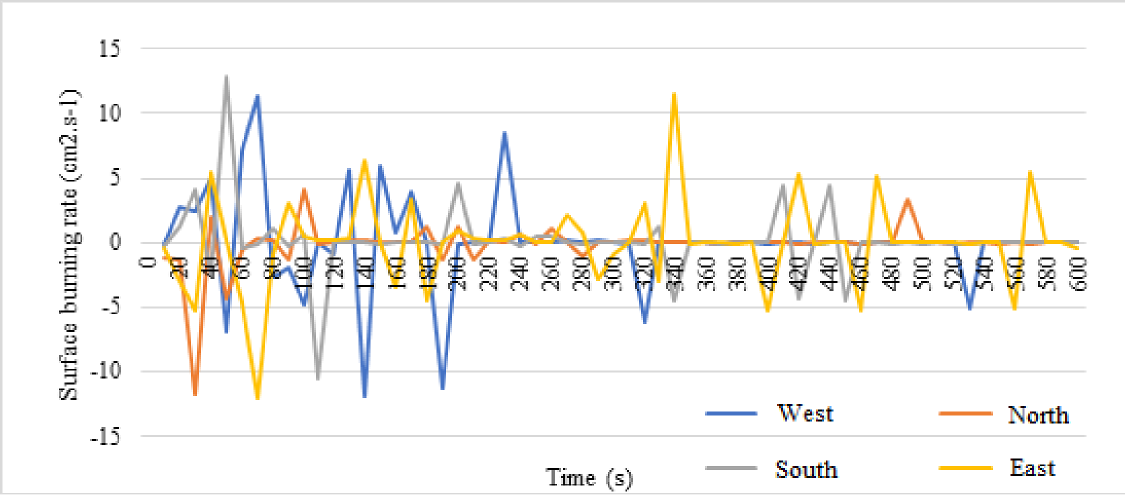

Fig. 30 Course of the surface burning rate in four directions in 10 s intervals

In Fig. 30, it is possible to detect phases in which the burning took place faster (flame burning phase) and phases where the burning rate values reached lower values (smouldering phase). In the direction to the south (to T5) from the centre of the bowl, the maximum value of the surface burning rate of 12.8 $cm^2 \cdot s^{-1}$ was reached in 50 s from the start of the fire test. In the direction to the west (to T2) from the centre of the bowl, the maximum value of the surface burning rate of 11.3 $cm^2 \cdot s^{-1}$ was reached in 70 s from the start of the fire test. In the direction to the east (to T4) from the centre of the bowl, the maximum value of the surface burning rate of 11.5 $cm^2 \cdot s^{-1}$ was reached in 340 s from the start of the fire test. In the direction to the north (to T3) from the centre of the bowl, the maximum value of the surface burning rate of 4.1 $cm^2 \cdot s^{-1}$ was reached in 100 s from the start of the fire test.

The values of the surface burning rate reached not only positive but also negative values. The reason is mainly fuel heterogeneity. In the case of a homogeneous fuel, the propagation would be constant, but the heterogeneity of the fuel caused differences in the time required for preheating the fuel and its subsequent ignition. At the same time, after burning off the fuel in the parts near the place of initiation, it subsequently cooled down, which caused the reduction of the total area with a temperature above 400°C.

In Fig. 31, we present the course of surface burning rate in 1 s intervals.

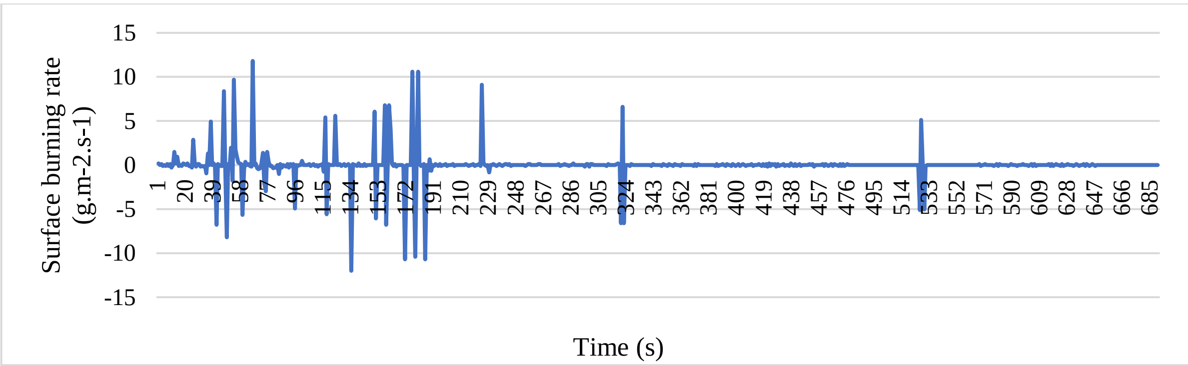

Fig. 31 Course of the surface burning rate in 1 s intervals

3.5 Automated delineation of flame outlines

For the completeness, we also present the image processing methodology/algorithm applicable in the Idrisi Terrset environment, as well as an example sample of the outputs from the image analyses aimed at identifying the flame outlines (2D visualization of the flame) from the sequence of frames obtained from the video recordings.

File/Import/Desktop Publishing Formats/JPGIDRIS (Output Reference Information/Plane)

File/Display/SEPARATE	Creates separated images (raster) from 24-bit colour or any other binary image in RGB channels. For further analyses select raster *Band 2.*
Digitize/Polygon	Serves for creation of polygon vector layer (test dish outline) based on raster file (image). Specify the name of the file and digitize the outline of the test dish by continual clicking on the left mouse button.
RASTERVECTOR	Converts the vector file with test dish outline to raster file. The spatial parameters of creating raster file should be copied from raster *Band 2* (select it from the list).
Idrisi GIS Analysis/Image Calculator	(*Raster file with outline of the test dish*raster Band2)* Creation of a raster reducing the image extent to area with test dish and flame.
Idrisi GIS Analysis/Database Query/Reclass	Reclassification of raster values into two classes based on thresholding the flame spectral values. (In study, the reclassification of raster values with threshold of 190 was applied for flame detection).
Composer/Add Layer/Vector	Visualization of the 2D surface of the flame within the test dish. Using this procedure, we overlay the raster image of the 2D flame with a vector one representing the outline of the dish (Fig. 32).

Fig. 32 Flame area during the fire test 1 in time of 20 s

Outputs (raster files) of image analysis from the Idrisi TerrSet environment can be further processed (calculation of flame height) in this environment these outputs can be used after exporting them to ASCII text format as input data to other program environments such as MATLAB to process further calculations.

4 Conclusions

The main objective of the study was to identify and verify the suitability of the applications of digital image analysis tools in fire engineering. For the processing of the study, the Fluke RSE600 thermal imaging camera was selected and procured after conducting market research regarding the available devices and their technical parameters. The Fluke RSE600 thermal imaging camera, including the supplied software, demonstrated not only the quality and accuracy of measurements, but also its durability and ability to work in extreme conditions. The possibility of connecting via WIFI multiplies its usability in direct deployment.

We used several computer programs, libraries, and online tools to process and evaluate the measured data. We used several in duplicate to compare their usability for image analysis.

The results of the study are original. For the analyses, several progressive technologies were used, such as thermal imaging, digital technologies intended for the creation of video recordings, but also for pre-processing and image analysis of digital recordings, including infrared images.

As the benefit for the field of science, the study verified the possibilities and appropriateness of the application in the work of applied digital technologies for the study of fire behaviour and the automated derivation of its selected parameters (e.g., the development of temperatures during a fire over time on the surface of the sample, calculation of the area rate of burning over time, detection shape and height of the flame, etc.).

The study provides guidance for conducting similar experiments with the use of digital technologies aimed at studying fire behaviour, even in the case of other types of materials, as well as studying the dynamics of fires in closed spaces.

The implementation of thermal imaging camera and a video (optical) camera into the fire tests is a progressive method allowing further and deeper study of fire dynamics parameters which cannot be captured by human eye or measured another way. The digital outputs themselves are a key input to image analyses and the creation of algorithms enabling the automated derivation of selected fire parameters from them. And finally, use of thermal imaging helps researchers to understand the relationship of fuels and fire effects.

From the point of view of the fire test results achieved and presented here, it is necessary to state that due to the variability of conditions that significantly affect the behaviour of forest litter during a fire, it is necessary to carry out enough repetitions under the same conditions (environment, fuel moisture content, etc.), until the variability of the results will not be reduced to an acceptable level. However, this presupposes the initiation of extensive and long-term laboratory research.

Acknowledgments

This research was funded by the Slovak Research and Development Agency, grant number APVV-17-0005 (40 %) and grant number APVV-19-0612 (40 %); and by the European Commission, H2020-LC-GD-2020-3, project ID: 101037247 (20 %).

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ΔDelta
16(1): 38-48, 2022
DOI: 10.17423/delta.2022.16.1.106

Comparing the Weathering Process of Gasoline in Selected Residues by HS-GC-MS Method

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Original scientific paper

Received: 18.07.2022; Accepted: 26.07.2022; Published: 31.07.2022

Abstract

The main goal of the paper is to determine the changes in the selected gasoline residues distribution in samples of cotton carpets due to weathering. EVO 95 gasoline was used as a fire accelerator and a cotton carpet was used as a matrix. After various durations of weathering time (0-360 min), which was achieved by evaporation in laboratory conditions. Residual gasoline compounds were determined in the carpet fibers using gas phase extraction (HS) in combination with gas chromatography (GC) and mass spectrometry (MS). The biggest changes were in the reduction of the intensity of the most volatile compounds (alkylalkanes). Toluene decreased from a total proportion from 17.66% (0 min) to 5.74% (360 min). Minor changes occurred in the group of alkyl derivatives of benzene (1,3,5-trimethylbenzene), which is also considered as one from the fifteen marker compounds of the gasoline. Conversely, heavier compounds (naphthalene) showed an increase in a total proportion from 0.068% to 0.49%. These results provide experimental evidence and a strong theoretical basis that gasoline loses its intensity significantly during first 6 hours and it is difficult to identify. Analysis of the samples from the fire scene that were exposed to elevated temperatures leads to significantly different residue distributions compared to weathering under room temperatures. Our results indicate the need for rapid sampling and subsequent timely analysis of fire debris.

Keywords: cotton carpet; fire accelerator; fire debris; fire investigation; gasoline; HS-GC-MS; weathering

1 Introduction

Deliberately started fires are a widespread crime aimed at destroying objects, property, including the destruction of physical evidence. Cheap and widely available hydrocarbon-based liquids are often used as accelerators because they increase the speed and spread of a fire [1, 2]. The most common ignitable liquid (IL) found in arson is gasoline as it can be obtained easily and cheaply in most of the world. Even the use of a small amount of IL can cause significant monetary losses and endanger human lives [3, 4].

The identification of ILs is an important step in the analysis of the fire scene. Determining the presence of an IL provides valuable information about the cause of the fire, as investigating the presence of an IL can lead to the detection of a crime. While identifying the IL is useful for law enforcement agencies, it is not always easy. Conditions affecting the positive identification of the IL include the amount of sample that was allowed to evaporate and the substrate or matrix on which the sample was taken [5, 6].

Gasoline is a complex mixture that consist of a wide range of various volatile hydrocarbons, a complex mixture of branched, cyclic alkanes and aromatic compounds. Gasoline is a middle distillate of hydrocarbon-containing petroleum, mainly in the range of C4 to C12. It also contains various components that improve its properties (benzene and isooctane) as fuels. It is most often produced by fractional distillation of crude oil and treated by cracking and other processes [7, 8]. Characterizing the composition of gasoline and the proportion of the individual compounds is extremely difficult, as it depends on many factors, mainly the parameters of the crude oil from which the gasoline is produced [9, 10].

In cases where an IL has been used, a small amount of unburned fire accelerator may remain in the wreckage of the fire to detect and subsequently identify its presence. Among the several analytical systems available, GC-MS is one of the most widely used in forensic laboratories worldwide [11, 12]. It is used for separation as well as for qualitative and quantitative analysis of different types of complex organic samples [13]. It offers high resolution, sensitivity, selectivity, and specificity for the investigation of ILRs from fire debris [14, 15].

The chromatographic data are manually interpreted after the analysis by analysts or forensic chemists to determine if traces of ILs are present in the fire debris samples. This final evaluation step of the analysis is a potential problem as data interpretation is a particularly challenging task due to the extreme chemical diversity and complexity of analytes and matrices [16, 17].

Another challenge in fire investigation is a weathering process, which distorts the chromatographic profile due to evaporation or partial combustion, leading to the loss of more volatile compounds. When the sample evaporate, the peaks shift towards the later eluted fractions. This phenomenon is often described as a pattern of weathering [3]. Comparing the weathered sample with the library of unweathered sample mass spectra can help in interpreting the results of the analysis [18].

Changes in the concentration ratios of hydrocarbons such as benzene, toluene, ethylbenzene and xylenes (BTEX) are mainly caused by evaporation and dissolution processes. As stated in ASTM E1618, the presence of marker compounds is required to claim that the sample contains traces of gasoline in the samples. According to the American Society for Testing and Materials, these compounds must be present in order to reliably demonstrate the presence of gasoline [19, 20].

On the other hand, the ASTM E1618 standard does not specify the need for quantification, nor does it specify the thresholds of individual markers. Therefore, the presence of at least some of the above compounds is quite sufficient to demonstrate the presence of gasoline in the samples. To a large extent, this decision-making process is based on the experience of the analyst [21, 22].

When ILs are exposed to ambient conditions, the liquids can evaporate in a process called weathering. Of all the components in the liquid mixture, the most volatile components with the highest saturated vapor pressure evaporate the fastest. Weathering changes the relative amounts of components in the mixture, which makes it difficult for the analyst to compare weathered residues with unweathered samples of ILs. The weathering process takes place at any temperature ranging from room temperature to temperatures exceeding 1000 °C during a fire. The identification of gasoline and other mixed hydrocarbons in fire debris is the most complicated problem, as long-term exposure to high temperatures radically changes the chemical composition of gasoline [15, 23-25].

Controlled weathering almost always involves longer evaporation times at lower temperatures than under actual fire conditions and in no way captures the effects or sources of variation expected under real conditions such as pyrolysis. When a sample of gasoline is exposed to severe weathering, four compounds are most often missing when comparing the chromatograms, namely ethylbenzene, *m*-xylene, *p*-xylene, and *o*-xylene [21, 26, 27].

The aim is to determine the changes of selected gasoline compounds in cotton carpet samples due to different lengths of deliberate weathering under laboratory conditions. The assumption is that the more volatile gasoline compounds lose most of the signal intensity after a few hours, and after this time its chemical composition changes significantly.

2 Material and Methods

Fire accelerator

Gasoline (EVO 95, E10 Slovnaft, Bratislava) was used as a fire accelerator. Gasoline was obtained from a local petrol station and then at the volume of 5 mL was applied to the surface of the carpet. The same batch of gasoline was used to conduct the same condition and chemical composition.

Matrix

A woven carpet ARYA 05 measuring 80 × 150 cm, 100% cotton with a pile height of 0.5 cm, a fiber density of 1,400 g / m^2 was used as a matrix for capturing gasoline. The carpet was purchased from a local carpet store and then was cut to uniform samples of 5 × 5 cm.

Weathering

The samples were allowed to weather under laboratory conditions at 20 °C. Carpet fibers were removed at intervals of 0, 15, 30, 45, 60, 90, 120, 190, 240, 300 and 360 min. The designation was supplemented by a numerical data, where the number represents the weathering time. From each carpet, 3 fibers were taken one piece from two edges and one from the central part.

Analytical system

The analytical determination was based on the ASTM E1388 and ASTM E1618 methods. Boundary conditions were set and optimized based on calibration measurements and previous research [28-30]. Residual volatile compounds were obtained by gas phase extraction (static HS). The gas phase was subsequently analyzed by gas chromatography with mass detection (HS-GC-MS). A Headspace Autosampler 7697A (Agilent) with an HP7890A gas chromatograph (Agilent) and a VL MSD 5975C mass spectrometer (Agilent) was used.

The gas phase extraction took place at 60 °C for 15 min and the gas phase was metered into the chromatographic column. The volatiles were separated on an HP 5MS column (30 m, 0.25 mm, 0.25 µm, Agilent) with a temperature program of 40 °C for 4 min, a heating rate of 6 °C / min to 250 °C, with a carrier gas flow (He) 0.8 mL / min, in split mode 500 : 1. Mass detection was performed at 70 eV electron ionization and conditions: source temperature 200 °C, detector temperature 150 °C.

Sample evaluation

All peaks were identified by mass spectral data. The identity of each compound was then confirmed by searching their mass spectra in the NIST library. A total number of 65 samples were analysed and evaluated with 5 replicates of each time interval, supplemented with reference samples of clean gasoline and pure carpet.

Due to the complex properties of gasoline, only well-separated and symmetric peaks were selected for data analysis. For this reason, only those compounds that were determined for each sample were retained.

The reason for choosing three compounds is that we can imaginarily divide the chromatographic profile of gasoline into three areas. The first area ranging from 0 to 7 min consists of the most volatile compounds (toluene). The second is the transition area from 7 to 14 min, which consists of compounds (1,3,5-trimethylbenzene) that are not subject to such extensive weathering. The third area in the chromatographs consists of the most stable compounds (naphthalene) ranging from 14 min upwards. The comparison of these selected compounds was chosen precisely because of their representativeness for the given areas of the chromatograms.

Statistical evaluation

The peak areas of significant compounds that were the same for all samples were counted and then the percentage of the selected three compounds was calculated and subsequently averaged. This procedure was repeated for all differently weathered samples taken at the same time intervals. For the sample averages of each time interval, we calculated the standard deviation, and a trend line was plotted in the graphs. The statistical evaluation was performed using STATISTICA 12 software.

3 Results and Discussion

By comparing the obtained chromatograms of selected compounds of pure gasoline absorbed in the carpet fiber, different trends were demonstrated. Looking at the intensities of compounds obtained from unweathered samples and samples weathered for 360 minutes, a significant difference is apparent. The intensities of the individual compounds, especially the more volatile ones, i.e., up to a retention time of about 4 minutes, are greatly reduced. A representative of the category of the most volatile compounds is toluene, which is shown in Fig. 1. Comparing the amounts of the compounds determined, toluene showed a decrease from 17,67% (0 min) to 5,74% (360 min). When converted to an absolute decrease in terms of peak size, the decrease represents approx. 91,64%.

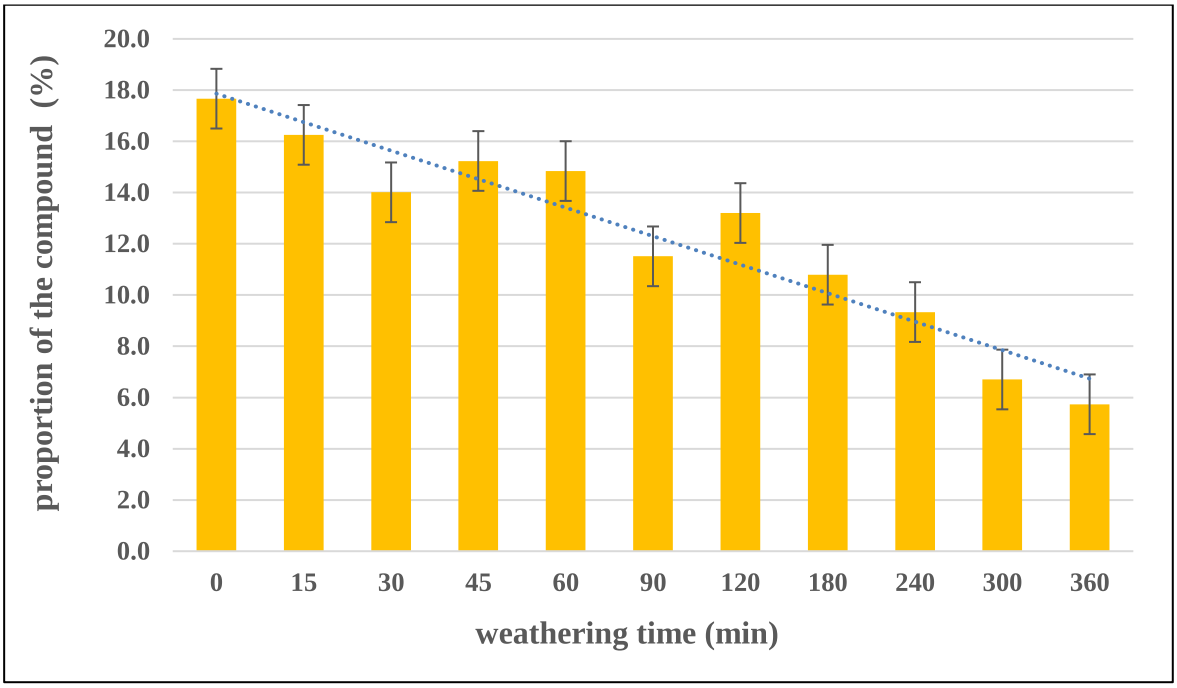

Fig. 1 Changes in the intensities of the toluene analytical signals at different weathered samples

The change occurs after about 5 minutes of retention time, where the differences in this area are no such significant. In this area, the individual intensities stabilize for different sample variants. Fig. 2 shows the compound 1,3,5-trimethylbenzene (TMB), which is also considered as one from the indicators of the gasoline. 1,3,5-TMB increased in 360 min by 1,61% over the reference sample, which is not a significant difference if we consider the proportion percentage from the total proportion of all compounds. When converted to an absolute decrease in terms of peak size, an increase appears here approx. 14,24%.

