Key Engineering Materials
ISSN: 1662-9795, Vol. 952, pp 83-93
doi:10.4028/p-4F8ed8

Submitted: 2023-02-01
Accepted: 2023-05-02
Online: 2023-08-18

Experimental Investigation of the Flammable Properties and Factors of Wooden Products Exposed to the Fire Impact

DUBININ Dmytro[1,a*], LISNIAK Andrei[1,b], SHEVCHENKO Serhii[1,c], GAPONENKO Yuri[1,d]

[1]National University of Civil Defence of Ukraine, 94, Chernishevska str., Kharkiv, 61023, Ukraine

[a]dybinin@nuczu.edu.ua, [b]ptarr@nuczu.edu.ua, [c]shevchenkosn@nuczu.edu.ua, [d]gaponenkoyurii66@gmail.com

Keywords: thermal decomposition, pyrolysis zone, char layer, depth of char, OSB and WPB.

Abstract. Consideration was given to the issue of the integrated evaluation of the flammable properties and factors of wooden products (Oriented Strand Boards, OSB and Wood Particle Boards, WPB) as basic flammable construction materials exposed to the action of fire. The experimental data obtained for flammable wooden products during the experiments carried out to define the dependence of temperature on the time of fire impact, to measure and substantiate the charring depth of wooden products, to determine degradation zones affected by fire and their sizes (area, width and length) and to compare a change in the specimen mass before and after the tests have been given. The experimental data confirm and substantiate the pyrolysis processes of wooden products during the fire spread.

1 Introduction

To achieve energy independence, the EU countries have approved the long-term “Roadmap 2050” plan for the countries with underdeveloped economy to reduce the emission of carbon into the environment [1, 2]. In this context, the construction sector has short-term and long-term prospects for the reduction of carbon emissions due to the selection of the materials with a low effect on the environment and also due to the selection of energy-efficient structures [3, 4, 5]. An extended use of wooden products is a part of the solution of the problems relating to the ensurance of the energy-efficiency for this plan. However, from the standpoint of environmental situation it raises many questions [6-10]. In addition, the use and operation of wooden products as construction materials demands the observation of the fire safety requirements. Summarizing the above, we can state that the problems of environmental ecology and fire safety of wooden products are of vital importance and require additional research.

Research papers [11, 12] state that the wood pyrolysis results in the formation of the wood char and also liquid and gaseous products. Liquid products leave the hot zone partially in the drop phase partially in vapors and in combination with uncondensed gases form the steam-gas mixture. The most extended class of solid combustible materials smoldering in this way includes wood, paper and other lignocellulosic products [13, 14]. It is known that the pyrolysis includes certain changes in the chemical structure of the solid combustible material due to the heat impact [15]. In addition, the authors of the papers [16-18] also carried out the investigations to predict the fires in the premises that pose a threat to the life and health of people [19, 20]. Therefore, the ensurance of the human security is the primary task of the fire rescue units that arrive at the place of call [21-22].

Figure 1 depicts physical and chemical changes during the material pyrolysis [23]. It should be noted that the composition and properties of pyrolysis products are primarily affected by the type of wood and its quality, the size of the raw material particles and the initial moisture content in the raw material, the rate of heating, the time of exposure of the raw material to any given temperature, final heating temperature, the circulation rate of the gas flow through the wooden layer and other factors.

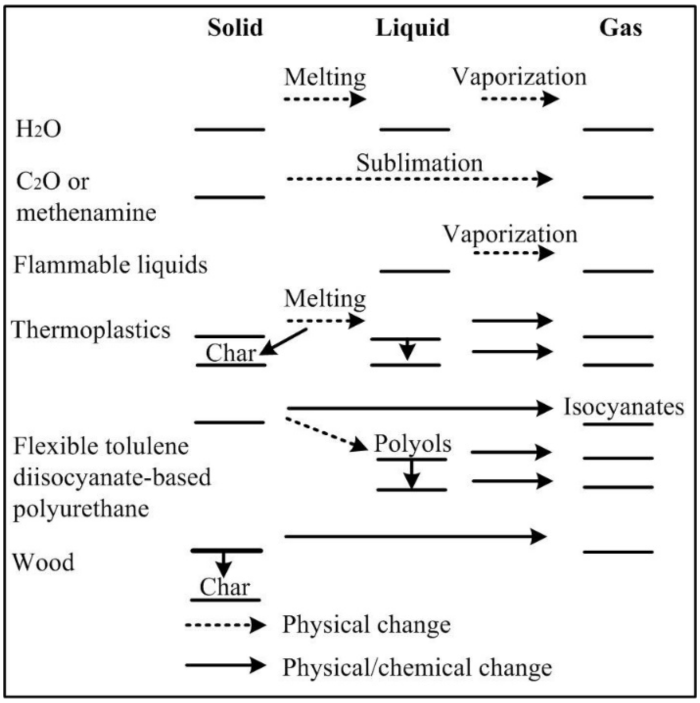

Fig. 1. Physical and Chemical Changes During Thermal Decomposition [23]

The charred material can be detected during inside fires [24]. The charred flammable material (wood) shows the cracks and blisters. To carry out investigations of the fire spread in this area, we use the methods [23] based on the determination of the charring depth of solid flammable materials (Fig.2) [23]. Let's give consideration to the papers delving into the research of this subject-matter.

