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Heating and charring of timber constructions with thin-layer fire protection

Прогрев и обугливание деревянных конструкций с тонкослойной огнезащитой

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Ключевые слова: огнестойкость; пожарная опасность; деревянные конструкции; огнезащита; прогнозирование; обугливание; древесина

Abstract. The results of fire tests of constructions (beams) with fire retardant film coating in one-side fire effect under standard temperature fire regime are shown in this article. Intensity dynamics of samples heating and their charring process in thickness and along the perimeter were chosen as the key indicators. It is shown that the use of thin-layer non-swelling fire retardant coatings does not influence the intensity dynamics, in case of high-temperature exposure generates from the side of the bottom edge, however, but is able to localize the burning action effectively, thereby producing a positive impact on the level of fire hazard and fire resistance of building constructions. The directions of possible development of methodological approach to the calculation and analytical assessment of fire retardant indicators and classes of fire hazard of timber constructions with non-construction fire protection have been determined.

Аннотация. Приведены результаты огневых испытаний конструкций (балок) с огнезащитными пленочными покрытиями при одностороннем огневом воздействии в условиях стандартного температурного режима пожара. В качестве ключевых показателей были выбраны интенсивность динамики прогрева образцов и процесса их обугливания по толщине и по периметру образца. Показано, что применение тонкослойных не вспучивающихся огнезащитных покрытий не оказывает влияния на динамику прогрева, в случае действия источника высокотемпературного воздействия со стороны нижней грани, однако способно эффективно ограничивать распространение горения, оказывая общее положительное влияния на уровень пожарной опасности и огнестойкости строительных конструкций. Определены направления возможного развития методических подходов к расчетно-аналитической оценке показателей огнестойкости и классов пожарной опасности деревянных конструкций с неконструктивной огнезащитой.

1. Introduction

For many years buildings and constructions fire protection problem with the use of timber constructions attracts attention of researchers from different countries [1–8]. Through these research papers, quite abundant knowledge about patterns of wood burning process, the influence of various individual chemical substances and their mixtures on the processes of thermal decomposition of timber-based material, interrelations of charring parameters with constructions fire retardant indicators and also, methods and types of fire protection have been formed [9].

However, researches, as a rule, are limited to the study of timber constructions properties on its base under high temperature effect with the use of relatively small samples (hinges, beams and construction elements) [10, 11], including in the presence of fire retardant materials [12]. For all of those purposes the complex of physicochemical methods of investigation such as thermal analysis and various calorimetric methods are as actively used as laboratory methods of assessment of fire and technical materials characteristics (combustibility, flammability, flame spread, smoke-forming ability and toxicity of combustion products) [13–17].

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In majority cases these methods allow to assess the capacity of relatively thin (10–15 mm, rarely – to 70 mm) wooden samples with fire protection to resist the effect of ignition sources of different power. However, the characteristics obtained as a result cannot usually be scaled for the purposes of predicting the behaviour of timber constructions of different sections, areas, humidity and ages under standard or real fire regimes.

Certainly, it is possible to attract large scale fire tests for these purposes. In different countries methodological approaches to the assessment of fire hazard and fire resistance of building constructions are similar [18–23], and, as a rule, such researches involve the need to prepare full-scale constructions [24–26] and test results of not more than 2 or 3 identical constructions, what makes it difficult to perform statistical analysis and to assess the reliability or the relevance of the experimental data obtained. In particular, in recent years, during a series of experiments, the authors have shown the capacity of fire retardant impregnating compositions including surface coating to increase the class of timber constructions fire hazard and fire resistance [27–29]. There are some works devoted to the study of fire hazard and fire retardant of timber constructions processed by intumescent [30, 31] and thick coating [32, 33], as well as with construction fire protection [34, 35]. However, the presented results need to be further approved, and their interpreting remain challenges of methodological and technical nature, in particular, an assessment of such an important indicator of timber construction as the charring dynamics is often carried out with the basis on indirect criteria, such as the heating dynamics in the places where thermocouples are situated [29, 34], since it is not possible to examine constructions after completion of the test.

In the light of wooden house buildings development and the need to provide objects with fire safety using wood as the main construction material [36, 37] the development of methodological approaches to the integrated assessment of indicators that characterized fire resistance of timber constructions and necessary for mathematical modelling of constructions behavior under standard and real thermal fire regimes gain special pertinence and significance.