A similar finding was made by Chalmers et al. [31] who investigated the negative effects of weathering to which the samples were intentionally exposed. They found out that 1,3,5-TMB and ethylmethylbenzene were the least sensitive substances.

On the other hand, Willis et al. [15] also showed by the results that there was an increase in the marker compound 1,2,4-TMB. This is an interesting finding, as it was originally assumed that as they are marker compounds (trimethylbenzenes) they should be present in very similar amounts with minimal differences.

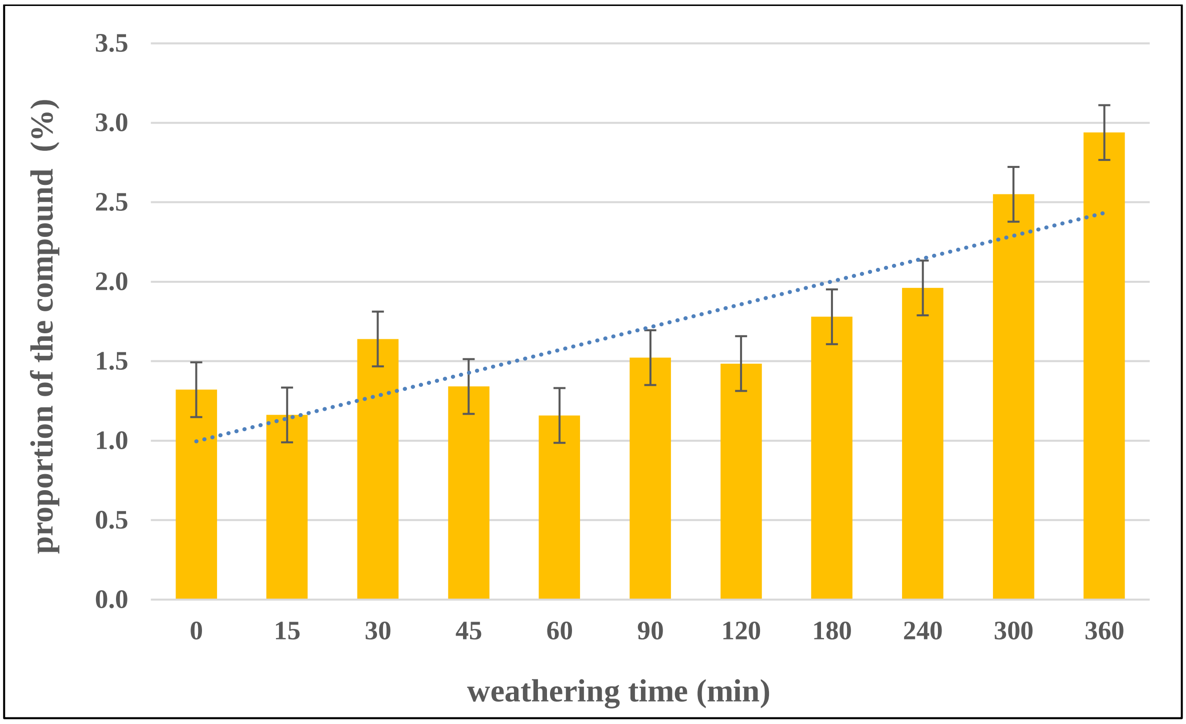

Fig. 2 Changes in the intensities of the 1,3,5 – trimethylbenzene analytical signals at different weathered samples

Fig. 3 shows the area of the chromatogram with a retention time of 15 min where the most stable compounds occur. A representant of this category of compounds with the highest vapor pressure is e.g., naphthalene. As can be seen, the intensity of naphthalene increases over time. If we compare the reference sample (0 min), or the sample weathered for 15 min with samples weathered for 300 min, or for 360 min, the naphthalene intensity increased approximately from 0.068% to 0.49%. If we convert this increase into an absolute increase in terms of peak size, the increase is approx. 52.6%.

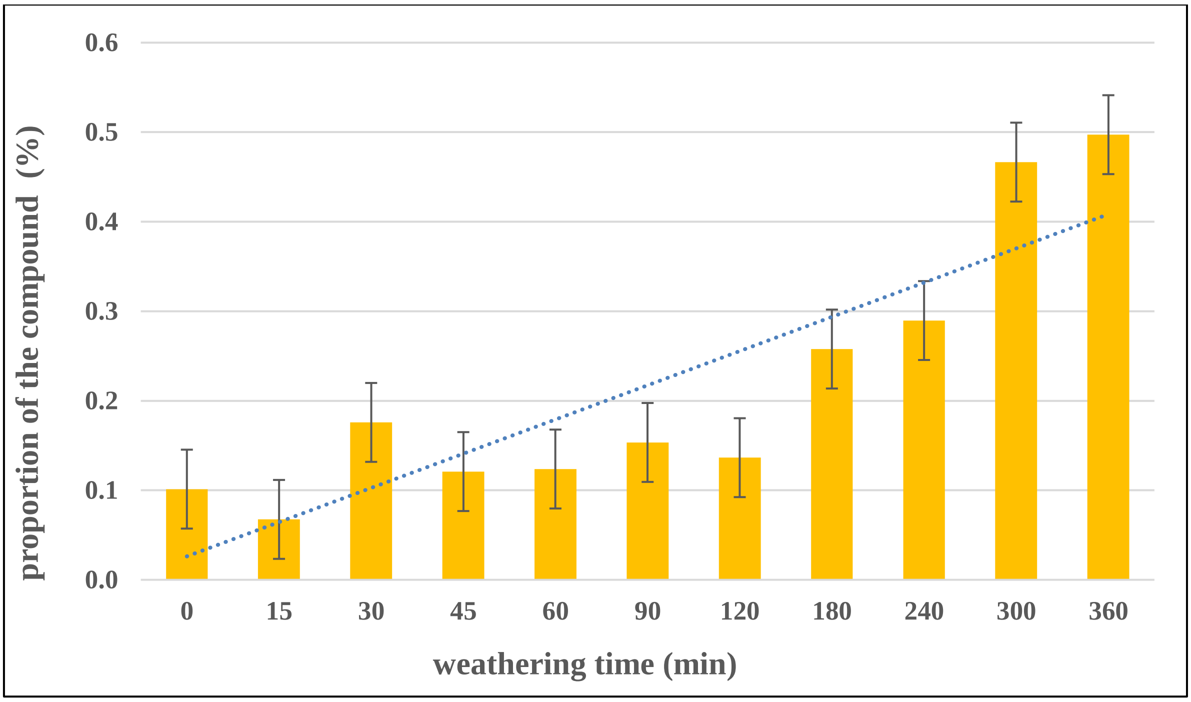

Fig. 3 Changes in the intensities of the naphthalene analytical signals at different weathered samples

As predicted by Ferreiro-Gonzalez et al. [32] the relative increase is due to the loss of volatiles, which evaporate faster. The most volatile hydrocarbons present in the sample do not overflow the headspace and release even the most volatile compound in larger quantities is easier and more efficient.

The same findings were made also by Willis et al. [15], who reported that the least volatile compounds, which eluted last in GC, showed a sharp increase in intensity in the later stages of weathering.

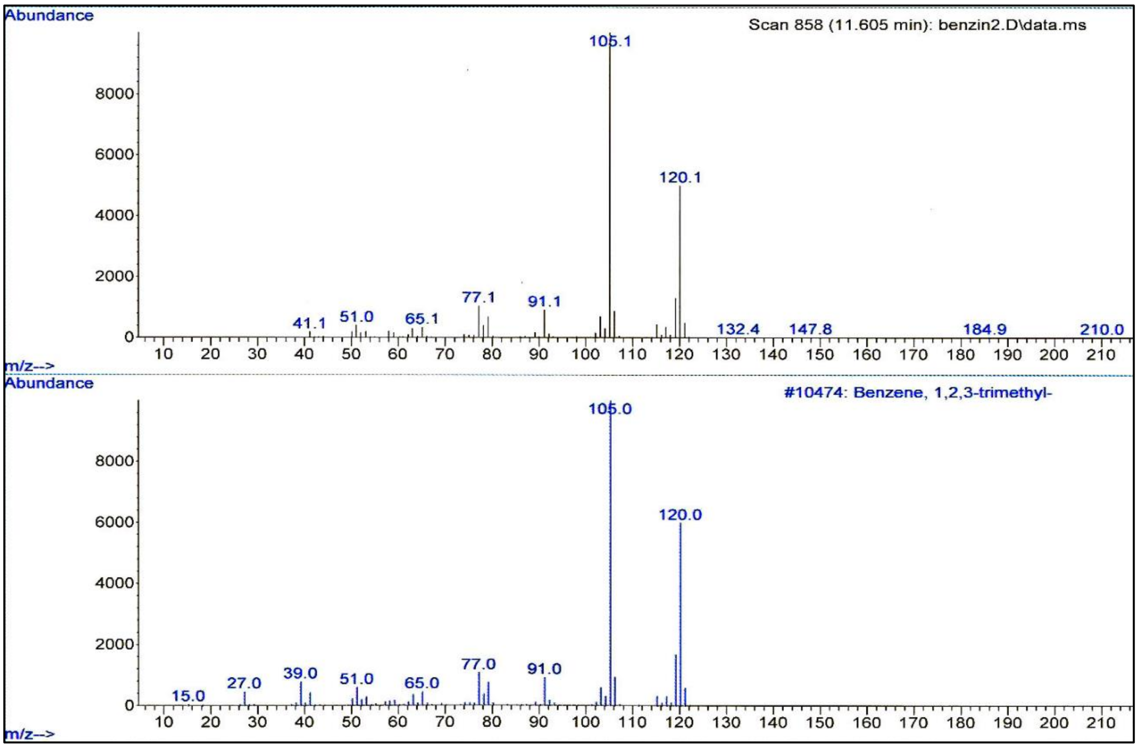

Fig. 4 Comparison of the mass spectrum of 1,2,3 – trimethylbenzene (up determined mass spectrum, down mass spectrum from the NIST library)

The identified peaks of the individual compounds were subsequently compared with the NIST spectrum library. Figure 4 shows the mass spectrum of 1,2,3-TMB.

Fig.5 shows a selected part of the chromatograms obtained by analysis of differently weathered samples. The most volatile gasoline compounds are shown, for example a group of aliphatic hydrocarbons and a C1 derivative of benzene (toluene). Different color curves represent different weathered sample variants. The black curves characterize the compounds determined by analysis of reference samples taken and sealed immediately after the addition of gasoline. The largest weathering time interval is represented by the purple color, which belongs to the samples weathered for 360 min.

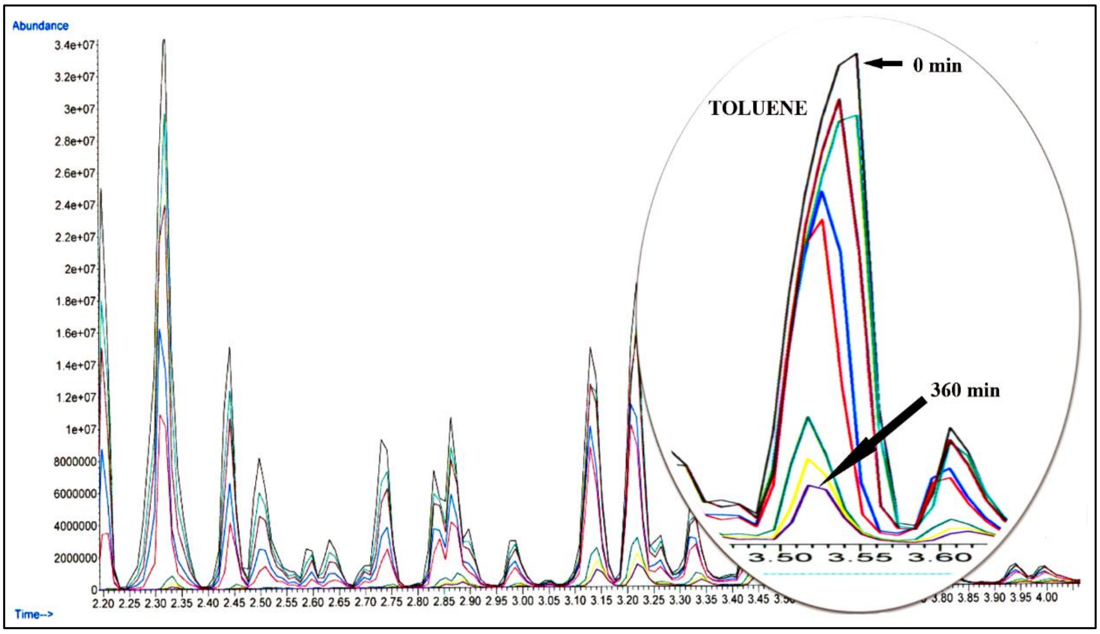

Fig. 5. Part of the chromatogram of lighter hydrocarbons with the retention time from 2 to 4 minute

It is possible to observe a trend on the chromatograms that over time (longer weathering) there is a decrease in intensities around volatile compounds, i.e., retention time approx. 2 - 5 min. Looking at the course of the individual chromatograms, it is possible to observe a significant difference between the intervals of 180 minutes (red color) and 240 minutes (green color). From the above, it can be assumed that gasoline loses most of its signal intensity during the weathering process after a time ranging from 3 to 4 hours.

Aliaño-González et al. [33] state that a significant change is expected after a time of 0 to 6 hours with a significant decrease in signal intensities, which means that the weathering process is most pronounced after the first few hours.

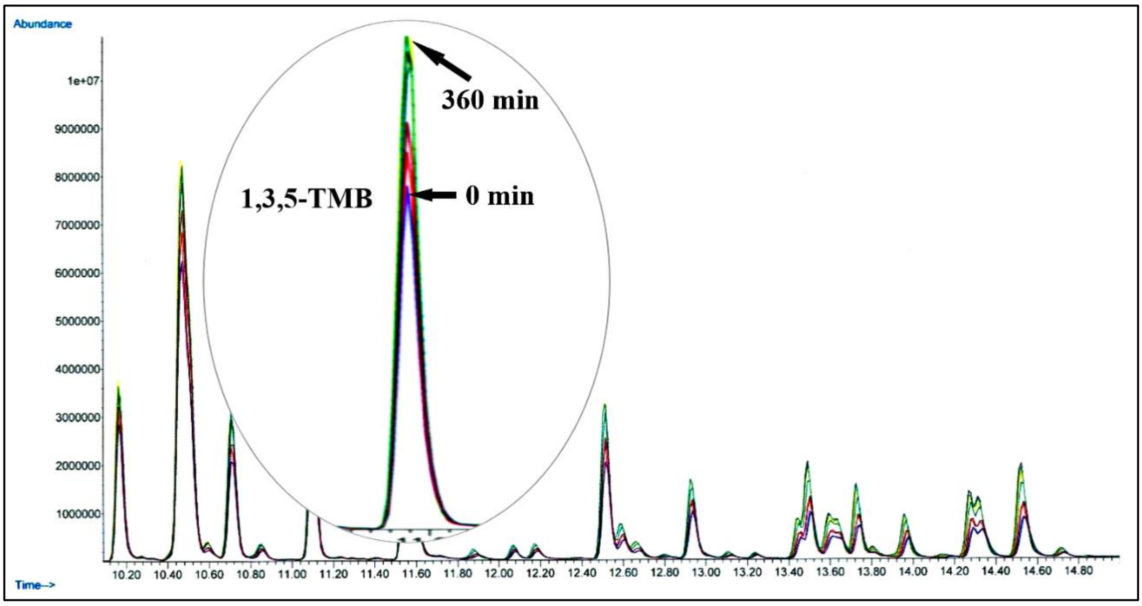

Fig. 6. Part of the chromatogram of more stable hydrocarbons with the retention time from 10 to 15 minute

For the transition area (Fig. 6), which also includes the above-mentioned gasoline indicator (1,3,5-trimethylbenzene), this change in intensity is minimal.

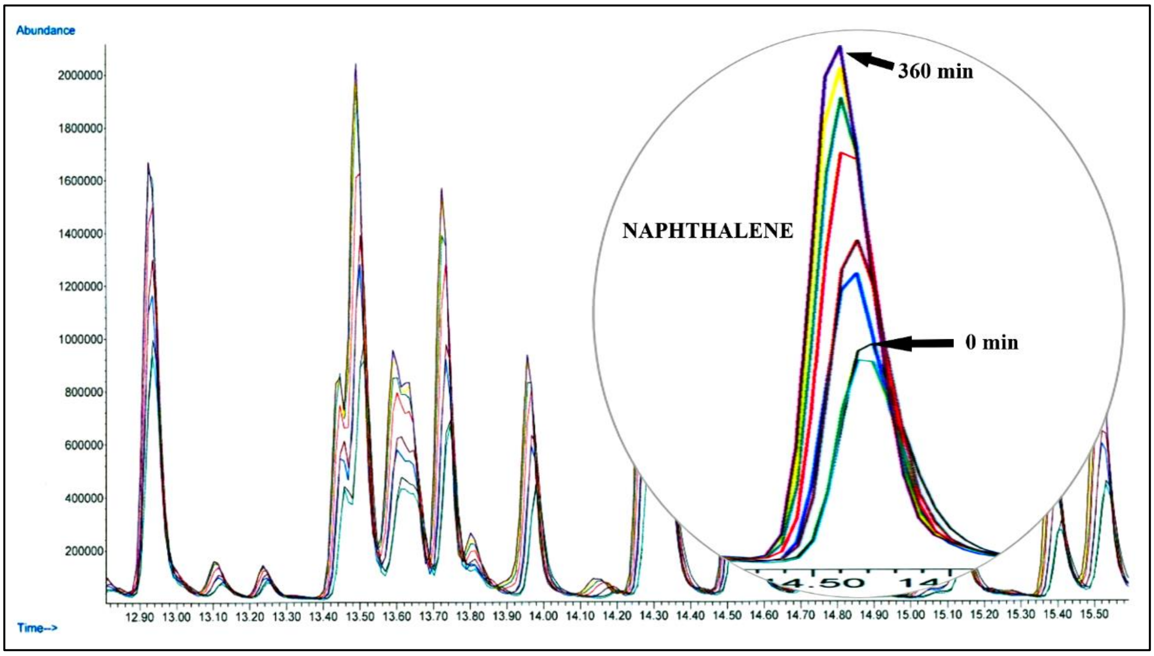

Fig. 7. Part of the chromatogram of heaviest hydrocarbons with the retention time from 13 to 16 minute

The opposite trend is manifested in the area after the RT of about 14 minutes (Fig. 7), where the intensity increases over time. Higher proportions of compounds were determined in longer weathered samples.