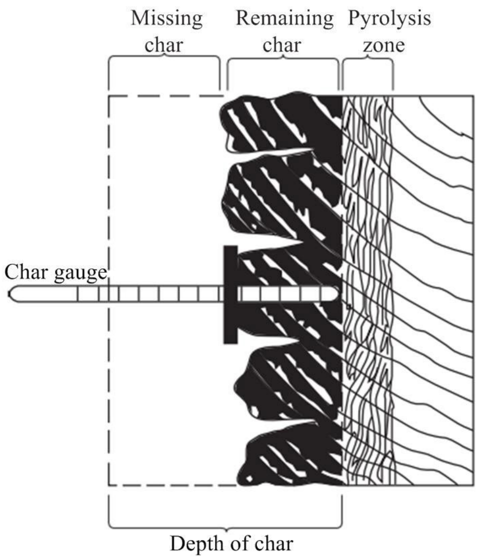

Fig. 2. Measuring the depth of char [23]

Paper [25] describes the experimental studies using WPB specimens exposed to the fire impact. The obtained test data show that the charring height and the area are increased with an increase in the heat release rate, however the experimental time has no essential effect on these parameters. The charring depth and volume are increased both with an increase in the experimental time and the heat release rate. However, these experiments were carried out taking into consideration the impact of flame incoming from the ventilation channel. In this case, the fire spread occurs with no effect of external factors (the openings in the premises) and it differs significantly from the spread of the inside fire.

The authors of the paper [26] carried out investigations to define a change of temperature inside the compartment and also the height of the flame that goes through compartment openings. Based on the research done and the data obtained we suggest a general model that characterizes the height of the external flame for the compartments of a different scale with the specified nondimensional rate of the release of the excess heat taking into account the size of openings and the temperature in the upper part inside the compartment. However, the research done deals only with a change in the temperature inside the compartment, though the flame height and a change in the structure of the solid flammable material during the fire spread in the compartment were not taken into consideration.

The authors of the paper [27] carried out appropriate tests to define the charring depth and the fire spread rate for cross-laminated bamboo slabs. During the tests the three specimens were used. One specimen was not treated with the fire-proof composition, another specimen was applied with the fire-retarding coating and the third specimen was impregnated with flame retardants, but first of all the specimens were exposed to the action of fire on the one side with the furnace temperature meeting ISO 834-1:1999/Amd 2:2021 requirements. Based on the test data, we suggested the temperature profile model to predict the slab temperature. It should be noted that this research was done to contribute to the development of the high-rise bamboo constructions that recently gained popularity in this country in the construction sector. However, other countries actually do not use these materials for construction purposes.

Scientific paper [28] describes the investigations carried out to determine the charring of wooded structures protected with the standard lime-based plaster. The obtained data show that the plaster layers of a substantial thickness are able to provide the same initial protection of the constructions as the plasterboard plates showing the same time of the start of charring and the charring rate of the protected wood up to the time of its falling off. The research done is aimed at the preservation of historical buildings and constructions built of wood. However, the wood charring depth, the pyrolysis or the thermal decomposition of wood were not studied during this investigation.

Paper [29] describes the investigations carried out to define the charring of the materials of a different thickness and the heat flow intensity. The research data show that the material thickness has a great effect on the material heat transfer and the temperature was taken into consideration not only in the area of the fire impact but also on the external side of the material. The research data also show the advance of the fire spread on the material surface not only due to the fire impact but also due to the heat conduction and it allows us in its turn to continue investigations in this field.

The authors of the paper suggest carrying out experimental investigation to determine specific features and combustion parameters of wooden products exposed to the fire impact. The research done enables the solution of the problem relating to the prevention of fire and the spread of it in the case of the use of wooden products as construction materials and furniture inside the dwelling houses and constructions.

The purpose of this research was to carry out the experimental studies of the thermal decomposition (pyrolysis) of wooden products during the fire spread determining simultaneously the charring depth as a function of temperature and time, a change in the mass and sizes of degradation zones after the fire impact.

2 Materials and Research Methods

During the investigations ordinary OSB [30] and WPB [31] with the dimensions of 300 × 200 × 10 mm were used as wooden products. Experimental investigations were carried out in three stages. During the first stage of investigation, the boards were exposed to the impact of fire using the flame burner Flame Gun The Electron Strikes A light NO.920 with the balloon for 220 g of gas manufactured in China. In this case the gas burner was arranged along the specimen length and the flame was at a distance of approximately 10 mm from the specimens as shown in Fig.3.