The development of capabilities of systems and means of mathematical modelling and computer-aided design of multi – layered systems through various options of possible impacts that call for a need of improving constructions and their fragments test methods are relevant to the current circumstances. The review of approaches to the evaluated estimate of rationed indicators taking into account the development of numerical modelling methods should be provided [25].

Under the current principals [38–41] to the evaluated estimate of timber constructions fire resistance, it is assumed that the construction is subject to three- or four-side fire effect (Figure 1), and the effect of fire protection is determined by the ability to provide heat insulation of the protected surface [38, 42]. The impact of non-constructive fire protection is not actually taken into consideration, it is assumed that losing the thermal insulating capacity by the facing leads to "the instant complete charring" of the construction, after which the charring rate of all the sides becomes higher or equal to the standard rate (0.65 mm for wood of coniferous trees, in case of one-side heating) [38], regardless of the presence of surface or deep flameproofing that seems to be not in conformity with their effective role [28, 29].

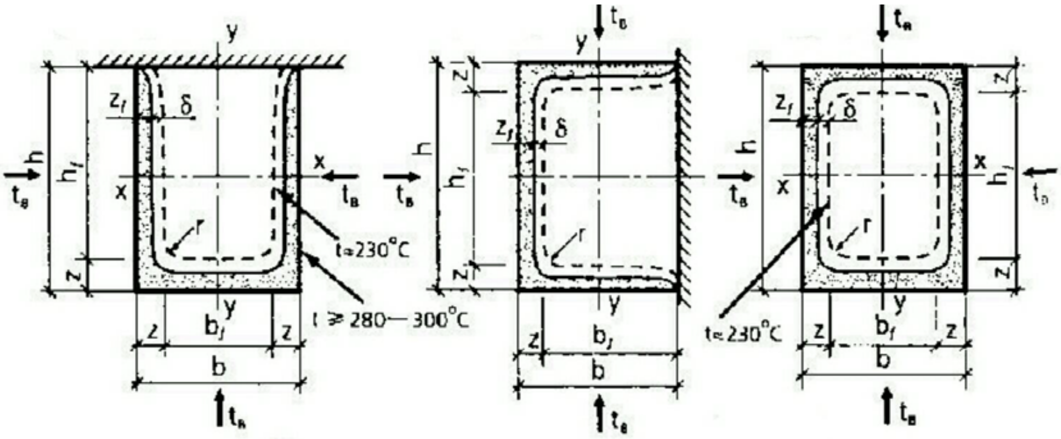


Figure 1. Fire effect schemes taken into account by the calculated methods [41]

The aim of the work is the formation of the methodological approaches to the evaluated estimate of the influence of flameproofing on the indexes of the fire hazard and fire resistance of timber constructions.

Allowances and simplifications made in the calculated methods are related in many ways to the imperfection of the methods of fire resistance experimental evaluation. As a result, the possibility to apply methods of calculated prediction of non-standard constructions used in the modern timber construction is strictly limited. In fact, it is possible to say that, under the following frameworks, convenient correcting factors are selected for each technical solution, according to the test results.

In the current work the following tasks of influence of flameproofing with the use of thin film coating on the indexes are being solved:

- Dynamics of timber constructions heating under one-sided fire effect of the standard fire temperature control;
- Flame spread on the surface outside the zone of fire effect;
- Charring rate of timber constructions under one-sided fire effect.

These parameters are defined for both unprocessed constructions and fire-proofing constructions with the use of thin-coat roll film coating (thickness 1.5 mm).

To explore the behaviour of timber constructions with non-thermal-insulting fire protection under one-sided fire effect, to develop methodological approaches to the assessment of fire protection efficiency in relation to the constructions and the predictive assessment of fire hazard and fire resistance of constructions with non-construction and thin-layer fire protection new film fire retardant coatings on the base of commercially produced film-forming oligomer systems laid on glass-cloth reinforcing framework have been chosen [43, 44]. The mechanism of fire-protection action of the applied coatings is determined by forming a filter barrier, which prevents the mass transfer between the flammable substrate and the environment, on the surface of the protected material.