Composition analysis for various gasoline compounds by the PCA method performed by Turner and Goodpaster [5] showed that compounds with boiling points up to 155 °C are most susceptible to weathering. In contrast, long chain alkanes and lower substituted aromatics are susceptible to microbial degradation regardless of boiling point. As further stated, 1,3,5-TMB and 2-ethyltoluene are not only resistant to weathering but are also the least susceptible to microbial degradation.

Swierczynski et al. [22] investigated the possibility of determining gasoline on various matrices by HS-SPME-GC-MS. By TIC comparison, they found that the highly volatile components in gasoline (short chain alkanes, cycloalkanes, light aromatics) rapidly evaporated from cotton samples within 1 hour. Heavier aromatics such as 1,2,4-TMB, 1,2,3-TMB, 1,2,4,5-tetramethylbenzene, long chain alkanes (n-undecane, n-dodecane) and naphthalenes were found in the cotton samples even after 1 day.

Dhabbah et al. [34] investigated the effect of synthetic carpet thickness on the possibility of determining weathered ILRs. They analysed burned carpet samples by SPME-GC-MS. Samples were analysed at various times after quenching (suffocation) 0.5 to 5 hours. It was concluded that no detectable residues of gasoline remained in the samples of the burned 5 mm carpet after 5 hours. Under the same experimental conditions, no gasoline residues were detected after 2 and 3 hours in the case of carpet samples with a thickness of 15 and 25 mm. This may be due to the adsorption behaviour of the gasoline on the carpets, which more easily adsorbed on the thin surface of the carpet and the gasoline was exposed to more radiant heat.

Samples of residues obtained after the fire provide the investigators with a wide range of evidence. If the fire scene is largely destroyed, it is possible that investigators will gather and interpret little, if any, evidence. In real fires, it is very important to take samples from the fire as soon as possible because a fire could cause different results on the gasoline profile due to uncontrollable factors such as uneven distribution of gasoline in the carpet sample, burning rate, fire intensity, air flow and fire spread, which could directly or indirectly affect the amount of accelerator residue obtained from fire debris. Among other authors, Lim et al. [2] reached this finding as well.

4 Conclusions

The paper deals with the study of weathering of selected gasoline compounds. The cotton carpet was used as a matrix to trap gasoline residues. The headspace gas phase extraction method with gas chromatography and mass spectrometry (HS-GC-MS) was used as a progressive laboratory method to monitor the weathering of selected compounds. The determined compounds form groups of aliphatic hydrocarbons are alkanes, aromatic compounds - benzene derivatives and polycyclic aromatic hydrocarbons.

Fire debris samples obtained after the fire provide for the fire investigators a wide range of interpretable evidence. As stated by ASTM standards, when interpreting the results of the analysis of fire residues by the analyst to correctly determine the presence of an IL on the fire, it is quite sufficient to identify marker compounds that belong to IL. In the case of gasoline, the presence of indicator is among others for example the above mentioned 1,2,3-trimethylbenzene and 1,3,5-trimethylbenzene.

The results show that prolonged exposure of gasoline to the ambient conditions potentially leads to difficulties interpreting the results. The analysis showed that the most susceptible compounds for weathering are the most volatile hydrocarbons. The largest difference in the intensity changes of the selected compounds can be observed after four or five hours. On the other hand, the heaviest hydrocarbons increased significantly in intensity and the peaks of these compounds increased. However, despite the five parallel samples taken from each weathering time interval, the results may not be completely accurate as these experiments are characterized by great variability and heterogeneity.

In conclusion, it should be noted that the analysis results proved that time has a significant effect on the determinability of gasoline in fire debris samples. On the other hand, it is important to perform comparative analyzes of samples that have been weathered for various durations of time with pure samples, as the correct interpretation of laboratory analysis results plays a key role in fire investigation.

Acknowledgments

The submitted work was supported by the Agency for Research and Development based on contract no. APVV-17-0005 (50%) and Scientific Grant Agency VEGA, project 1/0454/20 (50%).

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FIRE PROTECTION & SAFETY Scientific Journal
16(1): 49–62, 2022
DOI: 10.17423/delta.2022.16.1.107

Comparison of Personal Capacities Management Processes in Fire and Rescue Service and in Private Sector

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Communication

Received: 19.06.2022; Accepted: 14.07.2022; Published: 31.07.2022

Abstract

Management means carrying out modern administration in the broadest sense. The basis of this work was to point out the specifics, factors and influences that separate the management of human resources in the business environment and the Fire and Rescue Service. On the other hand, there are many factors that apply in both environments. The main objective of the study was to compare human resources management in the conditions of the Fire and Rescue Corps as one of the components of the state administration and the private sector with the aim of identifying differences in the implementation of individual human resources management activities considering the specific tasks of the Fire and Rescue Corps to improve human resources management in the Fire and Rescue Service. A comparison method was used for this purpose. The methods of selecting candidates in both environments were compared, while in the results we pointed out the disadvantage of the service office in determining the number of positions in the conditions of the Fire and Rescue Service. Another comparative criterion was the procedure for selecting a candidate for admission to the civil service / employment. The comparison of human resources management in the private sector and in the Fire and Rescue Corps as one of the components of the state administration, description of penetrations and differences pointed to the lack of long-term strategic human resources planning, problematic determination of the right level of centralization and decentralization in human resources management in the Fire and Rescue Corps. The comparison of admission procedures showed an effective pre-selection of candidates carried out in the private sector, which, if incorporated into the current legislation, would significantly simplify, and streamline the process of selecting new officers of the Fire and Rescue Service.

Keywords: Fire and Rescue Service; personal management; private sector

1 Introduction

The subject of interest in the theory and practice of management has been a person in the work process for several decades. Ways of proper management of human resources are sought. But it is worth emphasizing that there is no single right approach to management that would guarantee the excellence of organizations. This is influenced by various historical circumstances and environment, the focus of the organization, the correspondence between the management's ideas about workers and their real characteristics, and on this basis the position and role of a person in the work process. Other factors are changes in job demands and other, conditioning factors.

Practice on the entrance into third millennium proves that the human factor plays a much more significant role than in the past. The cultural attributes of modern work, but also the specific nature, lie in the ability to work in a team, collaborate, establish, maintain relationships and be able to manage such a team. The main requirements for employees in all types of organizations move from the principles of dependence such as reliability, loyalty, job security, belonging to the organization, to adaptability factors, which are individualism, tenacity, flexibility, and readiness for change.

The aim of this study is to compare already existing knowledge about human resources management in the private sector and in the Fire and Rescue Service (FRS). The subject is the definition of intersections, differences, and the resulting proposals for improvement in the field of drawing up personnel strategies and selecting applicants for the civil service.

2 Human resources management in general

Armstrong (2007) [1] states that "*human resources management is a strategic and logical approach to managing the most valuable thing an organization has — people who work in an organization and who individually and collectively contribute to achieving the organization's goals*."

The role of management is to acquire, manage and allocate resources so that they bring the greatest possible benefit in achieving the organization's goals. Personnel management is an integral part of management, and it is necessary for it to perform these tasks when dealing with its subject, which is workers. There is a reservoir of energy in the workers, the activation of which can increase labour productivity. The development of the theory and practice of management strengthened the position of the human factor in the organization and modified the requirements for human resources management. [2].

In this regard, it is possible to highlight two levels of perception of personnel, which sufficiently justify the need for their management:

- Workers are an elemental component of the organization’s system; they are input into the transformation process.
- Workers are a source or can be a source of new energy, ideas and decisions that increase the competitiveness of the organization.

The conditions for the perception of workers as a resource are their competence and willingness (motivation) of workers to be creative, active, and responsible. Also important is the ability of an organization to recruit, shape, develop and reward workers so that they are willing to participate in the competitiveness of the organization, that is, to manage human resources in such a way as to generate positive motivation. Human resources can be a positive factor for an enterprise, i.e., able, and willing to implement new approaches and behavioural changes, or a critical– negative factor.

The basic objectives of human resources management can be defined according to the following areas [1]:

- Economic area:
  - Optimal use of human labour in combination with other factors of production to achieve the necessary performance of the organisation and its adaptation to the requirements of the environment.
  - Improving the structure and improving the quality of functioning of the organisation's human resources.
  - Increasing creativity and the economic appreciation of this potential and the resources invested in its development.
  - Setting and maintaining the organization's personnel costs at the optimal level.
  - Implementing an activity-stimulating remuneration system and increasing the ability of each worker.
- In shaping the working climate and in the social sphere:
  - Fulfilment of the personal goals of workers associated with the performance of work for the organization.
  - Helping to identify with the organisation's objectives.

- Motivating the worker to self-development, upskilling, and a creative approach in solving the problems of the organisation.
- Creating the preconditions for job satisfaction, the content of the work, the working environment, and the internal climate of the organisation.

There is a seemingly competitive relationship between economic and social objectives, due to the impact of these objectives on the costs of the enterprise. Personnel costs are high (both relative and real) and thus negatively affect the overall costs of the company and thus, in fact, the competitiveness. If personnel costs are reduced, this will bring an effect, but only in the short term. In the long run, this will translate into a decrease in the quality of the functioning of workers and a deterioration in the performance of the entire organization. However, account must be taken of the result of economic activity, which, based on lower efficiency, necessarily leads to a reduction in these costs. The solution is to use such motivators that create the preconditions for the identification of employees, management, and owners.

3 Human resources management from a historical perspective

Human resources management is a product of the interpersonal relationship movement in the early twentieth century, when researchers began documenting ways to create business value through strategic workforce management. Initially, the function was dominated by transactional work such as payroll and benefit management, but due to globalization, company consolidation, technological progress, and other research, human resources are now focused on strategic initiatives such as mergers and acquisitions, talent management, succession planning, industrial and labour relations, and diversity and inclusion [3]

There is no single right approach to management that would guarantee the excellence of organisations. This is influenced by various historical circumstances and environment, the focus of the organization, the correspondence between the management's ideas about workers and their real characteristics, and on this basis the position and role of a person in the work process. Further, changes in demands on the performance of work and other, conditioning factors.

The development of personnel work during the twentieth century can be divided into three periods, into which the development of management theory is usually divided. These are the classical directions of management in the thirties, the development directions in modern management from the forties to the seventies, and at the same time the directions of management from the eighties. All periods are characterized by differences even in ideas about a person in the work process.

The issue of man in the labour process came to the attention at the beginning of the twentieth century. Taylor's conception of management is based on the idea of a rational-economic person . This is a person who performs work exclusively to provide for basic needs. He is unreliable, passive, obediently performs work tasks, refuses responsibility, and expects financial gain. The subject of interest of McGregor's theory was the labour productivity of workers. It was assumed that its increase would occur based on a simplification of work, after training the workforce to perform simple, constantly repetitive tasks under constant control. Discipline was required from the worker, and his remuneration was conditional on compliance with the norm. Motivation has been influenced through reward and sanction, which is simple, but does not include comprehensively the complexity of human behaviour. [4]

In the thirties, under the influence of the Hawthorne experiments and in response to an overly technocratic concept, a significant change occurs. An approach was formed, the subject of which was human relations. From the conclusions of the experiments, it emerged that, because of rationalization, work has lost its meaning for a person, and the latter, therefore, seeks satisfaction in interpersonal relationships. The impact of the group was considered stronger than that of the financial incentive and the so-called control management. These are characteristics of a social person who strives to reduce social needs and needs for recognition and respect. Social care is considered an effective tool for influencing work motivation.

Despite the reservations, the opinions of representatives of the theory of human relations were considered valuable, since they prove that the worker must be perceived as a human being, not a machine, thereby essentially elevating the corporate resource in question above others. The essential conclusion of this theory was that the performance of workers is not only affected by the material and technical provision of work, but also by interpersonal relationships and the social atmosphere.

In the late forties, a behavioural approach to personnel work began to be formed, which deals with the study of human behaviour in an organization. [5] Attention is paid to the individuals. Psychologists examine the inside of a person, his needs and the causes leading to action and behaviour. Motivation theories seek explanations. This approach deals with the issues of working groups and leadership issues. The influence of managers' behaviour on the performance of workers is investigated. The ideal leader is the one who respects and trusts the workers and at the same time shows a high degree of structure. He tries to achieve maximum performance by organizing work.

In the early sixties, Blake, and Mouton [6] constructed the so-called management grid and defined an ideal manager, oriented equally towards subordinates and working in a team style of leadership.

The humanistic model of management based on the change in ideas about a person presents the pattern of a self-actualizing worker who has his needs and who seeks the meaning of work. In this model, the worker is given the opportunity to realize his potential for the benefit of the organization in the performance of work that is supposed to be diverse, meaningful, coherent, significant, and adequately autonomous. Such work is supposed to bring inner satisfaction to the worker. This fact implies a transition from extrinsic motivation to intriguing, that is, internal. The model of humanistic management assumes a change in the role of the manager. The emphasis is on the role of leader, not controller.

In the eighties of the twentieth century, under the influence of changes in employee perceptions, an approach to management in terms of human resources was promoted. Workers are considered a key corporate source of work, management ideas in terms of human resources. Management in the sense of McGregor's theory X and Y [7] perceives them as people who have a positive relationship with the work and like to solve individual tasks independently, responsibly, and creatively. Based on the diagnosis, ways and possibilities are sought so that work motivation is influenced by accepted internal and external rewards. The approach can be considered progressive.

As a result of globalization, personnel work has seen a significant change towards its improvement and adaptation to new conditions in Slovakia and the world. Along with the growing presence of multinational corporations and the employment of people of different nationalities, changes in some human resources management processes are noticeable. [8]

Developmentally, there were different opinions. The different perception of workers was also formed by the establishment of personnel work. In the development of personnel work, we can define different stages in relation to the aspect of role and hierarchical position in the organization, namely personnel administration, personnel management, and human resources management.

State administration is a public administration carried out by the state and has an irreplaceable role in it. In this sense of the word, state administration is the core of public administration. It is derived from the very essence, position, and mission of the state, from the nature and method of realization of state power.

To create an effective public service and successfully promote public administration reform, it is necessary to systematically improve the human resources system, which would guarantee the success of the achievement of goals and priorities in state governance [9].

A prerequisite for the quality performance of state administration tasks is the creation of an optimal organizational structure of the state administration system, both central and local government bodies. Weaknesses in human resources management in state administration are:

- High degree of uncertainty for civil servants due to frequent legislative changes and changes implemented in rapid succession without the necessary interdependence with the Civil Service Act and other laws.

- Imbalance in the conditions for the performance of the general civil service compared to civil servants in the force to the detriment of civil servants – an imbalance even when comparing the conditions of public service or employment under the Labour Code [10].
- Negative perception of the civil service by the public.
- Unattractiveness of the civil service for graduates and professionals from other fields.
- Administrative complexity of the management of civil servant relations, the procedural complexity and duration of proceedings under the Civil Service Act.

Employment relations in central government bodies can be divided into three main groups of legal relations:

- Civil servant relations related to the performance of civil service by civil servants.
- Employment relationships of employees when performing work in the public interest in connection with the performance of dependent work in an employment relationship (public service).
- Legal relations related to the performance of civil service of officers of the Police Force of the Slovak Republic, the Prison and Judicial Guard Corps of the Slovak Republic, officers of the Fire and Rescue Service, customs officers, professional soldiers of the armed forces in the service.

The centralization of human resources management in the civil service took place at the level of processes and tools, strategic management and human resource planning remains decentralised. The Office of the Government of the Slovak Republic is responsible for the coordination and management of human resources in the state administration, which only partially carries out these activities. This does not include long-term planning of staff numbers, analysis of the consistency and horizontal consistency of the various remuneration regulations, programmes for talented officials and support for the rotation of officials between service offices, or more demanding issues also named by revision (regional remuneration system, collective bargaining organisation, etc.). Coordination and strategic management require job definitions comparable to those of the private sector. [11]

The strengths of the civil service, which have an impact on the management of human resources in state administration, consist of the following:

- Civil service is viable, justified, and capable of carrying out the tasks for which it was set up.
- Civil service has helped to fulfil Slovakia's integration ambitions.
- Civil service is classified as a standard European civil service built on the common principles of professionalism, impartiality, efficiency, and ethics.

The strategy of human resources management in state administration aims to:

- Professional recruitment and selection of quality civil servants providing services to citizens on the principles of ethics and in accordance with their requirements and expectations within the framework of the rights and obligations established by generally binding legal regulations.
- Continuous development of the abilities and skills of civil servants.
- Achieving a high level of motivation for civil servants and stabilising them in the civil service.

The efficiency of the functioning of structures in the field of civil service depends on human resources, with labour resources often accounting for the largest part of the costs. Measuring the actual return on investment becomes difficult. The situation has changed since the development of the first international standard for measuring human capital. Effective human relation strategies can have a positive impact on the performance of organizations. [12]

One of the most important issues in the management of human resources in the state is the degree and method of centralization and coordination. More centralisations can contribute to increasing equality, applying equal approaches and principles, while decentralisation gives management greater freedom of management and a better orientation towards the needs of a particular institution. The rate and level of delegation varies internationally. For a long time, Slovakia was one of the countries with a high level of delegation, except for the short existence of the Civil Service Office, which aimed to establish unified and central coordination of the civil service in almost all areas of human resources management. The delegation rate was partially reduced in 2017 with the adoption of a new civil service law, which brought about a change in terms of strengthening the centralization of some institutes and unifying the rules. [13]

The goal of planning in the civil service is "*to achieve an optimal number of motivated, flexible and efficient civil servants to ensure the efficient and high-quality performance of the civil service*". [14]

The Fire and Rescue Service is a multi-service system. Its components have the nature of a material, procedural, spiritual, and human character. The material component is represented by technology and equipment, the procedural component is all activities arising from the tasks of the service, and the spiritual component expresses the interests of the state in protecting the population from the danger of natural disasters.

The main component of any social system is a man. Officers of the Fire and Rescue Service are the main representatives of the quality of fulfilment of the tasks of the service. The question of quality is very closely related to the process of professionalization of the firefighting profession. The adoption of legislation, in particular the Act of the National Council of the Slovak Republic No. 315/2001 Coll. on the Fire and Rescue Service, as amended, and other related regulations represent a significant shift in this process, the final consequence of which should be to ensure ever faster, better, and more effective protection of the health and life of citizens, animals, property and their common environment from fires, natural disasters, accidents, and other emergencies. The legislative changes are intended, as a matter of priority, to strengthen the social importance of the firefighting profession, which has been partially achieved, by extending the scope and nature of the tasks performed by the Fire and Rescue Service.

The civil service of officers in the Fire and Rescue Service is the performance of the tasks of the service by officers in the service. Based on this fact, a description of individual functional places arises. An officer is a natural person who has been admitted to the service pursuant to Act No. 315/2001 Coll. on the Fire and Rescue Service [15]. Service is established with the state and the legal relations of officers are regulated by the Labour Code only in cases where the law expressly provides for it. The number of officers in the civil service and at the same time the amount of funds for the service income of officers of the civil service is approved by the Government of the Slovak Republic for each year when discussing the draft act on the state budget for the relevant year. The government may adjust in the number of officers in the civil service or in the amount of funds for the service income of officers of the civil service based on the approved law on the state budget for the year in question. During the calendar year, the adjustment in the number of officers of the civil service or in the amount of funds for the service income of officers of the civil service may be made by the government or based on its authorization, by the Minister of Finance of the Slovak Republic. The proposal for the number of officers in the civil service and the proposal for funds for the service income of civil servants are prepared by the Ministry of Interior in cooperation with the Ministry of Finance of the Slovak Republic based on the organizational structure of the service offices. The breakdown of the approved number of civil servants, broken down by function, following the organisational structure of the service offices, is approved by the Minister of Interior on a proposal from the President of the Fire and Rescue Service. Information on the composition and number of officers is communicated to the competent service authorities by the table of composition and numbers sent by the Ministry of Interior of the Slovak Republic. The head of the service office is obliged to monitor, ensure, and comply with the implementation of the approved systemization.

Among the individual departments of central state administration bodies, the most detailed intra-ministerial systemization of state-employment posts (SEP) is held by the Ministry of the Interior of the Slovak Republic, which, following its organizational structure, maintains a breakdown of the number of planned state-employment posts in the form of so-called tables of composition and number of departments under the competence of the Ministry of Interior of the Slovak Republic. These include the definition of each individual SEP, the place of work in the public interest, as well as civil servants in the service (officers of the Police Force, the Fire and Rescue Service and the Mountain Rescue Service), including the relevant systemization parameters of the function in the conditions of each department.