The OSB and WPB surface temperature was measured on both sides, in particular on the side of the flame impact of the gas burner and on the reverse side with the interval of 1 minute during 10 minutes.

Fig. 3. General pattern of experimental conditions: on the left side we can see the gas burner and the OSB specimen and on the right side we can see the gas burner and the WPB specimen

There was no flame impact during the temperature measurement on the surface of wooden products and a maximum temperature was recorded. The temperature was measured using the thermal imaging camera FLIR K33 manufactured by the FLIR Systems Estonia OÜ Company with the temperature range of 20 to 150°C and of 0 to 650 °C, the thermal sensitivity was < 40 мK at a temperature of 30 °C and the temperature measurement error was ± 4 °C or ± 4% at the ambient temperature of 10 to 35°C [32]. Fig 4 shows the research done.

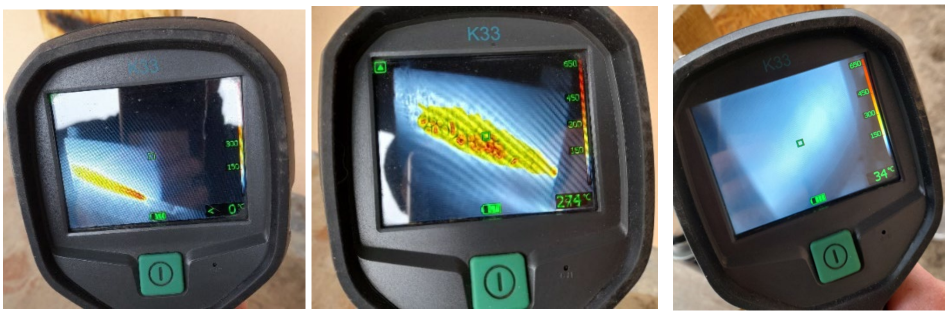

Fig. 4. Measuring the temperature on the surface of wooden products

During the second stage, the investigation was carried out to measure the depth of char (missing char + remaining char) according to the method [23] and to determine the sizes of the zones of wooden products exposed to the flame impact. The depth was measured using Digital Caliper manufactured in China with the measurement range of 0 to 150 mm and the measurement accuracy of 0.01 mm with the measurement error of 0.02 mm. Fig. 5 shows the measurements of the depth of char.

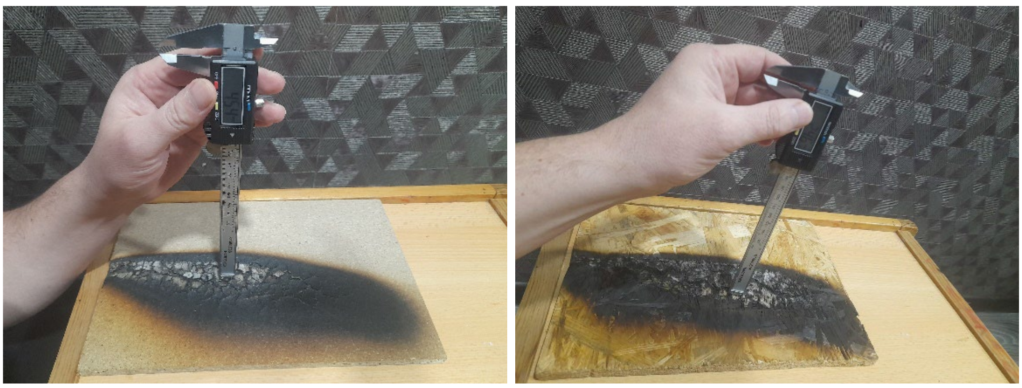

Fig. 5. Investigation and measurement of the missing char and remaining char according to the method given in [23]

During the third stage, the investigation was carried out to determine a change in the mass of wooden products before and after the tests. The mass was measured using Professional Digital

Table Top Scale manufactured in China, a maximum weighing weight is 500g, the error is within 0.1 g, the value of scale division is 0.01 g. Fig.6 shows the research done.

Fig. 6. Mass measurement data obtained for the specimens of wooden products before and after the tests

3 Discussions of Results

This paper delves into the investigations of the thermal decomposition of wooden products (OSB and WPB) used for construction purposes and for the furniture manufacture. During the first stage of investigations the data were obtained for the impact of temperature on the specimens of wooden products (OSB and WPB) both on the side of the flame impact and on the reverse side, as shown in Fig. Fig 7 and 8.