This coating, combined with vinyl and acetate glue system, provides I – II groups of fire protection effectiveness with from 5.5 up to 13 % mass loss, in accordance with adopted in Russia methods of effectiveness assessment of wood fire retardant materials according to the national standard of the Russian State Standard GOST R 53292-2009 [45], provides the transfer of wood and materials based on it into a group of inflame-resistant materials (the critical surface density of heat flux is more than 20 kW/m^2) which have moderate smoke-forming ability and do not spread flame on the surface.

2. Methods

To study features of influence of fire retardant means and materials on the fire hazard and timber constructions fire resistance indicators the approach that includes quantitative assessment of the tested beams heating dynamic and the levels of their thermal damage on the indicator of perimeter change of the cross sections are being offered. For this purpose the installation for thermophysical studies and tests of small fragments of flat constructions and individual components of their joining transition and fixing was used in the work [46].

The experiment was carried out in parallel for two samples of pine wood beams with a specific gravity of 455 kg/m^3 and equilibrium humidity of 12% with the actual sizes 135x135x600 mm without fire protection (sample # 0) and with fire retardant film coating (sample # 1).

The scheme of samples layout is shown in the Figure 2, to prevent (decrease) the mutual influence. The area between the samples was filled with two gypsum sheets with a thickness of 10 mm each, mechanically attached to the tested samples. Foam concrete blocks were used as non-combustible fill.

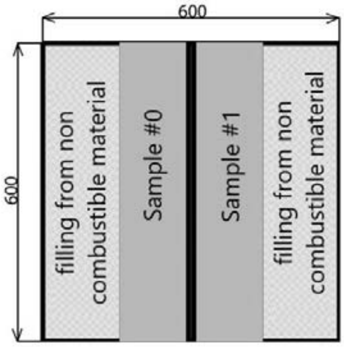
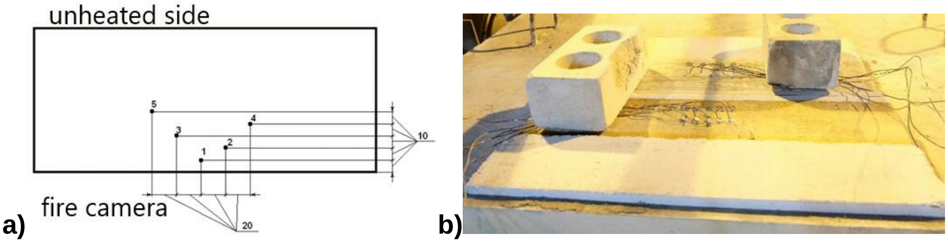


Figure 2. The scheme of samples layout in the test furnace

Each sample had thermoelectric converters (TS) at a depth of from 10 to 50 mm from the exposed surface in accordance with the scheme shown in the Figure 3.



a) b)

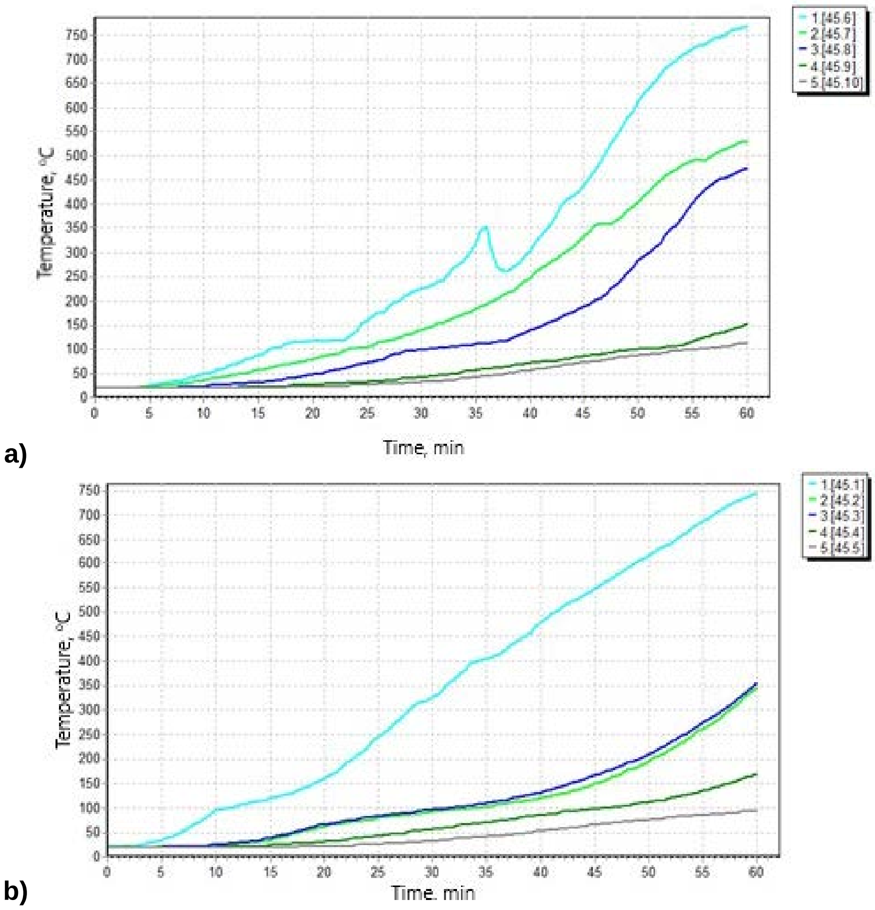
Figure 3. The scheme of technical support (TS) installation in wood beams: a) in cut; b) top view at the place of installation