To each planned SEP within the Ministry of Interior of the Slovak Republic are assigned the so-called systemization parameters (indicators) of the function, which serve to comprehensively define individual SEPs in the organizational structure of the relevant organizational unit. The breakdown in question corresponds to the total limit of the number of places approved by the Government of the Slovak Republic and is covered by the approved amount of salary appropriations for the relevant financial year. Each individual function is systemized in the table of composition and numbers of a given department, as a rule, with the following parameters (indicators): the name of the function, the type of function (civil servant, employment, police, firefighting), the grade, the department of the civil service expressed by the corresponding numerical code, the place of performance, for management functions the amount of the management surcharge, the specification of the function (if required or determined, it is indicated, for example, whether the function in question is financially covered by the reimbursement of wages EU funds, etc.), the nature of the work (expressed in numerical code), the category of jobs for statistical purposes, the qualification of education. Optionally, there is a requirement to consult classified information. [16]

4 Human resources management in the Fire and Rescue Service

According to the law, any citizen of the Slovak Republic who applies in writing for admission to the Fire and Rescue Service can become a officer of the Fire and Rescue Service if:

- is of good repute (extract from the criminal record) and has not been dismissed from the civil service for serious misconduct or three years have elapsed since the date on which the decision on dismissal became final,
- has full legal capacity,
- fulfils the qualifications required to perform the post to which he is to be appointed,
- is medically, physically, psychically, and mentally fit to perform the service,
- speaks the state language,
- speaks a foreign language, if this requirement for the performance of civil service is specified by the service authority in the staff regulations,
- resides in the territory of the Slovak Republic.

If there are free posts in the civil service in the Fire and Rescue Service, the admission procedure shall be announced publicly in the press or in other means of public communication generally accessible to the public (e.g., the Internet) three weeks before its implementation, indicating the place for submitting a written application for admission to the civil service.

However, the admission procedure may also be initiated by the application of the applicant. According to the Act on the Fire and Rescue Service [15], the head of the service office or a officer authorised by him is obliged to conduct an informative interview with the applicant, during which he is acquainted with the fundamental rights and obligations arising from the service, in particular the conditions of civil service and with salary and other requirements. Based on such an interview, a written record is made. In the admission procedure, the applicant must submit all documents requested by the service office and determined by law.

The specificity of the selection of officers is to assess his competence in relation to the performance of the service' tasks. He must undergo a medical examination, a physical fitness check and a psychological examination. At the same time, he also undergoes an oral interview or a written test.

The admission procedure verifies the applicant's knowledge, abilities, skills, and other requirements that are necessary or appropriate to the nature of the activities to be carried out in the civil service. It takes place regardless of the sex, race, colour, belief, religion, political or other opinion of the applicants, their national or social origin, membership of a nationality or ethnic group.

If the applicant has not complied with one of the conditions, the admission procedure ends with him.

The admission procedure also ends in the following cases:

- Issuing a decision on recruitment.
- Rejection of an application for recruitment on the grounds that there is no free post in the service to which the application for recruitment relates.
- Withdrawal of the application for recruitment.
- Rejecting an application for recruitment without justification.
- Death of the applicant.

The service office shall, within 30 days of the end of the recruitment procedure, but no later than six months from the date on which the application for admission to the service was submitted, notify the applicant in writing.

Based on the results of the recruitment procedures, the service office registers for a period of one year the successful candidates who have fulfilled the conditions for admission to the service. The subject of such records are the results of a medical examination, a physical fitness check and a psychological examination for a year. It is possible to appoint an applicant for the vacancy from the database of the service office thus created if it is possible to use the recorded results to assess his competence.

Based on a successful admission procedure and its selection by the Commission, the candidate is appointed to the post by decision. At the same time, he is also familiar with the length of professional experience and counted experience, the amount and composition of the service salary, the weekly service time, and the length of leave. Upon the establishment of a service relationship, officers must take a service oath.

As we mentioned above, the training and professional development of officers in the Fire and Rescue Service begins already when they are appointed to the service. However, the service shall ensure the regular upgrading of the qualifications of officers to maintain, improve and supplement the required knowledge, skills, abilities, and habits necessary for the performance of civil service in the Corps on an ongoing basis. The type and form of deepening of qualifications is determined by the Ministry of Interior. The results of deepening the qualifications of a officer become part of his assessment. Upskilling serves to obtain the necessary level of education so that the officer can perform tasks in another post in accordance with the needs of the service office.

5 Human resources management in the private sector

"*Enterprise it's people*" – the basic condition for the success of any organization, entrepreneurial or non-entrepreneurial character, is today to realize the value and importance of a person in the work process. If a manager proceeds from the philosophy that human capital represents substantial capital today, he knows that current practice requires looking for optimal paths of human resources management in each entity. Today, it is the people and their knowledge that decide the success and competitiveness of the subject. [17]

Personnel management can be characterized as a part of corporate management that focuses on human resources. It represents a summary of activities in the field of employee activities that are aimed at fulfilling the company's goals.

Human resources issues in the enterprise are dealt with by personnel management or human resources management. Usually, this area of management is defined as an activity that includes all managerial decisions and practices that directly affect the human resources of the enterprise. With other functional areas of management, it participates in achieving the so-called synergistic effect, which is influencing the goals of employees and the enterprise. [18]

Personnel strategies are usually the work of the entire management of the enterprise. All managers and all departments contribute to their creation. The natural guarantor is the personnel manager and his staff. Fundamental decision-making on the strategy of working with human resources must be conducted in the long term in accordance with the anticipated development of the enterprise. The strategy of working with people is a very sensitive matter.

A personnel strategy is a basic document that specifies, among other things, priorities in human resources management. [19] The aim of the investigation in this area is to find out whether human relation managers need such a document and, if so, what are the current trends in the priorities of the strategy.

Talent management, understood as a complex concept encompassing both the performance and personnel components, becomes a priority of personnel strategies. [19]

The personnel strategy in the private sector is based on the overall strategy of the enterprise. It is a basic prerequisite for personnel management. Progressive businesses have now become quite clear everywhere that even the best strategy, which is not secured and supported by people, remains on paper as a worthless document. Many managers openly admit that, regardless of the different advantages of modern technology, human resources are most essential for the success of an enterprise.

Personnel activities in the enterprise represent the executive part of the work of the personnel department. The Personnel Department ensures, organizes, and coordinates these activities, controls, and directs all other employees involved in personnel management and performance of personnel activities, and at the same time develops and continuously improves their methodology.

As basic personnel activities, we define:

- Job analysis,
- Personnel planning,
- Recruitment and selection of staff,
- Evaluation of employees,
- Deployment (assignment) of employees and the termination of the employment relationship,
- Remuneration,
- Company training of employees,
- Labour relations,
- Caring for employees,
- Personnel information system,
- Labour market research,
- Health care for employees,
- Activities focusing on the methodology of survey, detection, and processing of information.
- Compliance with labour and employment laws.

By analysing work activities in the company and their thorough analysis, a strategy is established for filling individual functions with suitable types of workers. In this step, the description and specification of the job is drawn up, in which the nature of the work, working conditions, and requirements for the employee are determined. Based on the plan, because of personnel planning, the number of individual jobs to be filled in a certain period is determined. These two steps are important for jobs that will be newly created to improve the organization of work in the company.

All preparation for staff recruitment should be subject to this. The internal and external resources of applicants need to be reassessed. The key step is to establish the sources, methods, documents, and responsible persons. The pre-selection, which takes place after the formulation of the job offer and the publication of the job offer, prepares a list of candidates, according to which they will be invited to the selection procedures. During the recruitment process, they are selected after preliminary sorting into:

- marginal (we can keep them in reserve),
- possible,
- unsuitable (which the business rejects).

Based on the references received, e.g., from previous employers, candidates are divided into candidates suitable and unsuitable for the job.

After the recruitment process, a selection is made and a final bid is drawn up for the selected candidate, which the candidate either accepts or rejects. If the addressed applicant rejects this offer, the enterprise has the option of calling the addressed applicant in reserve or repeating the selection.

5 Comparison of the creation of personnel strategies in the private sector and in the Fire and Rescue Service

Today, high-quality data is a key factor for strategic workforce planning, labour productivity growth, talent management, worker engagement and retention, performance management, dynamism, and mobility decisions.

In the business environment, the job description and specification, in accordance with the personnel planning of the enterprise, is drawn up by a particular enterprise to achieve its set goals according to its "tailor-made" needs.

The goal of strategic human resources management is to ensure the correct direction of interconnected programs and practical procedures to address long-term people-related issues, as well as a guide to successful action supporting the organization's strategy. [20]

Human resources in state administration in Slovakia are planned in relation to the competence of service offices and the state budget. [2]

Ministries and other central government departments determine for themselves the number of civil servant posts in their service, considering the limit approved for the financial year in question. Consequently, their systematization "also implies the number of civil servant posts for their subordinate service offices" [21].

In the Fire and Rescue Service, the number of individual jobs is given as indicated by systemization following the state budget. The job description and specification are drawn up in accordance with the performance of the tasks of the Fire and Rescue Service and according to the applicable legislation.

Based on the Survey of the Office of the Government of the Slovak Republic in 2014, it can be concluded that most of the service offices of the central bodies of the civil service plan civil servant posts and conduct their own intra-departmental systemization according to various criteria, from the simplest to the most complex ones, as shown by the positive example of the Ministry of Interior of the Slovak Republic. However, since the law does not provide for the obligation to plan the SEP following the organizational structure, there are service offices that do not do so. Similarly, they do not break down the SEP in relation to indicators such as grade or type of civil service or break down only some of the indicators.

If this planning is to be effective, it is essential to define jobs in the way that is done in both the private sector and the Fire and Rescue Service.

One of the reasons for the lack of long-term planning in human resources management and the number of civil servants is the time mismatch between long-term and short-term policy objectives

The time mismatch between long-term and short-term policy objectives prevents policymakers from committing to policies that require long-term implementation. Politicians prefer short-term goals because they know that they may no longer be in office after the end of the parliamentary term. [22]

The basic tool in the field of human resources management strategy in the civil service is long-term planning. The absence of systemic, knowledge and analysis-supported long-term planning is a fundamental shortcoming that occurred especially during the transformation of the economy in the first decade of its existence. The transformation has led many times along the paths of reform trial and error, characterised by inconsistent rationalisation measures and various delegations of competences without impact analyses, the liquidation of the institutions and bodies that were supposed to provide strategic concepts and the evaluation of policies before they are applied on the ground. These negative effects have occurred in all spheres of public administration, including strategic planning and human resources management.

Within the framework of the basis of the Strategy for human resources management in the civil service for 2015 – 2020, approved by the Resolution of the Government of the Slovak Republic No. 548/2015, it is stated that the current challenge for the public sector is to find solutions on how to implement economically sustainable concepts and policies, with a focus on the real public interest versus purely ideological ones, the partial and group or narrowly departmental approach used to date, including more trade unionist and evidence-based decisions. The strategy also confirms the absence of systemic long-term planning.

It also seems problematic that, during the financial year, most service offices, including the Fire and Rescue Service, make several organisational changes, while the procedural procedure for both designing and approving changes is not uniform, which in practice means that the service authorities can make changes to planning based on different criteria and rules. This situation prevents systematic and coordinated planning of the SEP in the service offices, prevents efforts to create a stable number of civil servants and civil servants, and allows for ad hoc changes in the organization and the SEP, which can become abusive as a potential tool for politicization.

Another factor entering the creation of a personnel strategy in state administration is the correctly selected level of centralization or decentralization in the field of human resources management.

Absolute centralisation or decentralisation does not exist. Tendencies towards one side or the other are manifested, while at all levels of management there are, to a certain extent, both centralization and a certain autonomy of lower management links in solving tasks. A prerequisite for the effective functioning of the organization is to ensure an optimal division of decision-making power, i.e., the optimal combination of its centralization and decentralization. Excessive centralisation leads to bureaucracy, excessive decentralisation tends towards anarchy. How much power to allocate to individual activities and to those who carry out these activities is decided by managers. When dealing with the relationship between centralization and decentralization of security management in the organization, it is necessary to take into account: consistently centralize the use of all information sources and ensure that each decision-making point has access to the necessary information, the decision to take quickly and close to the source of information, to observe the balance of the tasks issued and the powers that condition the performance of tasks, as well as the responsibilities arising from them, to clarify, which decision-making powers can be decentralised and which must remain centralised. Accordingly, powers can be divided into those: which cannot be decentralized and must remain centralized; which can be fully decentralized (delegated); which can be partially decentralized (delegated). [23]

By defining the recruitment procedure for officers to the Fire and Rescue Service and describing the selection of applicants in the private sector, we have highlighted the difficulty of selecting officers. Because it is a civil service in the branch of the specialized state administration, each officer must meet all the conditions for assessing competence, regardless of what service tasks he will perform in the corps.

Finally, we need to highlight some of the differences in some components of human resources management in the business environment and in the conditions of the Fire and Rescue Service.

In the business environment, the job description and specification, in accordance with the personnel planning of the enterprise, is drawn up by a particular enterprise to achieve its set goals according to its "tailor-made" needs.

In the Fire and Rescue Service, the number of individual jobs is determined by systemization following the state budget. It is not determined by the specific service offices occupying these posts. The job description and specification are drawn up in accordance with the performance of the tasks of the Fire and Rescue Service.

In the business environment, the enterprise itself determines the method of recruiting employees and based on pre-selection, it can reduce the number of applicants it invites to the selection procedures according to the criteria set by it.

Armstrong [1] defines a job as a set of related tasks performed by a person and thus fulfils the purpose of the job.

In the conditions of the Fire and Rescue Service, the service office is obliged to start the admission procedure with any applicant who submits a written application for admission to the civil service. However, the opposite of this fact is that each applicant must meet the conditions of eligibility to perform civil service to the extent stipulated by law, regardless of what tasks in the service he performs.

It is believed that future studies will deal more with personality traits, since they are key elements in the development of individual leadership skills. [24]

Human resources management, human potential, education and development of human resources, development and stabilisation of human resources, quality of life and care for human resources, motivation in the field of human resources management, economics, logistics, crisis management at national or international level are all topics that are moving the world, especially now, at a time when thousands of migrants are joining Europe. People are constantly facing various changes, new potential threats, or risks. The better and more efficient the care of human resources in the power sectors – the fewer problems there will be with the quality of life of each of us. [25]

Future studies should focus on the attitudes and behaviours of individuals to develop new theoretical concepts and better studies regarding human resources and leadership styles. [26]

The results according to the Fire and Rescue Service correspond to the international standards. The evaluation looks at the number of actions and victims, as well as property damage. In line with best international practice, it would be appropriate to introduce a comprehensive system that also monitors the efficiency, economy, and management of human resources.

The implementation of a competence approach to human resources management in the public sector would lead to the promotion of strategic orientation and integration of key areas of human resources management, including workforce planning, selection and recruitment, mobility (which is almost taboo in the public sector) and training and development of human capital.

We live and work in an era of technological progress that is unprecedented. In response to technological progress, the skills and flexibility requirements of the workforce are changing. At the same time, the entry of the young generation into the work process forces employers to change their human resources policy according to their requirements, a new trend is not to work for one employer for life and trendy independence. This means that potential talent has become an employer on its own and creates a new competitive environment with new flexible management methods compared to outdated managers of some companies. This trend affects the situation in the labour market. A quality workforce becomes an advantage especially for those who offer interesting working conditions, and it is not only about salary, but especially about the employer's relationship with their employees. [27]

Public administration management differs in many aspects from corporate management. First, it is essential to underline that public administration is not an economic market. Managers are often appointed based on political affiliation or the influence of interest groups, to the detriment of their competence. Organisations active in public administration are non-profitmaking in nature, so the main variable – "profit", used in the private sector, cannot be used here. The provision of public goods is in many cases highly unprofitable. The management of public administration is also particularly strongly influenced by factors that are absent in the private sector, in particular political factors, civil control, public opinion, public interest, and others. [28]

6 Conclusions

A key process of coordination is the strategic management and planning of human resources, which is based on qualified evidence and data. Strategic management transforms the organization's strategy into requirements for securing and overall management of human resources. Changes in public policies (digitalization of processes) or trends (e.g., aging) affect the number and profile of employees that the state and specific organizations will require. Human resource planning includes forecasting the number of required workers for various professions or supporting the acquisition of currently needed professions (hard planning). At the micro level, it can also deal with planning and deployment of employees in individual organizations (soft planning). Strategic management and planning in the Slovak civil service is still decentralized, even after the unification of rules in several areas. Thus, long-term planning of the number of workers, analysis of the consistency and horizontal compliance of various remuneration regulations, management of leadership (programs for talented officials) and careers between service offices, or more demanding issues also called revision (regional remuneration system, organization of collective bargaining, etc.) are not carried out.

The comparison of human resources management in the private sector and in the Fire and Rescue Service as one of the services of the state administration, the description of intersections and differences pointed to the lack of long-term strategic planning of human resources, the problematic determination of the correct level of centralization and decentralization in the management of human resources in the Fire and Rescue Service as well. A comparison of recruitment procedures showed an effective pre-selection of applicants carried out in the private sector, which, if incorporated into the current legislation, would significantly simplify, and streamline the process of selecting new members of the Fire and Rescue Service.

The level of human resource management is currently used as a criterion for evaluating the quality of the organization's activities. It is important to pay due attention to this part of management, whether in the private sector or in the Fire and Rescue Service. In the future, the introduction of the evaluation of the quality of human resources management in the Fire and Rescue Service would help to evaluate its activities more clearly.

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FIRE PROTECTION & SAFETY Scientific Journal
16(1): 63–70, 2022
DOI: 10.17423/delta.2022.16.1.108

Laboratory Investigation of Sessile Oak Wood Thermal Degradation

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Short Report

Received: 22.06.2022; Accepted: 30.06.2022; Published: 31.07.2022

Abstract

Fire resistance is an important fire parameter. Currently, wood that is flammable is often preferred as a building material. To protect the building from fire, we must know its fire characteristics, as well as fire resistance. According to the Act of the National Council of the Slovak Republic no. 314/2001 Coll. on fire protection, an investigator who investigates the cause of the fire, when and where the fire occurred, the initiators of the fire, and how the fires spread. To understand the fire behaviour, it is important to know the parameters such as wood properties, heat transfer in the wood and, finally, the thermal degradation of the wood. An equally important parameter is the thickness of the charred layer, thanks to which we can determine the charred rate from which the initiation time of a fire can be estimated. In this work, we loaded the samples with heat fluxes of 15 and 30 $kW{\cdot}m^{-2}$ and then we compared the initiation times of the samples. We also monitored the course of temperatures on thermocouples T1, T2, T3, T4 at the proposed heat fluxes. From the measured values, we determined the rate of charring, mass loss and the rate of burning at different thermal loadings. We also determined the thickness of the charred layer using manual measurements.

Keywords: oak wood; rate of charring; thermal degradation.

1 Introduction

According to the Act of the National Council of the Slovak Republic No. 314/2001 Coll. [1], a fire is an undesirable burning that is spontaneous, where several materials burn at the same time. It is very dangerous for the lives of people, animals and has devastating effects on property. For a fire to be initiated, it is necessary to establish the triangle of burning. Fuel and an oxidizing agent must be present. The burning triangle is also considered in the test methods. A fire has four phases: an initiation, propagation, fully developed fire, and the decay. A special category is represented by substances which are capable of self-ignition [2]. The most important stage is initiation. During it, a chemical reaction takes place to form a flame, heating the fuel so that gases are formed on its surface. When the gases reach the desired temperature, the molecules that make up the gases break down and the fragments thus disintegrated are combined with oxygen to form new molecules – water molecules and carbon dioxide. With imperfect combustion, even more products are produced [3]. When burning, pyrolysis sometimes occurs, which can proceed without an oxidizing agent. This is the decomposition of materials that are exposed to heat. Chemical and physical changes take place in this process [4].