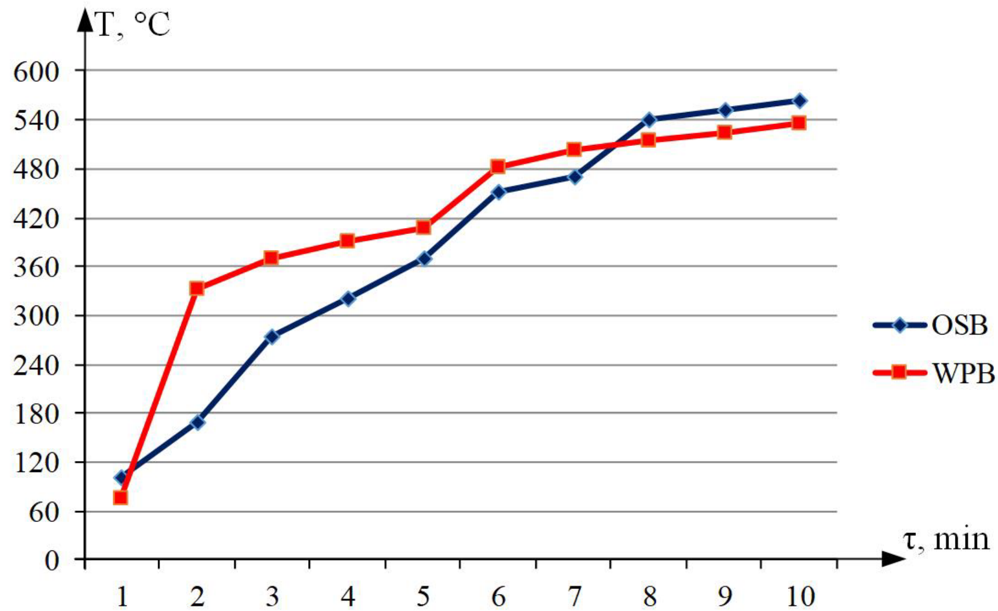

Fig. 7. The relationship of the temperature on the surface of wooden products (OSB and WPB) as a function of time on the side of the direct flame impact

Fig.7 shows that the WPB surface temperature rapidly attained the value of 332°C at the 2d minute in contrast to the OSB surface that showed a gradual increase in temperature attaining the value of 320 °C only at the 4th minute in comparison to WPB. And the features of the thermal decomposition (change in color, charring) of wooden products were noticeable after the 1st minute of the flame impact both for WPB and OSB. At the 8th minute the temperature on the surface of the specimens of wooden products remained actually unchanged and at the 10th minute a maximum temperature was recorded and for the WPB surface it was equal to 536 °C and for the OSB surface it was equal to 564 °C. When analyzing Fig.8, a rapid increase in temperature was recorded for OSB at the 9th minute and it was equal to 166°C that is primarily characterized by the burnout of the wooden product. As for WPB, the temperature is increased gradually with time and a maximum value of it was recorded at the 10th minute and it was equal to 134 °C and the specimen burnout was not detected in this case.

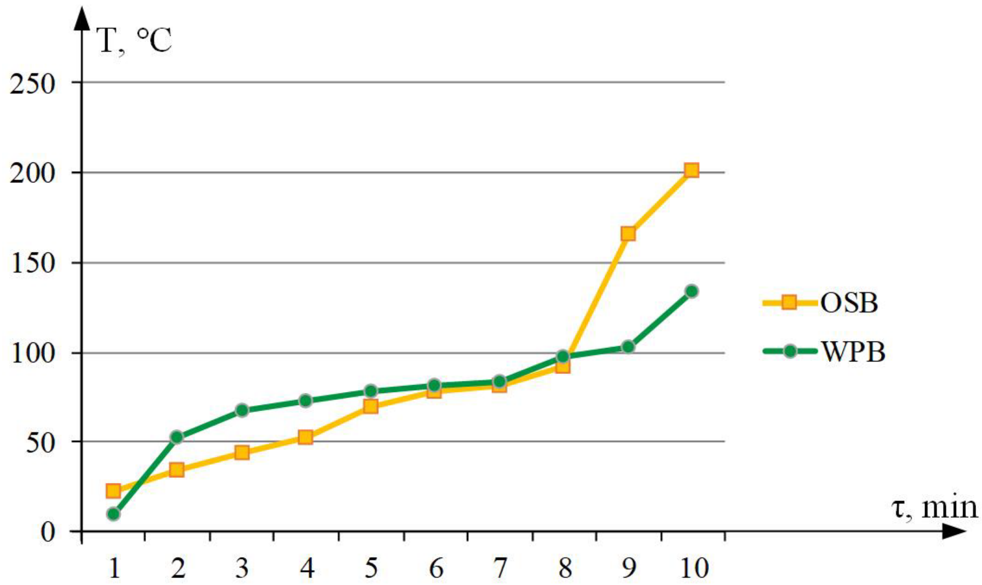

Fig. 8. The relationship of the temperature on the surface of wooden products (OSB and WPB) as a function of time on the reverse side of the flame impact

During the second stage of investigation, the measurement data for the depth of char were obtained. The data given in Table 1 were obtained using the method [23] taking into account the measurement period (Fig.2 and Fig5.). The missing char and the remaining char were measured thrice in different places to get reliable data. Afterwards, the depth of char was calculated as the sum of the values of the missing char and the remaining char. The obtained experimental data were processed using the method of least squares and are given in Table 1.