Tests, lasting 60 minutes were conducted in the conditions of the standard temperature regime in accordance with the requirements of ISO 834. Fire-resistance tests — Elements of building construction — Part 1: General requirements. The fixing of heating dynamics was conducted during the experiment. After fire exposure, the samples were subjected to forced suppression, the samples and char layers state was recorded and the charring depth was evaluated as well.

3. Results and Discussion

The comparative analysis of the heating dynamics of the tested samples (Figures 4-5) shows that fire retardant coating does not actually affect the heating dynamics of the samples in the temperature range of the decomposition of wood (150–200 °C [32]). In the specified temperature range, the growth rate of the temperatures is apparently determined by the features of the wood specific samples.

These results show that there is higher heating dynamics for the sample with fire retardant coating in the surface layer (Figure 4a). This phenomenon involves most likely the use as a reinforcing base of incombustible heat-retardant glass cloth and can be attributed to the difficulty of heat and mass transfer between the sample surface and the environment in the direction of decreasing the dissipation of heat, i.e. in fact, its accumulation takes place in the volume between the fire retardant coating and wood surface that is able to influence on the overall level of fire hazard of such a construction reducing its contribution to the formation of dangerous fire factors.



a)

b)

Figure 4. The dynamics of beam heating without fire protection (a) and with fire retardant film coating (b): 1, 2, 3, 4, 5 –numbers of thermocouple in accordance with the Figure 2