When a fire occurs, it is important to find out its cause. According to the Act of the National Council of the Slovak Republic No. 314/2001 Coll. on Fire Protection, the state fire supervision investigates the cause of the fire through the fire investigator. A special case for fire investigation is in wooden buildings. The fire resistance of these structures, or structures made of wood, depends on the rate of charring. According to this parameter, the degree of damage to wood can be determined, as well as residual wood, in which degradation processes have not taken place. The Eurocode 5 is used to calculate the fire resistance of wooden constructs [5]. When wood burns, thermal decomposition of the bonds of its components takes place, the chemical composition changes and new products are formed. A charred layer is formed, which is formed on the surface of the wood under high temperature loading. The formation of a charred layer has many advantages. It prevents air from entering the inner parts of the wood cross-section, relieves burning and exhibits very good thermal insulation capabilities [6]. The rate of charring is one of the most important properties of wood and wooden products. It is one of the input data for calculating the fire resistance of wooden structures. In addition, wood charring rate is a widely used parameter during fire investigations (7). The rate of charring of wood is influenced by the density and moisture content of the wood, the heat flow, and the concentration of oxygen in the air (8). The charring rates are calculated from the depth of charring and the time when the material is subjected to thermal loading (7). Lipinskas [9] found that the differences between the different types of wood (coniferous, deciduous) in the charring layer are very small, negligible. Charring takes place in the process of pyrolysis, which results in the specific mass of the wood being reduced (2).

The aim of the paper is to determine the selected parameters of Sessile oak wood for the study of thermal degradation processes: time to initiation, rate of burning, thickness of charred layer.

2 Material and Methods

The samples were produced from the Sessile oak stem harvested at the Kremenný Jarok locality, situated at an altitude of 320 m above sea level. This territory is under the administration of the University Forestry Enterprise of the Technical University in Zvolen (Slovakia). The stand age was ca. 110 years.

The size of samples used in the work was of 40 x 50 x 50 mm. Samples were air conditioned to a moisture content of 10 ± 0.15%. We subjected the samples to a thermal loading with two heat flux values, i.e., 15 and 30 $kW \cdot m^{-2}$. In the study, we repeated the test for each heat flux 10 times.

We carried out the measurement using a measuring apparatus, which is maintained at the Industrial Property Office of the Slovak Republic under utility model No. 9373 [10]. It is designed to measure the rate of burning and the rate of charring of polymers.

The testing apparatus consisted of a ceramic infrared lamp, digital scales, a control device, and a temperature measuring device. Using thermocouples, we measured the temperature in samples. The temperature measuring device and the scales were connected to a computer, and values were recorded every 10 s. The temperature in the sample was measured by the thermocouples, inserted into the pre-drilled holes. The holes were 10 mm apart (depth).

Each experiment lasted for 30 minutes.

We measured the thickness of the charring manually. Before testing, we measured the thickness of the samples at 9 different locations using a sliding gauge. Then, after thermal loading and subsequent cooling, we cleaned the sample, scraped off the charred layer, and measured the sample again in the same 9 places. At the end, we evaluated the results.

3 Results and Discussion

3.1 Results in relation to time to initiation

According to the measured values of the time to initiation, we can confirm the fact that the higher the heat flux, the less time the sample needed to initiate. The longest time for initiation needed samples thermally loaded by the heat flux of 15 kW·m^{-2}, which was of 140 s on average. On the contrary, we found the shortest time for samples loaded with a heat flow of 30 kW·m^{-2}, where this time was 24 s on average.

3.2 Results in relation to mass loss

The relative mass loss of a sample depends on the thermal loading duration as well as applied heat flux. For all samples, it was confirmed that the longer the heat flux acts on the sample, the greater the mass loss achieved by the sample. Based on the determination of the mass loss, we calculated the rate of burning of oak wood.

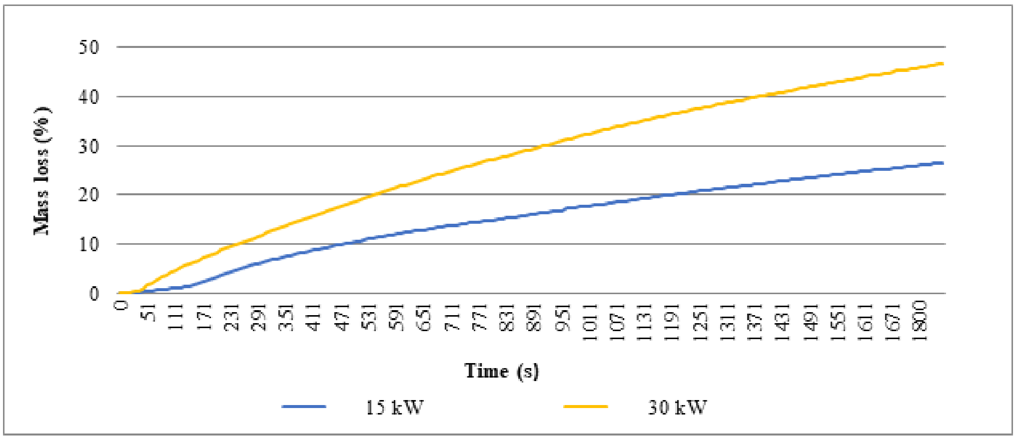

Fig. 1 Course of relative mass loss

From the graph (Fig. 1) we can see that if we set the heat flux to 15 kW·m^{-2}, the sample achieves the mass loss only less than 30 %. Conversely, at the heat flux of 30 kW·m^{-2}, the sample achieved almost 50 % of the mass loss.

3.3 Results in relation to rate of burning

The rate of burning, as well as the mass loss, depends on the time and heat flux that acts on the sample. The greater the heat flux acts on the sample, the sooner it reaches the maximum rate of deburring. As the heat flux increased, the rate of combustion also increased (Fig. 2).

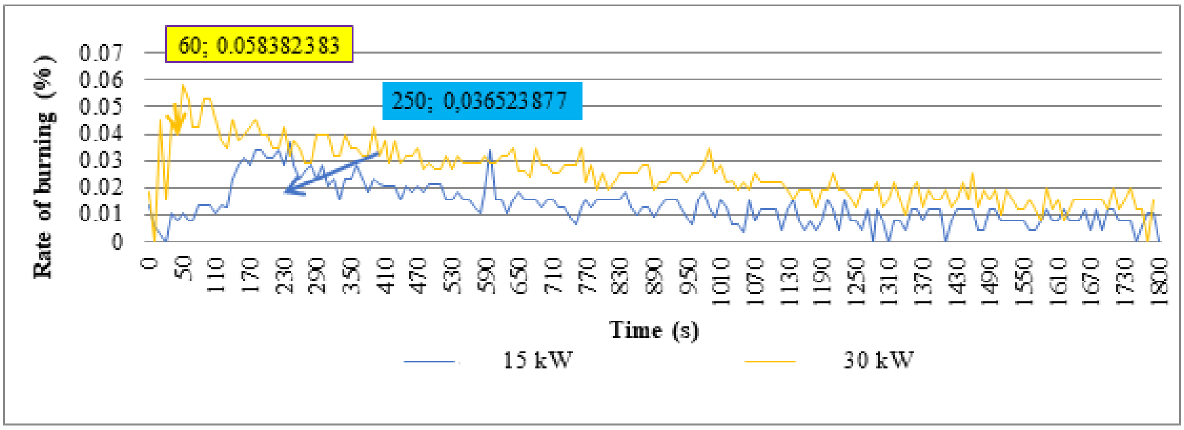

Fig. 2 Relative mass rate of burning course related to the heat flux applied

As seen in Fig. 2, when setting the heat flux to 15 kW·m^{-2}, the sample reached a maximum burning rate (0.036 %) in 250 s. This value of the rate of combustion was the smallest measured value. Conversely, when we set the heat flux to 30 kW·m^{-2}, the sample reached its maximum burning rate as early as 60 s. The achieved value was like that of a heat flux of 15 kW·m^{-2}, namely 0,060 %.

The course of temperatures in the sample affects the magnitude of the heat flux (Fig. 2). When higher heat flux applied to the sample, it reached the rate of combustion faster than when the heat flux was less.

3.4 Results in relation to achieved temperature course

The course of temperatures also depends on the thermal loading duration on the sample. For thermocouples T3 and T4, we did not reach the charring temperature. For the T2 thermocouple we reached a temperature of 300 °C only at the end of the measurement, but only at a heat flux of 30 kW·m^{-2}. If the samples had been exposed to heat flux longer, we would have measured the temperature of 300 °C on other thermocouples, too.

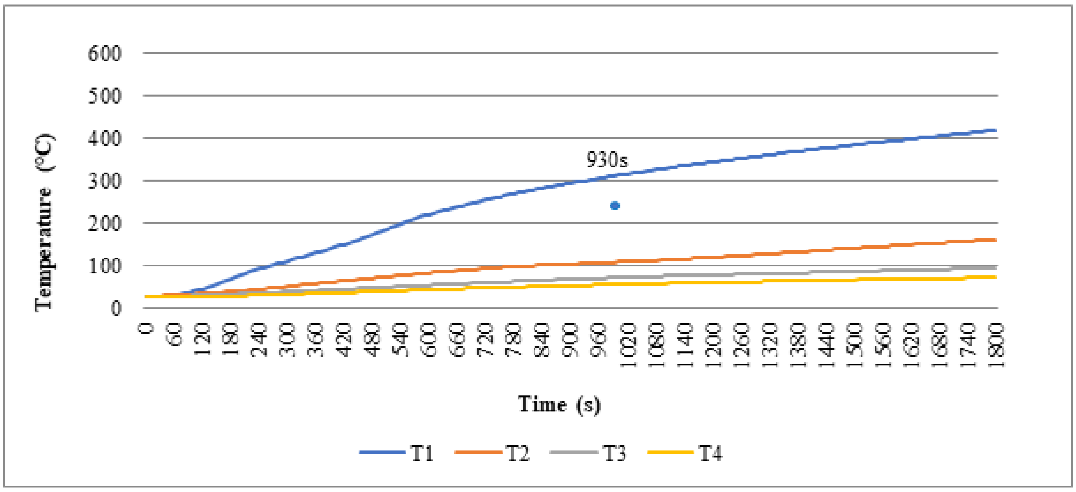

Fig. 3 Temperature course by thermal loading of 15 kW·m^{-2}

Figure 3 shows the course of temperatures in the samples under the thermal loading with a heat flux of 15 kW·m^{-2}. The highest temperature was reached by the sample on the thermocouple T1 (10 mm deep in the sample). Charring also took place only at this depth, since only the T1 thermocouple recorded the charring temperature of 300 °C at 930 s.

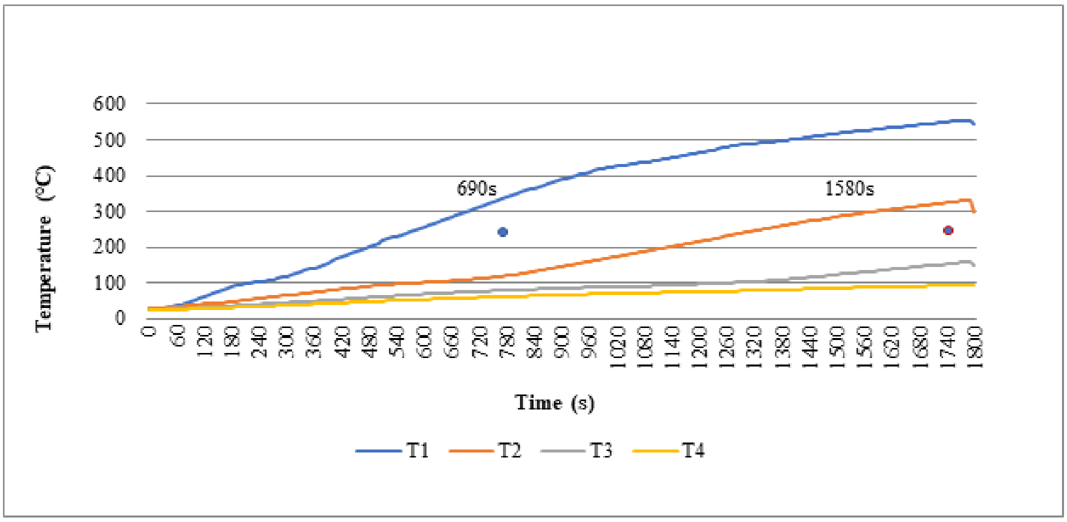

Fig. 4 Temperature course by thermal loading of 30 kW·m^{-2}

When the samples were loaded with a heat flux of 30 kW·m^{-2} (Fig. 4), the sample reached the charring temperature on two thermocouples, T1 and T2. On the thermocouple T1, it reached temperature of 300 °C earlier, already at 690 s. On the T2 thermocouple, the charring process began a little later, only at 1,580 s.

From the measurements, we found that the course of temperatures on individual thermocouples depends on the depth to which we insert the thermocouple, as well as on the heat flux and the time during which the sample is exposed to thermal loading.

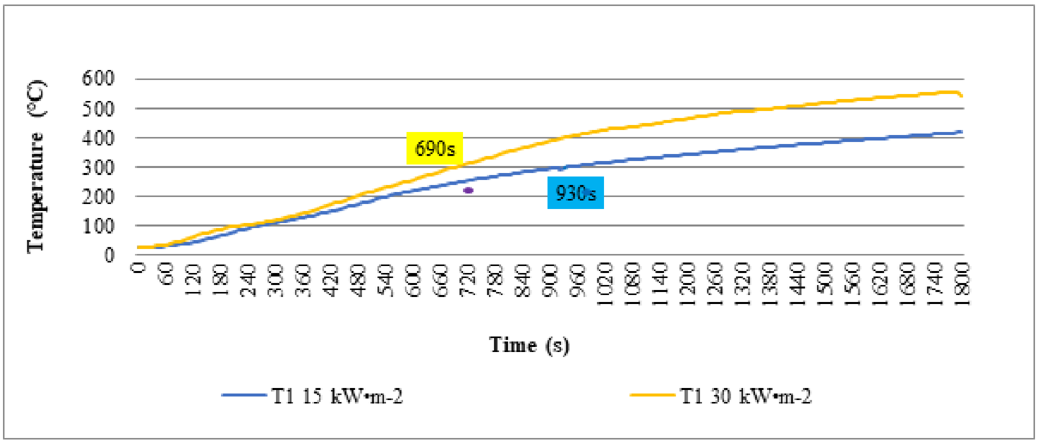

Fig. 5 Temperature course in the depth 10 mm underneath the sample surface

From the graph (Fig. 5), we can determine that on the thermocouple T1, placed 10 mm underneath the surface of the sample, the temperature of 300 °C was first reached by samples loaded with the heat flux of 30 kW·m^{-2} at 690 s. This temperature was most slowly reached by samples loaded with a heat flux of 15 kW·m^{-2} at 930 s.

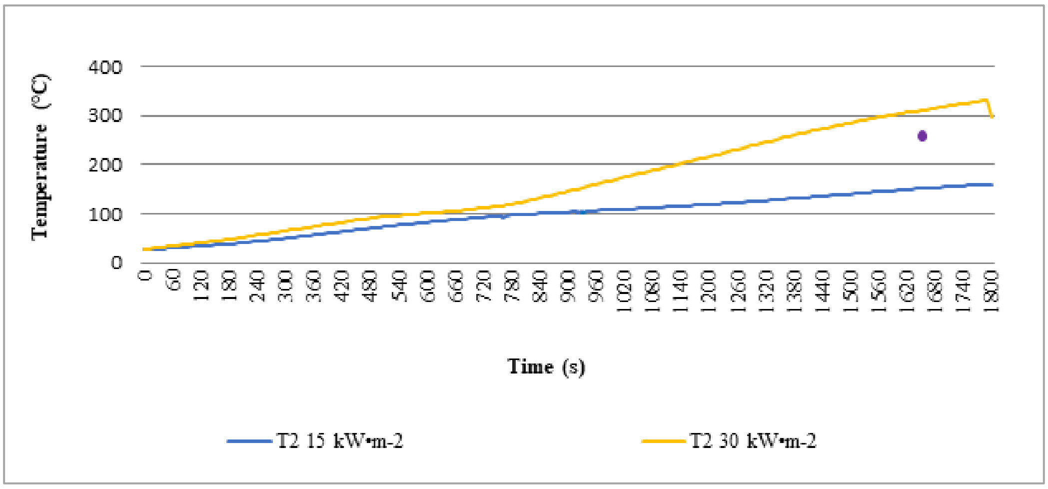

Fig. 6 Temperature course in the depth 20 mm underneath the sample surface

Thermocouple T2 inserted in the depth of 20 mm underneath the surface of the sample (Fig. 6) reached the charring temperature only under a thermal loading of 30 kW·m^{-2}, with a maximum heat flux of 30 kW·m^{-2}. The magnitude of the thermal loading was not sufficient for thermal degradation and subsequent charring formation.

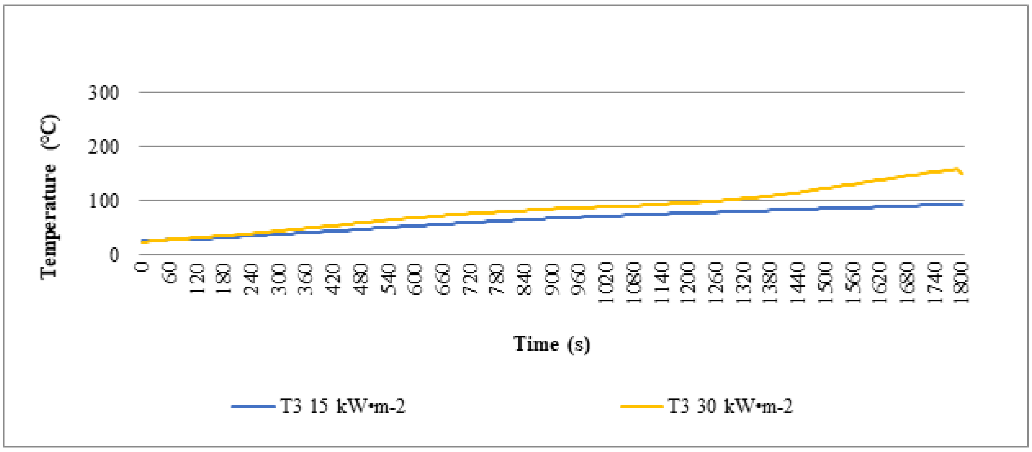

Fig. 7 Temperature course in the depth 30 mm underneath the sample surface

The thermocouple T3 which we inserted 30 mm below the surface of the sample (Figure 7) did not reach a temperature of 300 °C. There was no process of charring.

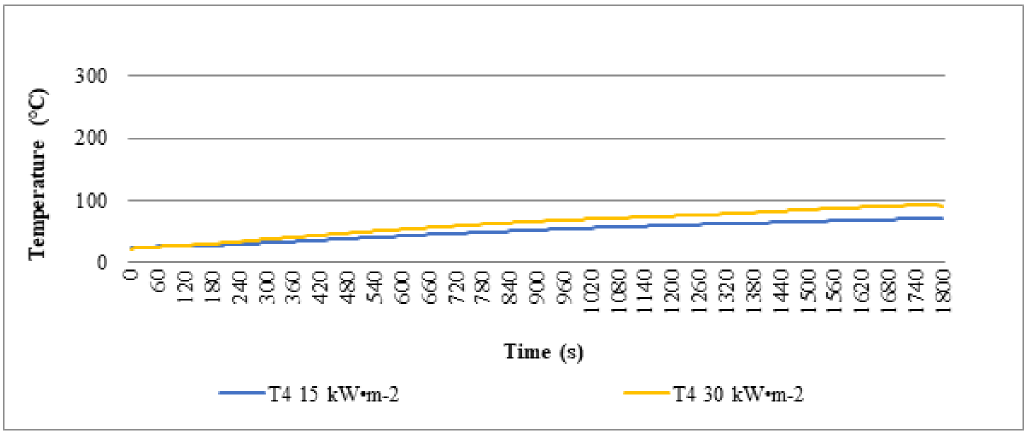

Fig. 8 Temperature course in the depth 40 mm underneath the sample surface

As with thermocouple T3, no charring occurred with thermocouple T4 (Fig. 8). The thermocouple inserted in the depth of 40 mm underneath the surface of the sample did not reach a temperature of 300 °C.