Table 1. Calculation data of the charring depth of wooden products (OSB and WPB)

Type of wooden products	Missing char, [mm]	Remaining char, [mm]	Depth of char, [mm]	Rms depth of char, [mm]
WPB	0.76	4.53	5.29	$5.24 \pm 0.102_{0.9}$
	1.09	4.16	5.25	
	1.21	3.96	5.17	
OSB	2.84	2.71	5.55	$5.78 \pm 0.342_{0.9}$
	3.22	2.63	5.85	
	3.47	2.47	5.94	

So, the root-mean-square (rms) depth of char for WPB was equal to $5.24 \pm 0.102_{0.9}$ mm, and for OSB it was equal to $5.78 \pm 0.342_{0.9}$ mm. When analyzing the measurement data for the missing char, we get for WPB a minimum value equal to 0.76 mm and a maximum value equal to 1.21 mm; as for OSB we get a minimum value equal to 2.84 mm and a maximum value equal to 3.47mm. When analyzing the measurement data obtained for the remaining char we get a minimum value for WPB equal to 3.96 mm and a maximum value equal to 4.53 mm and in the case of OSB a minimum value was equal to 2.47mm and a maximum value was equal to 2,71 mm. When comparing the measurement data it should be noted that the missing char values and the remaining char values are actually the same for OSB in contrast to WPB where the missing char values are much lower in comparison to remaining char values. However, the comparison of the values for the depth of char shows that these differ only by 0.5 mm both for OSB and WPB.

The investigation was carried out to specify the degradation zones [33] of wooden products (OSB and WPB) that were exposed to the flame impact according to Fig.9.

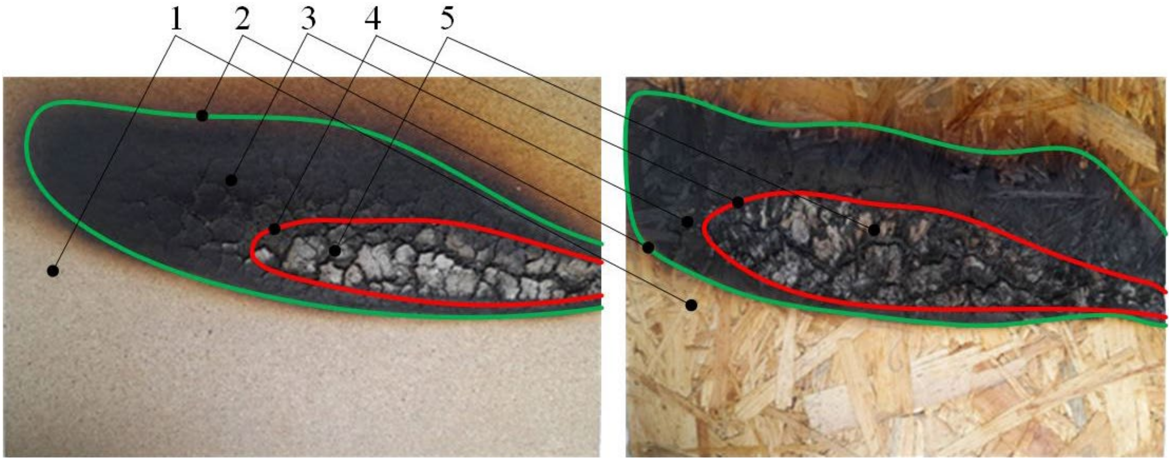

Fig. 9. Degradation zone of wooden products exposed to the flame impact: 1 – Unburned wood; 2 – Pyrolysis zone base; 3 – Pyrolysis zone; 4 – Char base; 5 – Char layer

During the investigation of the degradation zones of wooden products (OSB and WPB) that were exposed to the flame impact we specified the areas of those zones and their sizes (a maximum width and height). A specified area of degradation zones is given in Fig.10 and the obtained data are given in Table 2.

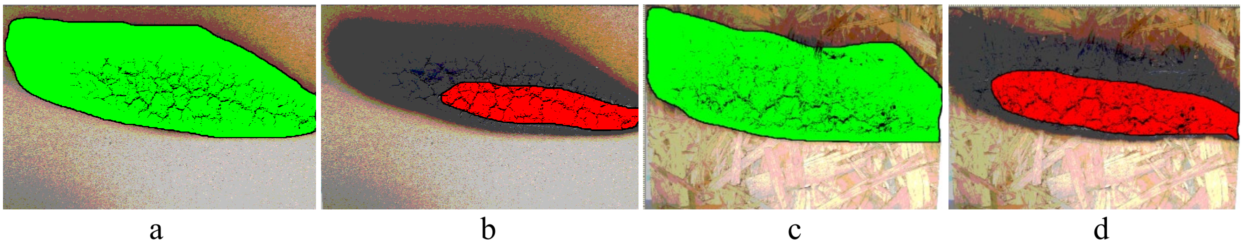

Fig. 10. Specified area of the degradation zones of wooden products exposed to the flame impact: a – Pyrolysis zone for WPB; b – Char layer for WPB; c – Pyrolysis zone for OSB; d – Char layer for OSB