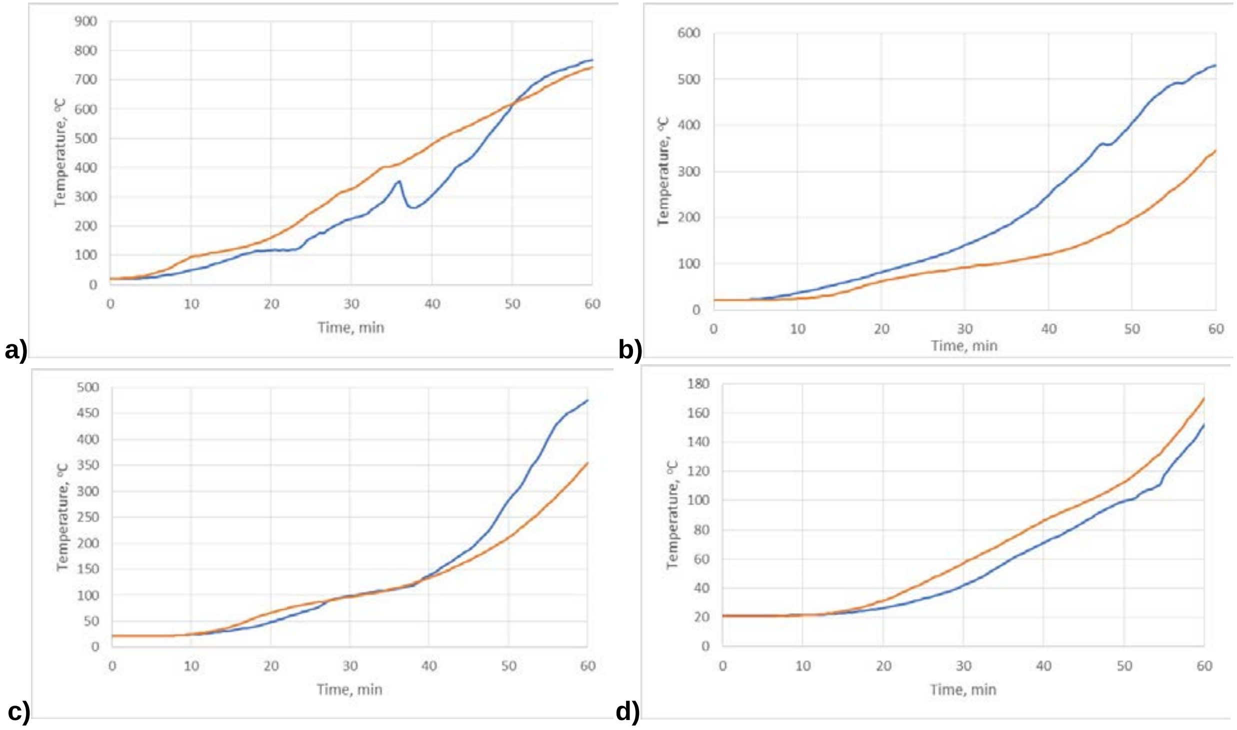


Figure 5. The dynamics of wooden beam heating at a depth of (a) 10, (b) 20, (c) 30, (d) 40 and (e) 50 mm from the exposed surface: 0 - without fire protection; 1 - with fire retardant film coating

In this case, the estimated average speeds of charring for unprotected wooden beams are in the range of 0.27 mm/min at the surface (TS No. 1) to 0.61 mm/min at a depth of 30 mm from the exposed surface (TS No. 3). For the sample with fire retardant coating the corresponding values are from 0.38 to 0.54 mm/min. Thus, according to the objective observations with one-sided fire exposure from the side of the bottom edge of the charring speed for both samples was in the same range.

Both tested samples had the same dynamics of achieving temperature of 100 °C in the sample volume (Figure 6), and thus [39, 40] the zone, overheated more than this temperature, is necessary to exclude from the fire retardant calculation.

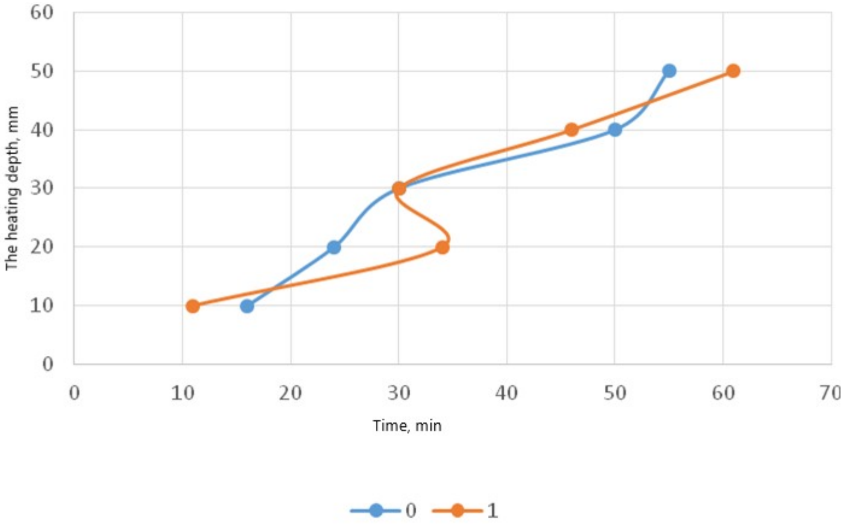


Figure 6. The dynamics of wooden beam heating with one-sided fire exposure: 0 – sample without fire protection; 1 – sample with film fire retardant coating

Minor differences in the heating dynamics, represented in the Figure 6, are most likely determined by the characteristics of timber constructions, the presence of cracks and defects (the type of wood). The combination of obtained data allows identifying the linear dependence of the heating depth from the time of fire exposure (Figure 7).