3.5 Results in relation to charred layer thickness

The thickness of the charring layer also depends on the magnitude of the heat flow. The greater the heat flux acts on the sample, the greater the thickness of the charring. We measured the thickness of the charring in two ways, manually and using a measuring apparatus. In both methods of measurement, the results were confirmed, they were almost identical.

When manually measuring the thickness of the charring layer, we found that the largest thickness of the charred layer was shown by wood at a heat flux of 30 kW·m^{-2}. It was up to 25.78 mm. Conversely, when we applied the sample with the heat flux of 15 kW·m^{-2}, the sample reached the thickness of charring only of 12.26 mm.

When measured the charring layer thickness by the second method, the mass loss of 26 % was achieved by the sample at heat flux of 15 kW·m^{-2}. The highest mass loss achieved the oak samples at a heat flux of 30 kW·m^{-2}, i.e., almost 50 %.

A more accurate method of thickness of charring measurement is a method using a measuring apparatus, since with the second method of measuring with a sliding gauge, the human factor may fail, which may result in measurement inaccuracies caused by inaccurate or incorrect work with the sliding gauge.

The thickness of the charring layer was also measured by other authors. Kocaefe et al. [11] studied aspen wood that was exposed to thermal loading in a thermogravimetric analyser. The samples had dimensions of 0.035 x 0.035 x 0.2 m. temperature was set at 220 °C. For 15 min, the mass loss was of 0,83 %. After 30 min, the mass loss increased to 1.79%. The highest mass loss of 2.12% occurred at 45 min. The experiment confirmed that the longer the sample was exposed to thermal loading, the extensive the mass loss.

In another experiment, Eseyin et al. [12] investigated the mass loss of torrefied cedar wood. The weight of the samples was 10 g and they exposed them to different heating rates (5, 10, 20, 30 $° C·min^{-1}$) and temperatures (100, 150, 200, 250, 300 °C) for 30 min. They described mass loss at temperatures of 200-250 °C as moderate. When they raised the temperature to 250-300 °C, the mass loss was more pronounced. The most extensive mass loss of 20 % was recorded at 300 °C.

4 Conclusions

We found that the greater the heat flux acts on oak wood, the faster initiation will take place and a fire will occur. If the sample is loaded with a smaller heat flux, its mass loss will be less than when loaded with a higher heat flux. The rate of burning of a sample is influenced by the value of the heat flux and the time of action of the heat flux on the sample.

We examined the course of temperatures when the heat flux changes on thermocouples at a depth of 10, 20, 30 and 40 mm. From measuring the charring rate of the sample, we found that the smaller the heat flux acts on the sample, the slower the charring takes place.

The achieved results from measurements can be applied in safety practice: in fire prevention, occupational health, and safety. For fire investigation purposes, information about the initiation time helps to predict the time of fire occurrence, which is very important for setting the fire reason. If we can determine the mass loss of wood, we also know the overall course of the fire and the duration of the fire, according to the verified conclusion that the longer a large thermal load is applied to the wood, the greater the mass loss of wood. The fire development rate can be determined using the data on wood burning rate. The charred layer of wood at the site of the fire is used to determine the fire temperature values (min. 300°C).

We can use these results as input data for computer-aided modelling of fire behaviour (compartment fires). The initiation time, the course of temperatures or the mass loss values can be used as inputs into the development of fire model for wooden structures in Ansys.

Acknowledgments

The submitted work was supported by the Agency for Research and Development based on contract no. APVV-17-0005 (50%) and Scientific Grant Agency VEGA, project VEGA 1/0115/22 (50%).

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FIRE PROTECTION & SAFETY Scientific Journal
16(1): 71–89, 2022
DOI: 10.17423/delta.2022.16.1.109

Advanced Methods and Approaches in Fire Safety of Buildings

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Case Study

Received: 18.07.2022; Accepted: 29.07.2022; Published: 31.07.2022

Abstract

The paper deals with the advanced of progressive computer-aided modelling tools in the practice of fire protection. The main of the implemented study was to solve a specific fire scenario, simulating the real conditions of the environment and fire and its spread, based on the practical application of computer-supported modelling in the PyroSim program, to point out the possibilities of applying these tools in the practice of fire protection. In this case, it was a fire on the 6th floor of block A in the main building of the Technical University in Zvolen. The fire scenario itself was created based on knowledge and experience gained from a tactical training with the same subject, which was connected also by declaring a practice fire alarm at the Technical University in Zvolen and evacuating the entire main building. Based on the knowledge and experience from the tactical training, which were also confirmed by the results of modelling and simulation of fire behaviour, risks were identified and measures were proposed for activities in terms of three aspects of ensuring the safety of persons in the event of a fire: penetration of information about the occurrence of a fire and subsequent measures of employees; declaration of alarm, evacuation, escape and verification of completeness of evacuees; construction-technical solution and condition of the object.

Keywords: fire safety of buildings; PyroSim; school facility; training fire alarm.

1 Introduction

The behaviour of fires in indoor areas is subject to fire engineering, which is also related to determining the degree of fire safety in buildings as well as in the design of fire safety equipment (systems). Of course, it all depends on the expected fire behaviour, which is in correspondence with material and constructions fire properties as well as environment conditions. The dynamics of indoor fire are also related to computer modelling of fires, which is currently used. There are several types of computer models, the most complex of which are CFD models. Modelling also plays an essential role in the current trend of integrating access into the fire engineering [1-9]. Computer-aided modelling is now an integral part of investigative procedures.

Modelling, but also describing the development of fire in fire dynamics, is based on data on the rate and amount of energy released, energy transfer mechanisms and environmental parameters. For the correct calculation (estimation) of the rate and amount of energy released, the decisive characteristic is the amount of combustible substance (fuel). To obtain input data, we can also use the results of experimental fire tests of flammable substances. In addition, for some types of flammable liquids, flammable polymeric solids and some products, accurate data on the heat released, the rate of combustion, the rate of formation and concentration of flue gases and others are available in various databases. Where such data are used, the availability and rate of oxygen access and ventilation conditions as well as escape routes for the evacuation of disabled persons shall be considered in a particular case. When modelling the behaviour of an indoor fire, when changing the parameters of a fire environment, computational fluid dynamics (CFD) systems are most often applied in practice, based on the application of field models, in this case specifically Fire Dynamic Simulator (FDS) and its graphical interface PyroSim. The SmokeView as well as Smartfire and Pathfinder environments are used to assess options for controlled evacuation of persons from the fire-threatened area.

PyroSim was developed by the American company Thunderhead Engineering (USA) in 2008. The basic functions of PyroSim include interactively creating a complex geometry of the space in which fire is modelled (creating models of buildings using floor plans, creating repetitive objects, curved walls, and other complex elements of buildings, such as a staircase, etc.), importing existing input FDS files and, to some limited extent, models created in the AutoCAD (Computer Aided Design software application developed for 2D, and 3D design). In addition to the geometry editor for FDS, the current version of PyroSim integrates the FDS system itself and the SmokeView visualization program, which is part of the FDS [10].

FDS is generally a complex program system that simulates the flow of fire-induced gases, the spread of heat by radiation, burning, estimating the concentration of substances released during a fire. It can simulate fires in various objects, such as buildings, garages, tunnels, technical equipment (e.g., cars). It does not need to model fire to deal with gas dynamics, so it can also deal, for example, with the movement of toxic gases in fireless areas. All input data is entered using a single text input file, and the most difficult part is often to define the geometry of the modelled space. For the simulation of a fire to be as accurate as possible, it is necessary to define the geometry and properties of all, for fire and its propagation of the inevitable, bodies and holes in each space. These can then, according to their chemical and physical properties, act as an obstacle to the spread of fire and gas flow, conduct or emit heat, or burn. They can also attenuate the intensity of a fire or be inert to it (they are not affected by it and have no effect on the fire).

At the same time, for a fire model, it is necessary to enter the actual amount of material by determining the thickness of the material. To represent the inclined surfaces of bodies in a rectangular lattice, there is a technique of "smoothing" the surface, in which the system performs calculations as with an uncooled surface, but the removal of turbulences that arise near the inclined surfaces represented in the rectangular lattice is programmed. The inclined surface in this case is visualized as a smooth surface. Among the necessary input parameters for body surfaces that need to be determined are the properties of the material. In FDS, devices for measuring fire parameters such as heat released, temperature of walls, bodies, or gases at points of space or in sections, gas concentration can also be included in the simulation. One of the most important input parameters in modelling is the maximum rate of release of heat produced from 1 m^2 in fuel-controlled fires.

This paper deals with the issue of fire behaviour modelling and the possibilities of applying computer-aided modelling tools to the practice of fire protection. Based on the practical application of selected computer models to solve specific fire scenarios simulating real environmental conditions and fire and its spread, the intention of the conducted study was to point out the possibilities of applying these tools in the practice of fire protection. In this case, it was a fire on the 6th floor of block A in the main building of the Technical University in Zvolen. In addition, the task was to find out the basic parameters for the development and spread of fire and smoke, to determine the parameters of the time required for the safe evacuation of persons from the fire-threatened area.

A similar issue was addressed by Xiao et al. [11] used the PyroSim software to numerically simulate a fire situation based on the size and volume of a prefabricated building construction site to ensure the safe construction of prefabricated buildings and improve the efficiency of the safe evacuation of construction personnel after a fire caused by improper operation during construction. The variation rules of smoke visibility, CO concentration, and ambient temperature in the construction site of prefabricated buildings were analysed and the available safe evacuation time was determined. Moreover, the Pathfinder software was used for simulation in combination with the physical attributes of personnel, evacuation speed, and personnel proportions. The time required for safe evacuation was determined and the factors influencing the evacuation time, such as the quantity and location of stacked prefabricated components, machinery, and appliances, and the number of on-site construction personnel, were analysed.

2 Material and Methods

In this section, the subject and object of research are characterized, the methodology used for processing the study is described.

The object of the research was to find out the basic parameters of the development and spread of fire and smoke, which originated on the 6th floor in the main building of the Technical University in Zvolen (TUZVO), to determine the parameters of the time required for the safe evacuation of persons from the fire-threatened area using progressive tools of mathematical and computer-aided modelling of fire development and controlled evacuation procedures.

The object of research was the 6th floor in block A of the main building of TUZVO.

The main building of TUZVO is located on T. G. Masaryka Street 24, 960 01 Zvolen, Slovakia. It is used for teaching full-time and part-time students, but also for the implementation of scientific and research activities by professional employees of TUZVO.

TUZVO main building consists of 3 blocks with a different number of floors. Block A consists of 8 above-ground floors, block B 7 floors and block C 6 floors. At the same time, the main building has 1 underground floor. The structural system has been assessed as non-combustible in accordance with Article 2.6 of STN 92 0201-2 [12]. In accordance with Art. 2.2.6 STN 92 0201-2, the fire height (h) was set at 25.5 m. The legislation currently in force dealing with the fire safety of buildings does not apply to the TUZVO building, as it was built before the regulations currently in force were issued.

A total of 6 escape routes lead from the building to the open air, the number of which varies depending on the floor, which creates difficult conditions for evacuation. From the 7th and 6th floors there are 2 unprotected escape routes. From the 5th to 1st floors there are 4 unprotected escape routes. The route of unprotected escape routes leads through corridors and staircases. The building has 2 main staircases located at the interface of blocks A/B and B/C. Main staircase A/B runs from the basement to the 7th floor, between the basement and the 6th floor it has a width of 2.5 escape lanes, from the 6th to the 7th floor it has a width of 2 escape lanes. The main staircase B/C leads from the basement to the 5th floor with a constant width of 2.5 escape lanes. At the end of block A there is a backup staircase connecting the ground floor with the 7th floor with a width of 1.8 escape lanes. At the end of block A there is a second backup staircase connecting the ground floor with the 5th floor with a width of 1.6 escape lanes. From the ground floor and its classrooms, a greater number of escape routes lead to the open air in different directions.

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The following materials were used in the structures and premises of the offices and laboratories located on the 6th floor of the main building of TUZVO, block A. Vertical structures (walls) are concrete, plastered with lime cement plaster. On the floor of the laboratory there is ceramic tile. The interior of the laboratory is equipped with furniture (chairs and tables) and built-in wardrobes made of chipboard. The windows are filled with glass filling. The glass used for filling window frames is an insulating double-glazed window achieving class 2 acoustic insulation parameters and with a heat transfer coefficient of Ug=0,1 W/(m^2·K). This is a product made of two simple drawn flat panes of glass with a thickness of 4 mm. The internal dimension of the gap between the glasses is 16 mm, and the gap is filled with inert gas with argon. All entrance doors are made of chipboard, while the thickness of the door is 50 mm. The floor in the hallway is made of PVC. The floor in the offices located on the 6th floor is made up of PVC covered with carpet.

In the case of a fire simulated, we entered the heat release rate of concrete at 1,000 kW/m^2 and the plaster at 100 kW/m^2 [13]. Glass belongs to fire response class A1, i.e., non-combustible. In the simulation, we specified its heat release rate at 500 kW/m^2 [13]. For chipboard used as cladding of built-in cabinets, as well as wooden furniture located in the laboratory, we used a heat release rate value of 2,250 kW/m^2 [2] in the modelling and simulation of fire in the PyroSim.

As part of the processing of the study, the documentation (including graphic changes in the project in the AutoCAD environment) and the calculation of all parameters necessary to ensure the fire safety of the object, i.e., the main building of TUZVO, were updated. This state was also used in the process of creating a 3D model of construction in the ANSYS environment (3D model Spaceclaim and conversion to STL format, which the PyroSim program works with).

2.1 Fire model and fire scenario

Modelling and simulation of fire and smoke propagation during a fire that originated in a laboratory located on the 6th floor in block B of the main building of TUZVO were carried out in PyroSim ver. 2014.4.1105, licensed by the Department of Fire Protection, which is also the graphical user interface of the Fire Dynamics Simulator (FDS) fire model. An important input into modelling was the input of heat release rate (HRR) values for all flammable elements of structures and interior equipment. The simulation duration was set at 3.5 min, which is the maximum permissible evacuation time according to STN 92 0201-3 [14].

The fire scenario was chosen in accordance with the theme of the tactical training itself associated with the training fire alarm, which preceded the modelling process itself and the knowledge of which we used in its creation. The fire originated in the laboratory of the Department of Wood Technology, which is located near the door leading from the corridor of the 6th floor of block A to the main staircase located between blocks A/B. The fire initiating source was turned on hot air oven, which, due to a technical error, did not turn off, overheated, while its surface temperature reached 1,000 °C for 60 s. The HRR data of other combustible materials in the room have been set in accordance with [2].

The monitored parameters were the transfer of combustion (smoke) and later fire products to the corridor and to neighbouring rooms within the standard time, i.e., 3.5 min, which is necessary to ensure the safe evacuation of persons from the fire-threatened area.

2.2 Theme of the tactical training associated with the practice fire alarm

The tactical training of Fire and rescue Service officers with the management staff, which took place on 03/09/2021 from 9.00 AM, with a focus on practicing how to deploy, manage forces and resources in fire destruction and evacuate persons from the premises of the main building of TUZVO and especially the 6th and 7th floors, was also attended by TUZVO employees.

The performed tactical training had several objectives:

- Practicing the method of deploying forces, managing forces and resources in extinguishing a fire in the premises of the TUZVO building on the 6th floor of block A.
- Practicing fire management and evacuation of persons with the establishment of a control headquarters and its simultaneous functioning with TUZVO employees included in the fire-alarm directives.

- Practicing the activities of commanding and intervening Fire and Rescue Service officers from several fire stations.
- Practicing cooperation in the deployment of forces and assets of the components of the Integrated Rescue System and related to the practice of the actionability of fire brigades, equipment as well as cooperation of Fire and rescue Service officers and members of the municipality volunteer fire brigades.
- Practicing the cooperation of Fire and rescue Service officers and employees of TUZVO.
- Practicing and mastering the operational-tactical peculiarities of fire and evacuation of persons from high-rise buildings.
- Verification of the deployment of mobile altitude equipment and climbing equipment.

The tactical training focused on:

- Evacuation of persons and destruction of fire.
- Activities of the management staff of the district headquarters of Fire and Rescue Service in Zvolen.
- Cooperation with TUZVO employees.
- Cooperation, deployment of municipality volunteer fire brigades.
- Possibilities of using boarding areas.

2.3 Training fire alarm at the Technical University in Zvolen

The training fire alarm began on 03/09/2021 with the detection of the EPS smoke sensor in the laboratory of the Department of Wood Technologies, which is located on the 6th floor of the main building of TUZVO, block A.

It was signalized on the electric fire alarm (EFA) control panel, which is located on the main gatehouse of TUZVO. The gatekeeper deactivated the sensor, closed the gatehouse and the main entrance to TUZVO, and went to check the situation by the main staircase between blocks A/B. After noticing smoke, which had already penetrated the stairs and the 5th floor in the meantime, she reported the fire to the emergency call line. She briefly announced the location of the fire, what and where it was burning, the extent of the fire and smoke Subsequently, she declared a fire alarm by calling *F I R E* and using electronic fire alarms. Subsequently, he also reported the fact by telephone to the fire reporting office.

After the alarm was sounded by the call *F I R E*, there was a gradual evacuation of persons mainly from the 7th - 5th floors of blocks A and B and subsequently the entire main building of TUZVO. Meanwhile, the attending porter returned to the main gatehouse, opened the main entrance for the purpose of entering the intervening firefighters, gave them information, and then personally and manually opened the side escape exits from the main building. The evacuees gathered in the open air near the fountain, where their presence was to be checked according to the status recorded in the attendance system. In the meantime, an inspection of the abandoned premises of the main building was carried out to search for disabled persons or persons to whom information about the fire did not penetrate.

In this case, although it was supposed to be a controlled evacuation, it was gradual but spontaneous, since the change in legislation created a situation where fire patrols in workplaces were abolished, since their existence is not required by the current legislation.

2.4 Draft measures in relation to improving the level of fire safety of the main building of the Technical University in Zvolen

The measures that were proposed pursued the objective of reducing the fire risk and thus the degree of fire safety by dividing the structure into several fire compartments, since today this structure forms one fire compartment, which means that in the structure the fire and combustion fumes will spread rapidly to all its premises, since there are no elements or fire-dividing structures that would prevent the spread of fire and combustion products to other parts for the required time, which is necessary to ensure the safe evacuation of persons and, where appropriate, also property.

Optimization of procedures for the controlled evacuation of persons was carried out using the tools of mathematical modelling and at the same time compliance with the conditions set by the relevant fire standard.

3 Results and Discussion

We divided the results of the study into 3 main parts. First, we present the results of the modelling and simulation of the fire from the PyroSim, although this was realized only after the implementation of the tactical training and based on observations, identified shortcomings, and updating data on the construction solution of the structure and its and their detailed examination. Subsequently, there are introduced the findings of performed tactical training, which took place in the main building of TUZVO in September 2021. Lastly, we propose the content of the new documentation of fire safety of the structure, i.e., the main building of TUZVO, considering the most serious shortcomings that prevent the safe and timely evacuation of persons from the area threatened by fire and combustion products.

3.1 Results of fire scenario modelling and simulation

In PyroSim, we performed a simulation of the fire that originated in one of the laboratories of the Department of Wood Technologies, in the main building of TUZVO on the 6th floor of block A (Fig. 1).

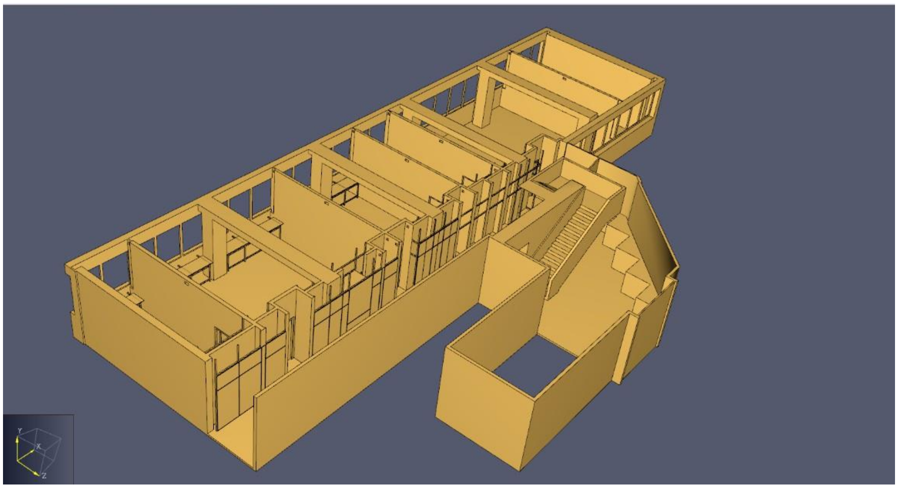

Fig. 1 3D model 3D model of the 6th floor spaces

The duration of the simulation was set to 3.5 min, which is the maximum permissible evacuation time according to the standards. The fire spread to the hallway / escape entry and was detected in the hallway / escape entry at 3.2 minutes (Fig. 2).