Table 2. Calculation data obtained for the zone sizes of wooden products exposed to the flame impact

Type of wooden products	Total area, [m^2]	Pyrolysis zone area, [m^2]	Char layer area, [m^2]	Pyrolysis zone width, [m]	Char layer width, [m]	Pyrolysis zone length, [m]	Char layer length, [m]
WPB	0.06	0.024	0.0051	0.116	0.045	0.698	0.194
OSB	0.06	0.028	0.0104	0.138	0.071	0.307	0.260

When analyzing the obtained research data we should note that the pyrolysis zone area for WPB is equal to 0.024 m^2 and for OSB it is equal to 0.028 m^2 and in this case the char layer area for WPB is equal to 0.0051 m^2 and for OSB it is equal to 0.0104m^2. Giving consideration to the area values and the sizes of the pyrolysis zone and char layer, we can state that these values are higher for OSB in comparison to those obtained for WPB.

Table 3 gives the research data obtained during the third stage of the investigations for a change in the specimen mass of wooden products (OSB and WPB) before and after the tests.

Table 3. Measurement data obtained for the specimen mass of wooden products (OSB and WPB)

Type of wooden products	Specimen mass before the tests, [g]	Specimen mass after the tests, [g]	A change in the specimen mass, [%]
WPB	425.05	385.55	9.29
OSB	413.58	369.57	10.64

The measurement data obtained for the specimen mass of wooden products (OSB and WPB) showed that the specimen mass decreased after the tests by 10.64 % for OSB and by 9.29 % for WPB. It should be noted that the difference in the change of mass of the specimens of wooden products makes up 1.34 % and it can be explained by a different structure.

According to [30], OSBs are multilayered boards made of wood shavings with addition of adhesive and according to [31] WPBs are the boards manufactured by the method of hot pressing of wooden particles mixed with the binder. In other words, OSBs consist of large wood shavings and WPBs consist of the shavings of a smaller size and if we consider the spread of fire, the expansion of fire on the solid combustible material and the obtained research data we will notice that the burning of wooden products that consist of large wood shavings (OSB) is more intensive and accordingly it occurs at a higher temperature and an increased flame expansion rate in comparison to wooden products consisting of wood particles of a small size (WPB).

To prevent the rapid expansion of flame on the solid flammable material it is reasonable to treat wooden products (OSB and WPB) with flame retardant compositions [34-37] or introduce novelty technologies into the material structure [38-42] and use the primary fire –fighting equipment to minimize the fire spread including the standalone and mobile fire-fighting tools using the mist water [43, 44] with technical performances given in [45-49].

The experimental investigations carried out to study wooden products (OSB and WPB) allowed us to compare and analyze their behavior during the flame impact, to substantiate the pyrolysis process or thermal decomposition taking into consideration the dependence of temperature on time, to study and specify the degradation zones of wooden products exposed to the flame impact and also their areas and sizes and accordingly analyze and specify a change in the specimen mass before and after the tests. The obtained research data will serve as a basis for the development of mathematical models within the framework of this research and allow us to improve the safe stay of people in the premises with available wooden structures, furniture and other wooden products (OSB and WPB).

Summary

Experimental investigations were carried out to determine the flammable properties and factors of wooden products (OSB and WPB) exposed to the fire impact. It should be noted that the wooden products (OSB and WPB) are the basic materials used for construction purposes and furniture manufacture. In addition, the research data enabled the measurement and substantiation of the dependence of temperature on the time of fire impact. The degradation zones of wooden products injured by the fire including their areas and sizes have been specified and a change in the specimen mass before and after the tests was analyzed. Hence, the studies of the dependence of temperature on time showed that the features of the thermal decomposition of wooden products appeared after the first minute of the flame impact and a maximum temperature recorded for WPB was equal to 536 °C and for OSB it was equal to 564 °C.The rms depth of char for WPB was equal to $5.24\pm0{,}102_{0.9}$ mm and for OSB it was equal to $5.78\pm0{,}342_{0.9}$ mm. The data were obtained for degradation zones of wooden products, in particular the pyrolysis zone area (WPB) was equal to 0.024 m^2, the pyrolysis zone area (OSB) was equal to 0.028 m^2, the char layer area (WPB) was equal to 0.0051 m^2, and the char layer area (OSB) was equal to 0.0104 m^2. The mass measurement data for the specimens of wooden products (OSB and WPB) before and prior the tests showed 10. 64 % for OSB and 9.29 % for WPB.

The obtained research data allowed us to establish that the burning of wooden products that consist of large wood particles (OSB) is more intensive and accordingly it has a higher temperature and an increased flame expansion rate on the surface of wooden products in comparison to those that are made of the fine wood particles (WPB).

References

[1] SAF Ukraine (Sustainable Agribusiness Forum). URL: https://saf.org.ua/ (date of access: 20.01.2022).