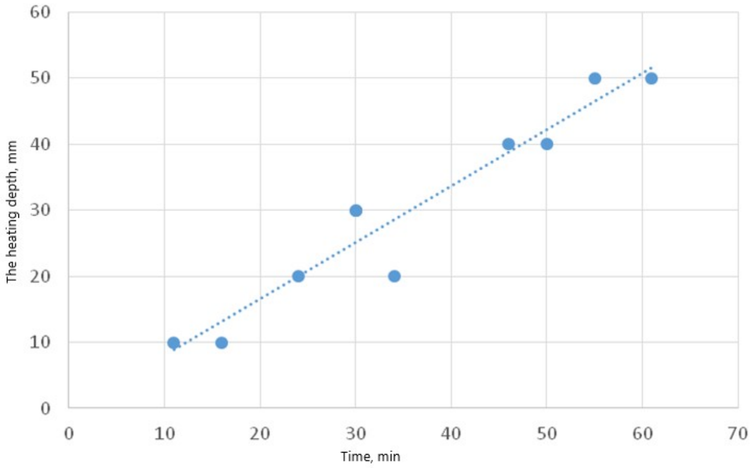


Figure 7. The dependence of the depth of wooden beam heating up to 100 °C from time of fire exposure from the side of the bottom face

Taking into account the obtained data, the intensity of the construction heating and charring process can be represented in the form of the equation 1 with the value of reliability of approximation 0.9235:

$$h = 0.8551 * t - 0.5261 - Z \tag{1}$$

where *h* is the depth of heating to 100 °C; *t* – time of fire exposure (standard temperature fire regime) on the bottom edge of a wooden beam, min.; *Z* is the depth of charring, determined as the product of the regulatory rate of charring [38, 41] at the time of fire exposure.

In accordance with the mathematical relation, looking at "normative" values of charring rate (0.65 mm/min) [33], at the time of fire exposure of the charring depth is 39 mm and overheated layer thickness is more than 11 mm. At the present time accepting under calculations the thickness of overheated layer is 7 mm [40, 41] that corresponds to 20–25 minutes of fire exposure.

Thus, according to the analysis of the data of objective control of dynamics of wooden beam heating with fire protection and fire resistance, the conclusion about absence of positive influence of the tested fire retardant coating on the level of fire hazard and fire resistance of timber constructions can be made. The similar conclusions can be made according to the results of the charring current depth changes from the side of exposed surface where the charring speed status for both samples were also close to 0.63 and 0.5–0.83 mm/min for both the untreated and fire retardant samples.

At the same time, the obtained data analysis allows identifying the range features in the behavior of investigated timber samples that need to be considered under fire hazard assessment and fire resistance of timber constructions with fire protection, and namely:

- before the violation of the integrity of film fire retardant coating there was no the features of flaming combustion above the sample surface (Figure 8b);

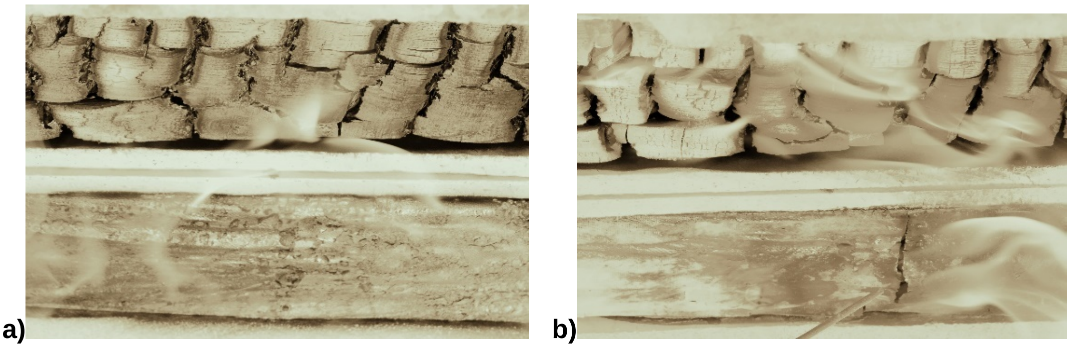
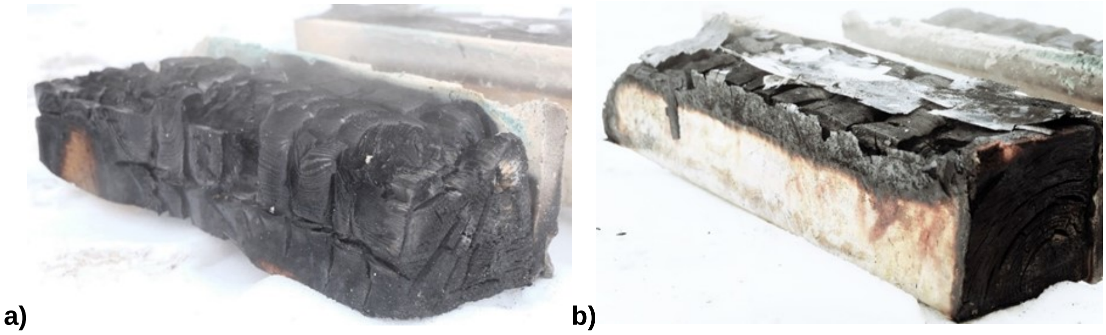