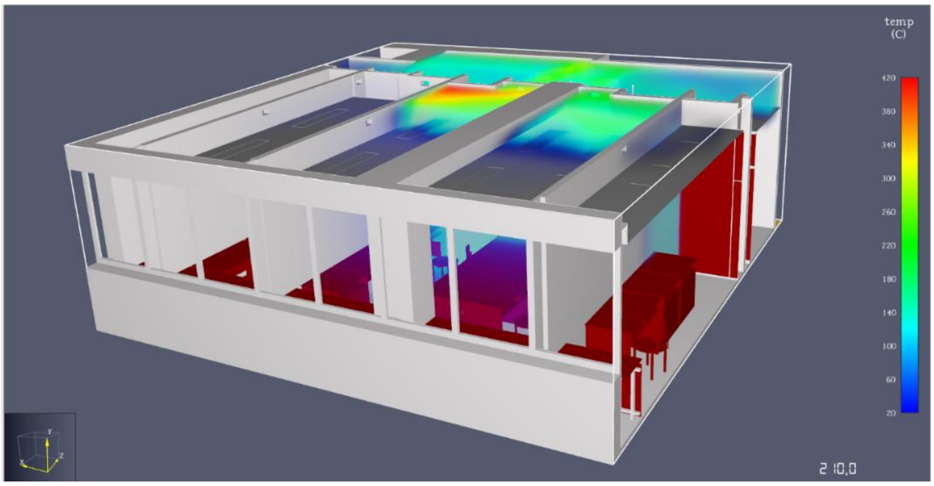

Fig. 2 Temperature zones of the fire spreading from the laboratory space to the hallway

Significant smoke and the gradual transfer of smoke to adjacent rooms were noticeable (Fig. 3, 4).

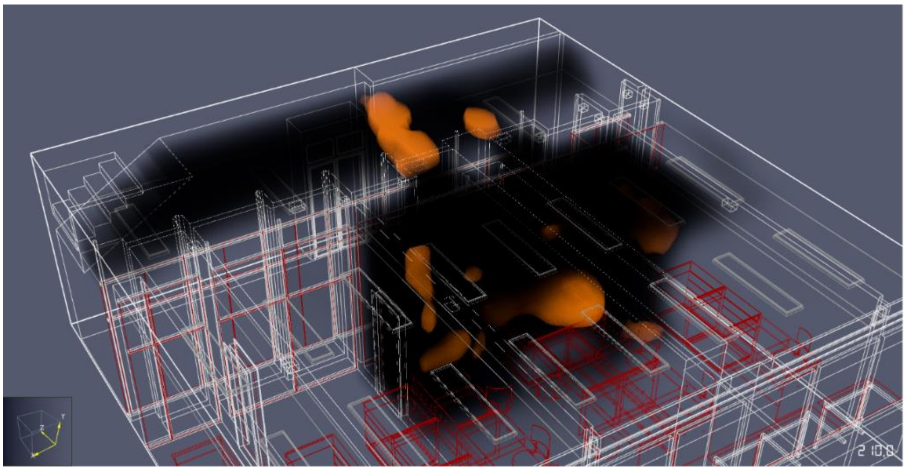

Fig. 3 Spread of smoke and fire from the laboratory to nearby rooms

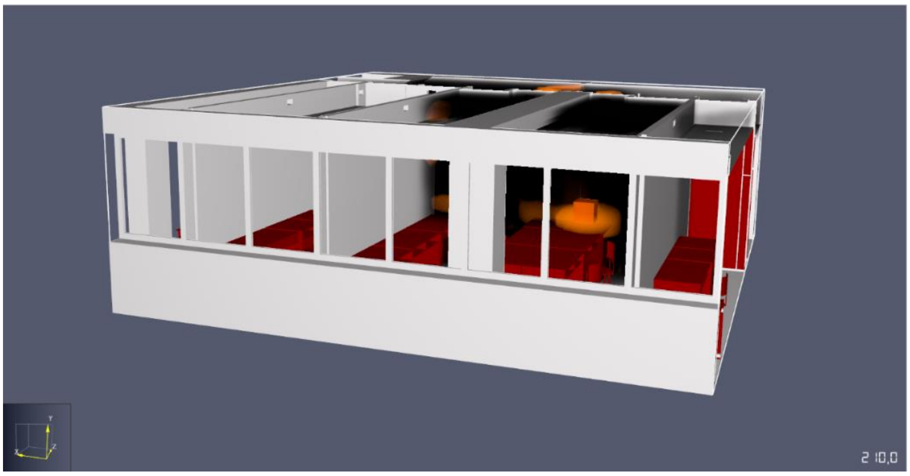

Fig. 4 Smoke transfer to other rooms

Fig. 5 shows the course of a curve representing the heat release rate (HRR) in space over the entire duration of the fire observed.

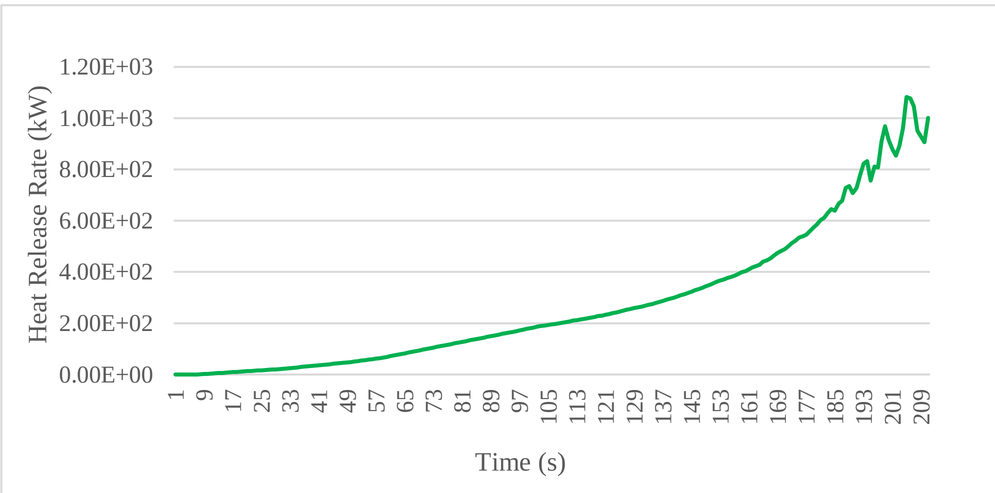

Fig. 5 The course of the heat release rate in an interval of up to 210 s

As seen from the course of the HRR curve, in the standard maximum time for the evacuation of persons from the fire-endangered area, i.e., 3.5 min (210 s), there is a significant increase in the rate of heat release, heating of surrounding combustible materials, increasing the values of total heat released (Fig. 6), the release of volatile substances and the subsequent spread of fire from source to surroundings. Of course, this is also related to the increasing formation of combustion products, which are toxic to the persons found in this environment.

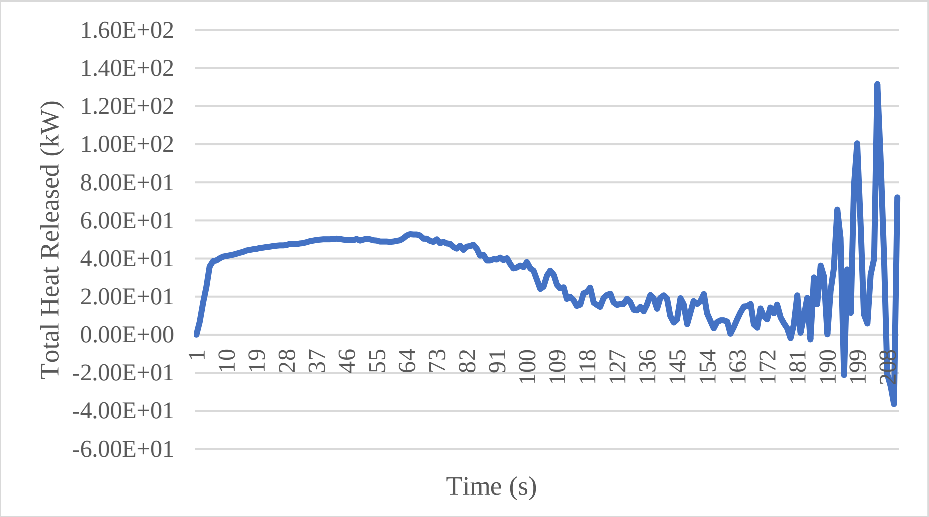

Fig. 6 Total heat release up to 210 s

In general, the heat release rate varies with time depending on the heat of fuel gasification and is directly proportional to the rate of burning.

The course of fuel burning rate values is shown in Fig. 7.

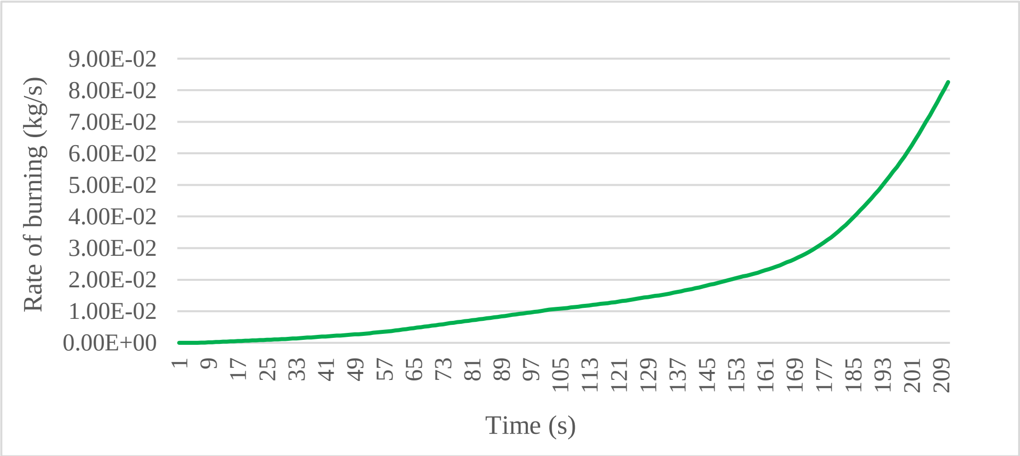

Fig. 7 Fuel burning rate up to 210 s

Fig. 8 presents the course of enthalpy values over time. These values follow the shape of a curve representing the course of the heat released rate, while these values increased significantly from approximately 193 s.

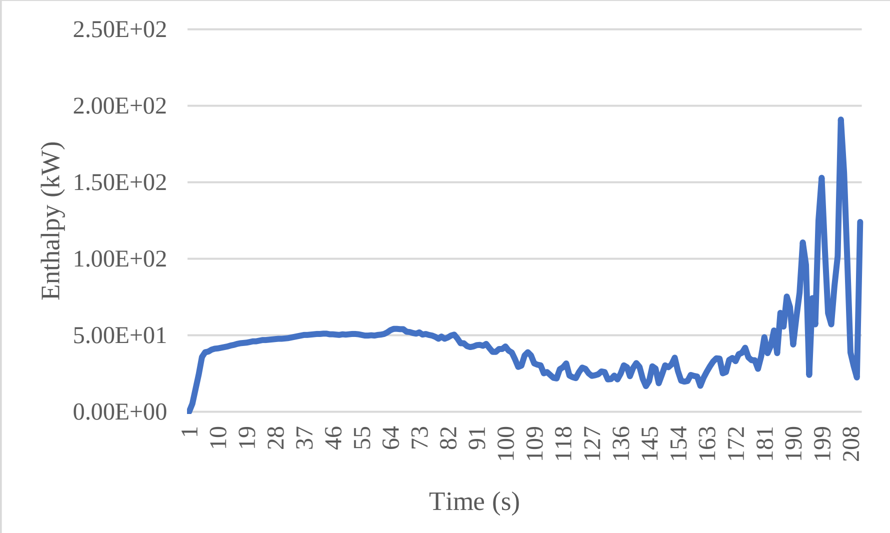

Fig. 8 Enthalpy values course

The results of the simulations presented here relate only to a time interval of 121 s (3.5 min), which is critical to ensuring the safe evacuation of persons. When observing the further development of the fire, we would also obtain additional information that is necessary for understanding the behaviour of the fire, the spread of combustion products in the space. These are more important at any given moment for the needs of designing the fire safety of buildings, for the identification of weak points in the construction, the design of suitable and effective fire-separating structures, shutters. From the point of view of evacuation, it is assumed that persons will already be evacuated from the area at a given time. At this point, the fire extinguishing work begins. Modelling the behaviour of fire after this interval also makes sense from the point of view of the safety of the intervening fire brigades, especially in terms of their potential intoxication with fire-produced combustion products.

3.2 Findings from the performed tactical training

The tactical training of officers of the Fire and Rescue Service with the management staff establishment took place on 03.09.2021. The focus was concerned to practice how to deploy, manage forces and resources when extinguishing fire and evacuating persons from the premises of the Technical University in Zvolen. The employees of TUZVO were also active participants of this training.

In this section, we present the findings of the performed tactical training, in the form of identified risk situations/states and the proposal of measures aimed at improving the current situation.

3.2.1 Getting of information about the fire and its further distribution

The subject of the training fire alarm assumed the detection of the fire by the smoke sensor of the electric fire alarm (EFA) with subsequent signalizing to the main gatehouse of TUZVO (also the fire alarm office) and the subsequent procedure of the gatekeeper in accordance with TUZVO internal fire safety documentation.

The following situations have been identified as risks related to the distribution of fire information:

- Absence of an operator at the workplace – toilet, inspection of the building, etc.
- Sighting of a fire by a natural person not using a detector but directly reporting it to the emergency call line.
- Occurrence of a fire in a place unprotected by EFA.

Based on the findings of the performed tactical exercise, the training alarm in the main building of TUZVO, the following measures were proposed.

- Re-assess the current form of safety and the subsequent internal processes after the sighting/reporting of a fire, focusing on the complexity of the measures, with particular regard to sufficient staffing of the initial measures – immediately after receiving the report, processes

should be started by several routes so that they are not tied to a single person, e.g. the porter / operator receives the report, immediately informs 3-4 other persons with specific tasks (e.g. open escape exits, provide lifts, inform the competent persons in the management) only then go to check the reported fire, after confirmation of the fire, followed by the declaration of an alarm for evacuation and the initial extinguishing intervention by designated employees.
- Extended EFA interface – e.g., opening of escape exits, illumination of the light signalizing of escape exits and direction of escape, activation of the sound of the internal radio using a sound loop, etc.

3.2.2 Put on the alarm, evacuation, escape and verification of the completeness of the evacuees

The alarm put on is realized only by shouting "F I R E" without the use of technical means with the absence of light signalizing.

Additional risks in this regard can be identified as:

- Information about the occurrence of a fire, put on the alarm with the need for evacuation does not reach all persons in the premises.
- Some of the persons ignore the alarm and remain in the object.
- There is no information about the number of persons located in the premises.
- In locked offices it is impossible to conduct a survey without forcibly entering.
- Private passenger cars parked on the so-called boarding areas and access roads for firefighting equipment form an obstacle.

Several measures have been proposed to improve the current situation:

- Reconsider the current form of putting on alarm using several forms, including sound and optical technical means (e.g., internal radio allowing controlled evacuation, light signalizing of the direction of escape and escape exits).
- Increase the intensity of staff training with an emphasis on evacuation under the new rules, including a reassessment of the modification of the job description, focusing on specific responsibilities and substitutability.
- Introduce a registration system of the number of persons in the building, including monitoring of individual entrances but also escape exits (e.g., infrared sensor at individual entrances and exits ensuring continuous monitoring of the number of persons in the building with the exit to several workplaces of superiors – no identification of an individual is required, an indication of the number of persons in the object expressed by an absolute number is sufficient).
- To conduct a regular training of fire alarm associated with the evacuation of all employees.
- Propose parking rules for private passenger cars with unambiguous user identification so that keys or a driver can be obtained if parking is necessary.
- Escaping persons should be concentrated in an area not restricting fire-extinguishing intervention so that when coordinating the evacuation, the space is individually determined by the evacuated sectors.

3.2.3 Constructions, technical solution, and condition of the building

The building consists of a single fire compartment with an extremely high number of cavities, heat transfers and combustion products as well as hidden paths of spread of fire and especially smoke.

The following situations are evaluated as a risk:

- Fire, and in particular combustion fumes, may spread uncontrollably throughout the building.
- Escape routes do not provide protection against fire, the capacity of escape routes does not correspond to the current number of persons in the building.
- Elevators do not have the character of fire or evacuation lifts and in the event of a power outage or deliberate shutdown without prior control, there is a risk of persons being trapped in the cabins.
- High fire loads on escape routes encouraging the spread of fire,
- High fire loads or impossibility of entering alternative escape options.

To improve the status quo, it is necessary:

- Reconsider building modifications aimed at creating protected escape routes on staircases and creating separate fire compartments on individual floors.
- Reconsider the possibilities of increasing the capacity of escape routes.
- Reconsider the possibilities of reconstructing elevators into fire or evacuation elevators.
- Reconsider the possibilities of reducing the fire load on escape routes (hallways, corridors).
- Reconsider building modifications reducing the number and interconnectedness of cavities by changing building materials and sealing penetrations with the required fire resistance.
- Free up all areas usable as replacement escape options (balconies, loggias, etc.).

It is necessary to deal with individual areas in interconnectedness, however, any area solved individually represents an increase in the safety of persons in the building, and for this reason we recommend the immediate adoption of measures depending on the implementation possibilities of TUZVO.

3.3 Proposal for measures to ensure the fire safety of the structure and the safe evacuation of persons

The content of this sub-chapter only provides an assessment of the current state of the main building of TUZVO with a proposal for possible measures to correct the identified shortcomings.

3.3.1 Fire compartments

The TUZVO building currently represents one fire compartment covering all above ground and underground floors. The legislation currently in force dealing with the fire safety of buildings does not apply to the TUZVO building, since it was built before the current regulations were issued. However, from the point of view of safety, the current state of the building is unsatisfactory.

Therefore, based on the findings of the conducted tactical exercise associated with the training fire alarm and the evacuation of persons from the main building of TUZVO, as well as calculations (evacuation time and permissible size of fire compartments), in accordance with the current legislation, in order to ensure the greatest possible safety of the structure, it is necessary to divide the structure into several fire compartments, where each floor and each staircase would constitute a separate fire section.