[2] Roadmap 2050. URL: https://www.roadmap2050.eu/ (date of access: 20.01.2022).

[3] B. Pospelov, et al., Studying the recurrent diagrams of carbon monoxide concentration at early ignitions in premises. Eastern-European Journal of Enterprise, 3/9 (93) (2018) 34–40.

[4] S. Vambol et al., Research of the influence of decomposition of wastes of polymers with nano inclusions on the atmosphere, Eastern-European Journal of Enterprise Technologies, 6/10 (90) (2017) 57–64.

[5] O.Z. Dveirin, O.V. Andreev, A.V. Kondrat'ev, V.Ye. Haidachuk, Stressed state in the vicinity of a hole in mechanical joint of composite parts, International Applied Mechanics, 57, 2 (2021) 234–247.

[6] S. Vambol et al., Analysis of the ways to provide ecological safety for the products of nanotechnologies throughout their life cycle, Eastern-European Journal of Enterprise Technologies, 1/10 (85) (2017) 27– 36.

[7] O. Rybalova et al., Development of methods for estimating the environmental risk of degradation of the surface water state, Eastern-European Journal of Enterprise Technologies, 2/10 (92) (2018) 4–17.

[8] V. Sadkovyi et al., Construction of a method for detecting arbitrary hazard pollutants in the atmospheric air based on the structural function of the current pollutant concentrations, Eastern-European Journal of Enterprise Technologies, 6/10 (108) (2020) 14–22.

[9] B. Pospelov et al., Use of uncertainty function for identification of hazardous states of atmospheric pollution vector, Eastern-European Journal of Enterprise Technologies, 2/10 (104) (2020) 6–12.

[10] D. Dubinin et al., Numerical simulation of the creation of a fire fighting barrier using an explosion of a combustible charge, Eastern-European Journal of Enterprise Technologies, 6/10 (90) (2017) 11– 16.

[11] M. I. Jahirul et al., Biofuels Production through Biomass Pyrolysis – A Technological Review, Energies, 5(12) (2012) 4952-5001.

[12] D. Dubinin et al., Experimental Investigations of the Thermal Decomposition of Wood at the Time of the Fire in the Premises of Domestic Buildings, Materials Science Forum, 1066 (2022) 191–198.

[13] B. Pospelov et al., Development of the method for rapid detection of hazardous atmospheric pollution of cities with the help of recurrence measures, Eastern-European Journal of Enterprise, 1/10 (97) (2019) 29–35.

[14] B. Pospelov et al., Defining the features of amplitude and phase spectra of dangerous factors of gas medium during the ignition of materials in the premises, Eastern-European Journal of Enterprise Technologies, 2/10 (116) (2022) 57–65.

[15] Y. Danchenko et al., Research into surface properties of disperse fillers based on plant raw materials, Eastern-European Journal of Enterprise Technologies, 5/12 (89) (2017) 20–26.

[16] B. Pospelov et al., Development of the method of operational forecasting of fire in the premises of objects under real conditions, Eastern-European Journal of Enterprise, 2/10 (110) (2021) 43–50.

[17] B. Pospelov et al., Short-term fire forecast based on air state gain recurrency and zero-order Brown model, Eastern-European Journal of Enterprise Technologies, 3/10 (111) (2021) 27–33.

[18] V. Sadkovyi et al., Development of a method for assessing the reliability of fire detection in premises, Eastern-European Journal of Enterprise Technologies, 3/10 (117) (2022) 56–62.

[19] B. Pospelov et al., Mathematical model of determining a risk to the human health along with the detection of hazardous states of urban atmosphere pollution based on measuring the current concentrations of pollutants, Eastern-European Journal of Enterprise, 4/10 (106) (2020) 37–44.

[20] S. Ragimov et al., Physical modelling of changes in the energy impact on a worker taking into account high-temperature radiation, Journal of Achievements of Materials and Manufacturing Engineering, 1(91) (2018) 27– 33.

[21] D. Dubinin et al., Research and justification of the time for conducting operational actions by fire and rescue units to rescue people in a fire | Istraživanje i opravdanje vremena izvođenja operativnih akcija vatrogasno-spasilačkih postrojbi za spašavanje ljudi u požaru, Sigurnost, 64 (1) (2022) 35– 46.

[22] D. Dubinin et al., Investigation of the effect of carbon monoxide on people in case of fire in a building | Ispitivanje djelovanja ugljičnog monoksida na ljude u slučaju požara u zgradi, Sigurnost, 62 (4) (2020) 347– 357.

[23] NFPA 921. Guide for Fire and Explosion Investigations. Massachusetts, 2017 [USA].

[24] B. Pospelov et al., Short-term forecast of fire in the premises based on modification of the Brown's zero-order model, Eastern-European Journal of Enterprise, 4/10 (112) (2021) 52–58.

[25] D. D. Karyaparambil et al., Flame heights and charring on a particle board – An experimental study, Fire Safety Journal, 134 (2022) 103675.