Figure 8. The samples surface condition with fire protection (from the bottom) and without fire protection (at the top) through: a) 20 minutes after fire exposure start-up; b) 50 minutes after fire exposure start-up

- in 40 minutes after fire exposure start-up there was both side and frontal surfaces fire outlet without fire protection (Figure 9), and for the sample with the fire retardant coating there was burning outlet only from the side of one of the frontal surfaces that had not undergone the flameproofing.

Figure 9. Fire outlet outside the fire camera in 40 – 45 minutes after fire exposure star-up

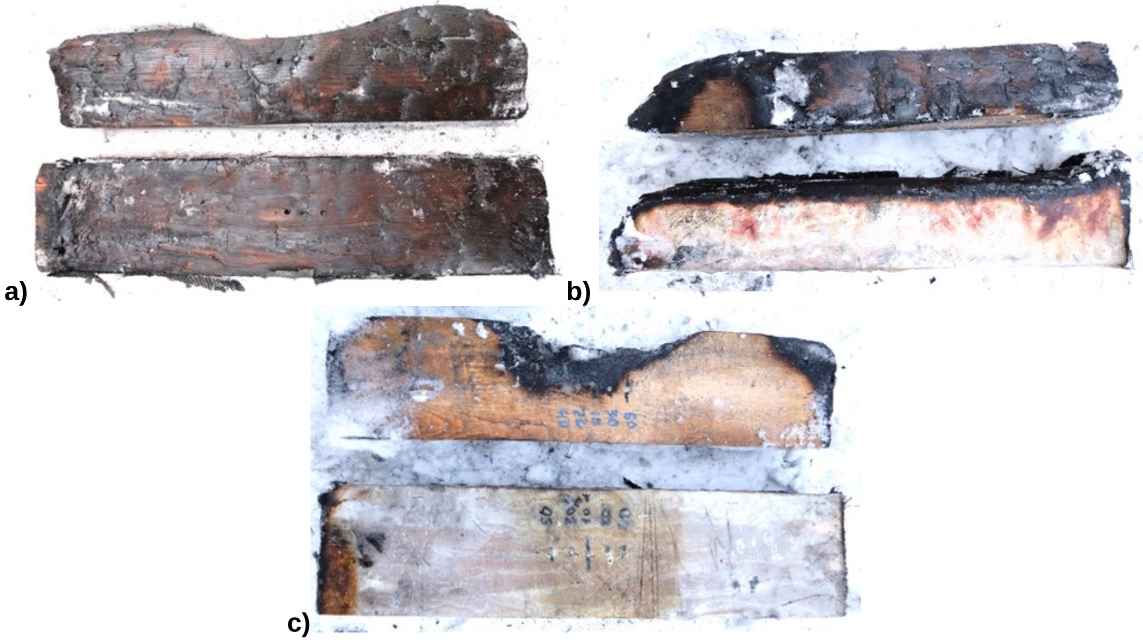
As a result of experiment the damage area for fire retardant coating sample did not exceed 40 % (Figure 10b), while the sample without fire protection had two totally charred frontal and side edges (Figure 10a) and the total area of damages exceeded 60 %.



a) b)

Figure 10. Samples appearance after testing: a) without fire protection; b) with film fire retardant coating

The rate of the sample charring without fire protection in the central part of one of the side edges has been reached 0.5 - 0.6 mm/min (Figure 11) while the sample of fire retardant coating of the side edge have remained intact.



a) b) c)

Figure 11. Appearance of the samples without fire protection (at the top) and with film fire retardant coating (at the bottom) after char seams removal: a) view from the side of exposed surface; b) view from the side of the top (unheated) surface (Figure 2)

The analysis of obtained data allows making the conclusions that the modern approach to the definition of the charring average speed indicator (mm/min) does not fully characterize the behavior of timber constructions in the terms of fire exposure (fire) and does not take into consideration the material features to propagate burning on the surface and support the burning without external heat flux. In majority cases the researchers consider that only exposed surface is charred [24, 25, 39, 40].