Recommended division of the structure into fire compartments:

Fire compartment N7.01 – 7th floor (8th above ground floor)
Fire compartment N6.01 – 6th floor (7th above ground floor)
Fire compartment N5.01 – 5th floor (6th above ground floor)
Fire compartment N4.01 – 4th floor (5th above ground floor)
Fire compartment N3.01 – 3rd floor (4th above ground floor)
Fire compartment N2.01 – 2nd floor (3rd above ground floor)
Fire compartment N1.01 – 1st floor (2nd above ground floor)
Fire compartment N0.01 – ground floor block A (1st above ground floor)
Fire compartment N0.02 – ground floor block C (1st above ground floor)
Fire compartment N0.03 – classroom B4
Fire compartment N0.04 – classroom B5
Fire compartment N0.05 – classroom B6
Fire compartment N0.06 – classroom B7
Fire compartment N0.07 - 7.07 – Protected escape route block A (alternate staircase block A)
Fire compartment N0.08 - 7.08 – Protected escape route block ABC (main staircases between blocks A/B and B/C including corridor on the ground floor)
Fire compartment N0.09 - 5.09 – Protected escape route block C (alternate staircase block C)
Fire compartment of elevator shafts

3.3.2 Fire risk

The fire risk in a non-production structure is expressed by the calculation fire load within the meaning of § 33 Decree of the Ministry of Interior of the Slovak Republic No. 94/2004 Coll. [15]. Due to the current state – the entire TUZVO building is one fire compartment, the fire risk was calculated at 36.9 kg/m^2. For the designed fire compartments, the calculation fire load would be as follows:

p_v (Fire compartment N7.01) = 21.99 kg/m^2
p_v (Fire compartment N6.01) = 26.36 kg/m^2
p_v (Fire compartment N5.01) = 28.86 kg/m^2
p_v (Fire compartment N4.01) = 36.19 kg/m^2
p_v (Fire compartment N3.01) = 37.13 kg/m^2
p_v (Fire compartment N2.01) = 37.58 kg/m^2
p_v (Fire compartment N1.01) = 35.60 kg/m^2
p_v (Fire compartment N0.01) = 33.75 kg/m^2
p_v (Fire compartment N0.02) = 28.27 kg/m^2
p_v (Fire compartment N0.03) = 37.36 kg/m^2
p_v (Fire compartment N0.04) = 38.36 kg/m^2
p_v (Fire compartment N0.05) = 39.79 kg/m^2
p_v (Fire compartment N0.06) = 40.83 kg/m^2

For protected escape routes, it is necessary to ensure that the accidental fire load is not more than 15 kg/m^2.

3.3.3 Size of fire compartments

The permissible area of the fire compartment is determined in accordance with § 4, par. 1, letter b) and par. 4, Decree of the Ministry of Interior of the Slovak Republic No. 94/2004 Coll. [15], according to equation 36 and Article 4.1.1 in STN 92 0201-1 [12]. For the entire building, the permissible size of the fire compartment is as follows:

$$S_{max} = 2{,}120\ m^2 \leq 12{,}490\ m^2$$

The permissible size of the fire compartment does not suit. Therefore, it is necessary to divide the structure into smaller sections. In the case of the proposed division, the condition is met, since the maximum area of the floor is 2,044 m^2, which is less than the maximum permissible area.

3.3.4 Determining the degree of fire safety of the building

The degree of fire safety of the fire compartment was determined in accordance with § 37, par. 5, Decree of the Ministry of Interior of the Slovak Republic No. 94/2004 Coll. [15], Article 3.3 and Table 3 in STN 92 0201-2 [12]. The fire compartment of the entire building is currently classified in the 3rd degree of fire safety (DFS). In the case of the recommended division of the structure into fire compartments, the stages are as follows:

Fire compartment N7.01 – 2nd FSD
Fire compartment N6.01 – 2nd FSD
Fire compartment N5.01 – 2nd FSD
Fire compartment N4.01 – 3rd FSD
Fire compartment N3.01 – 3rd FSD
Fire compartment N2.01 – 3rd. FSD
Fire compartment N1.01 – 3rd FSD
Fire compartment N0.02 – 2nd FSD
Fire compartment N0.03 – 3rd FSD
Fire compartment N0.04 – 3rd FSD
Fire compartment N0.05 – 3rd FSD
Fire compartment N0.06 – 3rd FSD
Fire compartment N0.07 – 7.07 – 3rd FSD
Fire compartment N0.08 – 7.08 – 3rd FSD
Fire compartment N0.09 – 5.09 – 3rd FSD
Fire compartment of elevator shafts – III. FSD

3.3.5 Determination of requirements for structural elements in the building

In Tab. 1, there are introduced the minimum requirements for constructions, which the building should meet.

Tab. 1 Minimum requirements for structural elements in the building

Item	**Structural element**	**Type of structural element and lowest fire resistance (min)according to FSD**	
		2nd	3rd
1	**Fire walls and fire ceilings:**		
	(a) on underground floors	60/D1	90/D1
	(b) on above-ground floors	45	60
	(c) on the last floor	30	45
2	**Enclosure walls:**		
	(a) ensuring the stability of a structure or part thereof:		
	1. in underground floors from the inside of the wall	60/D1	90/D1
	2. on the above-ground floors	45	60
	3. on the last floor	30	45
	(b) not ensuring the stability of the structure or part thereof	30	45
3	**Roof cladding:**	30	45
4	**Fire stoppings for openings:**		
	(a) on underground floors and on all floors between structures	45/D1	45/D1
	(b) on above-ground floors	30	45
	(c) on the last floor	30	30
5	**Supporting structures of staircases inside the fire compartment which are not part of the protected escape routes:**	15	30/D2
6	**Shafts and channels:**		
	(a) Fire compartmentation structures:		
	1. Shaft of evacuation and fire elevators	According to item 1	
	2. Shafts of other lifts	30/D1	45/D1
	3. Plumbing shafts and channels	45/D1	60/D1
	fire stoppings for openings in fire compartmentation structures:		
	1. Shaft of evacuation and fire elevators	According to item 4	
	2. Shafts of other lifts	30/D1	30/D1
	3. Plumbing shafts and channels	45	60/D1
7	**Load-bearing structures of roofs without fire subdivision function:**	30	45
8	**Load-bearing structures inside the structure, which ensure the stability of the structure:**		
	(a) on underground floors	60/D1	90/D1
	(b) on above-ground floors	45	60
	(c) on the last floor	30	45
9	**Load-bearing structures inside the fire compartment not ensuring the stability of the structure:**	30/D2	45/D2
10	**Load-bearing structures inside the fire compartment ensuring the stability of the structure:**	30	45

It is necessary to carry out an inspection of the ceiling structures and project precautions to prevent smoke and fire from passing between floors when a fire.

3.3.6 Spacing distances

Spacing distances are determined in accordance with § 80, par. 1 and par. 2 of the Decree of the Ministry of Interior of the Slovak Republic 94/2004 Coll. and pursuant to Art. 5.3.1 in STN 92 0201-4. Due to the current situation, where TUZVO has only one fire compartment, the separation distance from the main building along the entire height of the structure is 22.5 m. This is a large area that covers parking places around the building, adjacent grassy areas, technical areas, and park. Therefore, it is very likely that the fire will be extended to those adjacent areas.

However, if the structure were to be divided into fire compartments along the floors, the spacing distances would be reduced to 6 m for the entire 7th to 5th floors and 7 m for the entire 4th to 1st floors. The spacing distance for the ground floor is set up to 10.5 m due to the danger of falling particles.

3.3.7 Ensuring the evacuation of persons, determining the requirements for escape routes

The description of the escape routes that we considered when assessing the current state of evacuation has already been described in section Material and Methodology. Here we only provide descriptions of the necessary measures that must be implemented to to safely evacuate persons in the fire situation.

The number of persons who can be inside the building during the week, i.e., the workdays, is based on the current staffing and the capacity of the classrooms.

Ensuring the evacuation from the 1st to 7th floors is a key requirement. From the ground floor there are several possible evacuation routes, therefore the presence of persons on the ground floor is not considered in the calculation of the evacuation time of the TUZVO main building.

The calculation of the evacuation time is based on STN 92 0201-3, and a partial method of calculations upstairs was used. The number of persons to be evacuated from the considered floors is 1,433, which represents the maximum capacity of the school during teaching and the maximum occupancy of all lecture rooms and offices.

The first to count was the time of evacuation of persons from individual floors to the entrance to the staircase. Subsequently, the evacuation of persons from the building by individual staircases was gradually calculated. The resulting evacuation time is expressed by the sum of the worst evacuation time from each floor and the time of evacuation by staircase.

The 1st floor turned out to be the worst, since the most persons (339 persons) can be located there, due to the large number of classrooms. The resulting evacuation time was 2.52 min. The results of calculations related to evacuation by the staircases is shown in Tables 2-5:

Tab. 2 Calculation of evacuation time when using staircase A – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	42	1.8	10.9	25	30	1	**0.44**	0.78
6th – 5th floor	95	1.8	10.9	25	30	1	**0.44**	1.76
5th – 4th floor	169	1.8	10.9	25	30	1	**0.44**	3.12
4th – 3rd floor	213	1.8	10.9	25	30	1	**0.44**	3.95
3rd – 2nd floor	243	1.8	10.9	25	30	1	**0.44**	4.50
2nd – 1st floor	270	1.8	9.8	25	30	1	**0.39**	5.00
1st – Ground level	334	1.8	10.7	25	30	1	**0.43**	**6.18**
Ground level	334	1.8	2.0	30	40	1	**0.07**	4.64
			Total evacuation time (min)					**9.25**

Tab. 3 Calculation of evacuation time when using staircase A/B – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	47	2	8.7	25	30	1	**0.35**	0.78
6th – 5th floor	120	2.5	13.4	25	30	1	**0.54**	1.60
5th – 4th floor	252	2.5	13.4	25	30	1	**0.54**	3.36
4th – 3rd floor	355	2.5	13.4	25	30	1	**0.54**	4.74
3rd – 2nd floor	420	2.5	13.4	25	30	1	**0.54**	5.61
2nd – 1st floor	485	2.5	13.4	25	30	1	**0.54**	6.46
1st – Ground level	646	2.5	11.4	25	30	1	**0.46**	**8.61**
Ground level	646	3.72	18.0	30	40	1	**0.60**	4.34
				Total evacuation time (min)			**12.70**	

Tab. 4 Calculation of evacuation time when using staircase B/C – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
5th – 4th floor	48	2.5	14.9	25	30	1	**0.60**	0.64
4th – 3rd floor	135	2.5	14.9	25	30	1	**0.60**	1.80
3rd – 2nd floor	195	2.5	14.9	25	30	1	**0.60**	2.59
2nd – 1st floor	254	2.5	14.9	25	30	1	**0.60**	3.39
1st – Ground level	352	2.5	12.9	25	30	1	**0.52**	**4.69**
Ground level	352	2.9	35	30	40	1	**1.17**	3.03
				Total evacuation time (min)			**8.76**	

Tab. 5 Calculation of evacuation time when using staircase C – current situation

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
5th – 4th floor	12	1.6	10.6	25	30	1	**0.42**	0.24
4th – 3rd floor	23	1.6	10.6	25	30	1	**0.42**	0.49
3rd – 2nd floor	53	1.6	10.6	25	30	1	**0.42**	1.11
2nd – 1st floor	76	1.6	10.6	25	30	1	**0.42**	1.58
1st – Ground level	97	1.6	10.5	25	30	1	**0.42**	**2.02**
Ground level	113	1.6	2	30	40	1	**0.07**	1.76
				Total evacuation time (min)			**4.20**	

Where:

E – number of persons,
u – number of escape lanes on the escape route in accordance with STN 92 0201-3,
l_u – length of the evacuation route (m),
v_u – speed of movement of persons ($m \cdot min^{-1}$) in accordance with STN 92 0201-3,
K_u – capacity of the escape lane in accordance with STN 92 0201-3,
s – coefficient of evacuation conditions in accordance with STN 92 0201-3,
l_u/v_u – time of movement of persons (min),
$E*S/K_u*u$ – expected delay of persons due to evacuation conditions.

The A/B staircase proved to be the least suitable for the needs of evacuation of persons, as it accounts for the largest number of evacuees (646), since it covers the block A, the 7th floor and is the only staircase for the 6th floor of block B, too.

The resulting evacuation time is the sum of evacuation times up staircase A/B and evacuation from the 1st floor, i.e., 12.7 + 2.52 min = 15.22 min. This time is unsatisfactory, because the standard STN 92 0201-3 allows an evacuation time of only 3.5 min under these conditions.

Since the construction is built as one fire section, the critical situation that can occur is the shutdown of the A/B staircase due to severe smoke. Thus, block A would be reliant only on the alternate staircase, which would significantly prolong the evacuation, which could have fatal consequences. The estimated evacuation time without using the A/B staircase is 3.42 + 17.62 = 21.04 min. While the critical point is the 1st floor again, where there is no other escape option on the alternate staircase in block A, persons could stay up to 14.56 min. Critical place is also the 6th floor of block B, where persons on this floor would be forced to use an alternative escape option, which would have to be additionally created by Fire and Rescue Service forces on the spot.

Even in the case of modification of evacuation plans, it is not possible to carry out evacuation from the building within 3.5 minutes. The permissible evacuation time can be increased by building protected escape routes. Within the TUZVO building, it is possible to build protected escape routes of type A from all staircases. The backup staircases lead almost to the open space, the problem is the main staircases that lead to the ground floor of block B. Thus, the culmination of the protected escape routes could be carried out using the secondary entrance at classroom B3 and through the main entrance at the gatehouse.

Such an arrangement of escape routes makes it possible to increase the maximum permissible time for evacuation in accordance with STN 92 0201-3 to 13.5 min, of which 3.5 min falls on the evacuation of individual floors and 10 minutes for the evacuation of persons down staircases.

Considering current building arrangement, the time required for evacuation from individual floors to the entrances to the staircase is observed, since the maximum time is 2.52 min. However, the maximum permissible evacuation time up staircase A/B, where the time is increased by 2.7 min compared to the permissible value, is not observed. The time of evacuation up the A/B staircase is the highest, as the main strain is placed on it. The evacuation time can only be reduced by lightening the A/B staircase so that the load on the staircases is equalized as far as possible. This was achieved by arranging the movement of persons so that block A uses staircases A and A/B. Block B would primarily use staircase B/C and block C would use the alternate staircase C. The resulting evacuation times can be seen in Tables 6-9:

Tab. 6 Calculation of evacuation time when using staircase A – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	41	1.8	10.9	25	30	1	**0.44**	0.76
6th – 5th floor	94	1.8	10.9	25	30	1	**0.44**	1.74
5th – 4th floor	169	1.8	10.9	25	30	1	**0.44**	3.13
4th – 3rd floor	225	1.8	10.9	25	30	1	**0.44**	4.17
3rd – 2nd floor	264	1.8	10.9	25	30	1	**0.44**	4.89
2nd – 1st floor	293	1.8	9.75	25	30	1	**0.39**	5.43
1st – Ground level	349	1.8	10.7	25	30	1	**0.43**	**6.46**
Ground level	349	1.8	2	30	40	1	**0.07**	4.85
Time of movement of persons (min) / Total evacuation time (min)							3.06	9.53

Tab. 7 Calculation of evacuation time when using staircase A/B – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
7th – 6th floor	48	2	8.7	25	30	1	**0.35**	0.80
6th – 5th floor	121	2.5	13.4	25	30	1	**0.54**	1.61
5th – 4th floor	222	2.5	13.4	25	30	1	**0.54**	2.96
4th – 3rd floor	273	2.5	13.4	25	30	1	**0.54**	3.64
3rd – 2nd floor	305	2.5	13.4	25	30	1	**0.54**	4.07
2nd – 1st floor	340	2.5	13.4	25	30	1	**0.54**	4.53
1st – Ground level	437	2.5	11.4	25	30	1	**0.46**	**5.83**
Ground level	437	3.7	18	30	40	1	**0.60**	2.94
Time of movement of persons (min) / Total evacuation time (min)							4.08	9.91

Tab. 8 Calculation of evacuation time when using staircase B/C – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
5th – 4th floor	59	2.5	14.9	25	30	1	**0.60**	0.79
4th – 3rd floor	141	2.5	14.9	25	30	1	**0.60**	1.88
3rd – 2nd floor	189	2.5	14.9	25	30	1	**0.60**	2.52
2nd – 1st floor	243	2.5	14.9	25	30	1	**0.60**	3.24
1st – Ground level	388	2.5	12.9	25	30	1	**0.52**	**5.17**
Ground level	388	2.9	35	30	40	1	**1.17**	3.34
Time of movement of persons (min) / Total evacuation time (min)							4.07	9.24

Tab. 9 Calculation of evacuation time when using staircase C – proposal

Route/coefficient	E	u	l_u	v_u	K_u	s	l_u/v_u	$E*s/K_u*u$
5th – 4th floor	30	1.6	10.6	25	30	1	**0.42**	0.63
4th – 3rd floor	106	1.6	10.6	25	30	1	**0.42**	2.21
3rd – 2nd floor	164	1.6	10.6	25	30	1	**0.42**	3.42
2nd – 1st floor	218	1.6	10.6	25	30	1	**0.42**	4.54
1st – Ground level	259	1.6	10.5	25	30	1	**0.42**	**5.40**
Ground level	259	1.6	2	30	40	1	**0.07**	4.05
Time of movement of persons (min) / Total evacuation time (min)							2.18	7.58

Through the redistribution and arrangement of the movement of persons, it was possible to reduce the evacuation time through the protected escape route to less than 10 min. Thus, the resulting evacuation time of the building was reduced to 3.42 + 9.91 = 13.33 min.

The area of the protected escape routes allows all evacuees pertaining to the escape route to stay simultaneously in the escape route area, thus ensuring their protection.

To create protected escape routes, it is necessary to carry out certain structural modifications in the spaces of the landings on each floor, namely the delimitation of staircases and stair landings, to achieve the fire resistance of the structures bounding the EI 60 protected escape routes. Fire doors with resistance EI-CSa 30/D1 or EI-CSa 45/D1 shall be installed at the entrances to protected escape routes.

It is also necessary to provide artificial ventilation, which will ensure the supply of fresh air to the protected escape route in the opposite direction of the escape route for at least 20 min.

On individual floors it is necessary to install equipment to coordinate the evacuation of persons.

In conclusion, it should be noted that standard STN 92 0201-3 states that structures with a fire height of more than 22.5 m must have at least one protected escape route type B. This type of protected escape route would require extensive structural modifications to be carried out in the construction and is difficult to implement for the needs of TUZVO. Regardless, four protected escape routes are quite sufficient and will significantly improve the conditions for evacuation from the building.

4 Conclusions

The paper deals with the issue of the application of computer-aided modelling tools in the practice of fire protection.

The main purpose of the implemented study was, based on the practical application of selected computer models for solving specific fire scenarios, simulating fire and its spread under real conditions, to point out, in a selected case, the possibilities of applying these tools in the practice of fire protection. In this case, it was a fire on the 6th floor of block A in the main building of the Technical University in Zvolen. In addition, the task was to determine the basic parameters for the development and spread of fire and smoke, to determine the parameters of the time required for the safe evacuation of persons from a fire-endangered area.

For the purposes of modelling and simulating the spread of fire in the space, the PyroSim licence was purchased, in which a fire simulation was carried out, the extinguishing of which and the simultaneous evacuation of persons from the area threatened by fire was the subject of a tactical exercise, which was carried out together with a practice fire alarm and the evacuation of the main building of TUZVO on 03/09/2021 from 9.00 AM. The knowledge gained from this tactical exercise, which used smoke detectors to simulate the spread of smoke in the interior of block A of the TUZVO main building, was also used in the creation of a fire scenario simulated in PyroSim.

The theme of the tactical exercise, its preparation and evaluation were part of the implemented study.

Based on the knowledge and experience from the tactical exercise, which were also confirmed by the results of modelling and simulation of fire behaviour, risks were identified, and measures were proposed for activities in terms of three aspects of ensuring the safety of persons in fire situation:

- Distribution of information about the fire and subsequent measures taken by employees,
- Putting on alarm, evacuation, escape and verification of number of evacuees,
- Construction-technical solution and condition of the building.

At the same time, as part of the study, the fire safety documentation of buildings was prepared, in which the main building of TUZVO is no longer a single fire section, but is divided into several fire sections, which made it possible to shorten the time for the safe evacuation of persons and also to reduce the size of spacing distances, which it is of great importance, especially from the point of view of identifying places suitable for the temporary concentration of evacuees.

The results of the study bring several practical solution topics in relation to ensuring the fire safety of buildings. The tools of computer-supported, but also mathematical modelling is a progressive tool enabling low-cost creation of fire scenarios, their modelling, analysis of results in relation to the basic parameters of fire dynamics, which enable understanding of fire behaviour and the search for suitable preventive measures or solutions from the point of view of fire safety design of buildings, especially of school facilities.

However, the results presented here are also applicable in the field of determining the causes of fires.

Acknowledgments

This research was funded by the Slovak Research and Development Agency, grant number APVV-17-0005 (70 %) and APVV SK-CN-21-0002 (30%)

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ISSN 1337-0863 (print)
ISSN 2585-9730 (online)