[26] X. Sun et al., Temperature evolution and external flame height through the opening of fire compartment: Scale effect on heat/mass transfer and revisited models, International Journal of Thermal Sciences, 164 (2021) 106849.

[27] Q. Lv, W. Wang, Y. Liu, Charring depth and charring rate of cross-laminated bamboo slabs exposed to a one-sided standard fire, Fire Safety Journal, 125 (2021) 103439.

[28] J. Liblik, M. Nurk, A. Just, Charring performance of timber structures protected by traditional lime-based plasters, Construction and Building Materials, 347 (2022) 128572.

[29] J. Xiao et al., Ablation behavior studies of charring materials with different thickness and heat flux intensity, Case Studies in Thermal Engineering, 23 (2021) 100814.

[30] DSTU EN 300:2008. Plyty derevynnostruzhkovi z orijentovanoju struzhkoju (OSB). Terminy ta vyznachennja ponjat', klasyfikacija ta tehnichni vymogy (EN 300:2006, IDT). Kyiv, 2008 [in Ukrainian].

[31] DSTU GOST 10632:2009 Plyty derevynno-struzhkovi. Tehnichni umovy (GOST 10632-2007, IDT). Kyiv, 2009 [in Ukrainian].

[32] A. Kondratiev, V. Pistek, L. Smovziuk, M. Shevtsova, A. Fomina, P. Kucera, A. Prokop, Effects of the temperature-time regime of curing of composite patch on repair process efficiency. Polym., 13(24) (2021) 4342.

[33] T. D. H. Le, M.-T. K. Tsai, Experimental Assessment of the Fire Resistance Mechanisms of Timber–Steel Composites, Materials, 12(23) (2019) 4003.

[34] K. Afanasenko et al., Epoxidized Dinaphthol Application as the Basis for Binder with Advanced Carbonation Level to Reducing its Flammability, Materials Science Forum, 1006 (2020) 41–46.

[35] A. Kovalov et al., Treatment of Determination Method for Strength Characteristics of Reinforcing Steel by Using Thread Cutting Method after Temperature Influence, Materials Science Forum, 1006 (2020) 179–184.

[36] V. Sadkovyi et al., Fire resistance of reinforced concrete and steel structures, Kharkiv: PC TECHNOLOGY CENTER, (2021) 180.

[37] Y. Otrosh et al., Assessment of the technical state and the possibility of its control for the further safe operation of building structures of mining facilities, E3S Web of Conferences, 123(3): (2019) 01012.

[38] Y. Danchenko et al., Research of the intramolecular interactions and structure in epoxyamine composites with dispersed oxides, Eastern-European Journal of Enterprise Technologies, 6/12 (90) (2017) 4–12.

[39] Y. Danchenko et al., Study of the free surface energy of epoxy composites using an automated measurement system, Eastern-European Journal of Enterprise Technologies, 1/12 (91) (2018) 9–17.

[40] K. V. Korytchenko et al., Enhancing the Fire Resistance of Concrete Structures by Applying Fire-Retardant Temperature-Resistant Metal Coatings, Materials Science Forum, 1038 (2021) 500-505.

[41] K. V. Korytchenko et al., Advanced detonation gun application for aluminum oxide coating, Multidisciplinary journal «Functional Materials», 27 (1) (2020) 224-229.

[42] A. V. Kondratiev, V. E. Gaidachuk, Mathematical analysis of technological parameters for producing superfine prepregs by flattening carbon fibers, Mechanics of Composite Materials, 57, 1 (2021) 91–100.

[43] D. Dubinin et al., Improving the installation for fire extinguishing with finely-dispersed water, Eastern-European Journal of Enterprise Technologies, 2/10 (92) (2018) 38– 43.

[44] K. Korytchenko et al., Experimental investigation of the fire-extinguishing system with a gas-detonation charge for fluid acceleration, Eastern-European Journal of Enterprise Technologies, 3/5 (93) (2018) 47– 54.

[45] A. Kasimov et al., Numerical study of the process of compressing a turbulized two-temperature air charge in the diesel engine, Eastern-European Journal of Enterprise Technologies, 6/5 (96) (2018) 49– 53.

[46] K. Korytchenko et al., Numerical simulation of initial pressure effect on energy input in spark discharge in nitrogen, Problems of Atomic Science and Technology, 122 (4) (2019) 116–119.

[47] K. Korytchenko et al., Experimental research into the influence of two-spark ignition on the deflagration to detonation transition process in a detonation tube, Eastern-European Journal of Enterprise Technologies, 4/5 (100) (2019) 26– 31.

[48] K. Korytchenko et al., Experimental investigation of arc column expansion generated by high-energy spark ignition system, Problems of Atomic Science and Technology, 118 (9) (2018) 225–228.

[49] K. Korytchenko et al., Challenges of energy measurements of low-energy spark discharges, 2020 IEEE KhPI Week on Advanced Technology (KhPIWeek), (2020) 421–424.