The impact of fire retardant materials on the construction behavior in the conditions of fire is able to be considered by the authors according to the size changes of the working sample cross section within the rate of the area reducing or perimeter cross section. Thus, before and after experiment the control of the perimeter length of the working cross section samples has shown that for the sample without fire protection the maximum perimeter reducing in the central part has been reached 160 mm, from 540 up to 380 mm. The rate of loss of the cross section was 2.7 mm/min that corresponds to two-side heating (perimeter calculated changes under one-side heating 1.3 mm/min) under standard charring rate is 0.65 mm/min. The maximum cross section reducing for the sample with fire protection was 80 mm, and the perimeter decreasing rate was 1.3 mm/min.

Making the analysis regarding the linear parameters of the process of thermal damage of timber constructions elements demonstrates uneven loss of the value of cross section sample, and also the impact of features of applying fire retardant materials technology for timber constructions, for instance, film fire retardant coating. The more objective assessment of fire retardant materials effectiveness for the constructions can be considered in assessing both samples heating dynamics and thermal burnout (charring) of their surface layer.

The main disadvantage of the perimeter length changes rate of the perimeter cross section is the difficulty of its standardization in the relation of the constructions with different rates of width and height. The possible solution to the problem can be the introduction of universal indicator that allows more accurately estimate the residual load capacity of timber construction in the process of fire impact (fire). Such an indicator can be "sector rate", characterizing the changes of timber constructions cross-section area. To this end, the cross-section was divided into 8 sectors (Figure 12), each monitoring the residual cross – sectional area with features of the temperature effect focus on the construction sample.

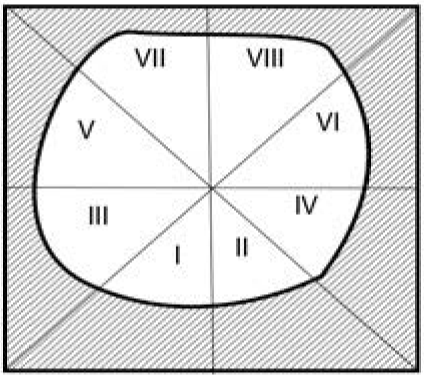


Figure 12. The example of dividing element cross-section of timber constructions on the sector

Methodological assessment of fire resistance of timber constructions may involve the solution of two main tasks:

- determining directly the square of residual (non – charred) cross-section, but not the thickness of the charring surface [40];
- assessment of strength characteristics of the residual cross - section with the temperature gradient. It is assumed that the individual indicators of the calculated retardants have to be applied for each temperature zone [47].

Thus, the changes rate of its area with the use of the finite elements method can be determined for each sector. It will allow with the use of hardware and software solve the task of identifying the residual value of the construction cross-section and its load capacity in the terms of fire depending on the direction and intensity of fire exposure, presence, type and method of fire protection. In future, this field requires very careful methodological work based on the opportunity of computer software use [48–50], focused on prediction of classification indicators of fire hazard and fire resistance of timber constructions.

4. Conclusions

The undertaken study and the obtained results lead to the following conclusions:

1. Under one-sided fire effect of the standard temperature fire regime on the side of the lower edge difference in heating dynamic of samples without fire protection and with thin - layer fire- protection do not have significant differences;
2. The presence of surface non-thermal-insulting flameproofing allows reducing the area of thermal damages by localizing them in the zone of external fire effect;
3. Flameproofing with the use of thin-layer non-thermal-insulting fire retardant materials and coatings does not significantly influence the index of average linear charring rate of timber constructions which is ranged from 0.5 to 1.25 mm/min for samples with or without flameproofing;
4. The use of thin-layer fire retardant coatings and materials allows slowing down the rate of the area reducing of the cross section of timber construction by limiting the flame spread outside the zone of fire effect. The use of thin-layer fire retardant coating for fire protection allowed reducing the rate from 2.7 mm/min for the sample without fire protection to 1.3 mm/min for the one with fire retardant film coating.

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