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Mathematical Simulation of Heat Transfer in the Structures of a Passenger Carriage Under the Influence of Forest Fires

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Abstract – *Forest fires have a negative impact on the functioning of the railway. The aim of the work is a mathematical modeling of heat transfer in the structures of a passenger carriage under the influence of radiation from a forest fire front. The originality of the study is explained by modeling heat transfer in structural materials of a passenger carriage under the influence of radiation from a forest fire front. Low and high intensity surface forest fires, crown forest fires are considered. Most of the previously published works are devoted to the analysis of the causes of forest fires, including the ones near the railway. The software implementation of the mathematical model is performed in the RAD Studio software in the high-level programming language Delphi. Mathematically, heat transfer in the materials of a passenger carriage is described by non-stationary differential heat conduction equations with corresponding initial and boundary conditions. In order to solve the partial differential equations, the finite-difference method and the locally one-dimensional method are used. Difference analogs of differential equations are solved by the marching method. The main findings of the study are: 1) physical and mathematical models of heat transfer in the structures of a passenger carriage under conditions of exposure to radiation from a forest fire; 2) the obtained temperature distributions in the inhomogeneous structure of the passenger carriage wall; 3) simulation has shown that a low-intensity surface forest fire causes a relatively safe forest fire impact scenario, while a high-intensity surface forest fire impact is a potentially dangerous scenario; 4) the scenario of the impact of a crown forest fire is unambiguously dangerous at any parameters; 5) the results obtained in this paper and the expected in future investigations will create a physical basis for the development of software for fire safety systems for rolling stock on the railway. The presented results are proposed to be used for forecasting, monitoring, and assessing forest fire dangers during the operation of the rolling stock of JSC Russian Railways.*

***Keywords**: Forest Fire, Danger, Heat Transfer, Impact, Passenger Carriage, Railway, Radiant Heat Flux*

Nomenclature

α_{in}	Heat transfer coefficient on the indoor boundary [W/(m^2 K)]
$B_{j.k}$	Boundaries of decision area and sub domains
c	Specific heat [J/(kg K)]
d	Initial distance to forest fire [m]
ΔT	Temperature difference between the heated area of the glass and the cold edge of the glass [K]
H_x, H_y	Spatial boundaries [m]
JSC Russian Railways	Joint Stock Company Russian Railways
λ	Thermal conductivity coefficient [W/(m K)]
q_{ff}	Density of heat flux from forest fire line [W/m^2]
q_{fd}	Heat flux depend on distance to forest fire [W/m^2]
q_{fh}	Heat flux depend on height of forest fire [W/m^2]
RAD Studio	Rapid Application Development Studio
ρ	Density [kg/m^3]
t	Time coordinate [s]
t_{exp}	Exposure time [s]
T	Temperature in carriage construction [K]
T_{ff}	Flame temperature [K]
v_f	Forest fire propagation speed [m/s]
x,y	Spatial coordinates [m]
xf	Current distance to forest fire to the end of exposure time [m]

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Indexes 1-4	Surface and inner part of carriage wall, glass package and air
Index 0	Initial parameters at t=0 s

I. Introduction

Forecasting, monitoring and assessment of forest fire danger is an important task when taking measures to ensure fire safety of the functioning of railway facilities [1], [2]. In the Russian Federation, forest fires occur for various reasons, including the result of anthropogenic load on forested areas [3], [4]. Objects of JSC Russian Railways are sources of anthropogenic pressure on forested areas [4]. On the other hand, the rolling stock of the railway is exposed to the negative impact of forest fires in the event of forest fires near to the railway line [5], [6]. The main factor affecting a forest fire is the radiant heat flux from the forest fire front [7]-[9]. In the general case, the density of radiant heat from the forest fire front will depend on the type of forest fire, the height of the flame and the speed of its propagation through forest fuels [10]-[14]. In this work, the approach of scenario modeling [15] of forest fire danger [16]-[22] should be used. For definiteness, the article considers the following types of forest fires: low and high intensity surface forest fires, crown forest fires and firestorms [23]-[26]. Meteorological characteristics correspond to the parameters on the territory of the Republic of Buryatia (Russian Federation) [27], [28]. Thus, the goal of the study can be formulated. The aim of the work is the mathematical modeling of heat transfer in the structures of a passenger carriage under the influence of radiation from a forest fire front.

The rest of the article is organized as follows. II. Background, III. Research Object, IV. Mathematical Statement, V. Results and Discussion, VI. Conclusion. Current published results on forest fire impact and constructional materials are described in the Background section. Research object (railway carriage) is described in the Research Object section. Physical and mathematical models are described in the Mathematical Statement section. Key findings and obtained dependences are described in the Results and Discussion section accompanied with some considerations and discussions. A summary of research and further developments are described in the Conclusion section.

II. Background

The analysis of the literature shows that there is a gap in the study of forest fires near railways, especially in the context of the impact of forest fires on the rolling stock of the railway. Some significant works in the field of forest fire analysis near railways are considered. The analysis shows that there is no work that would summarize such research and information on fire incidents. [29], which presents the history of forest fires on the railroad in the forests of Ontario (Canada), is particularly noteworthy. In fact, this is the only full-fledged work on this topic. Even in the early works of the last century [30], it has been indicated that the railway is the most frequent cause of forest fires. The authors of [29] have noted that in connection with the development of railway transport technologies, there has been a decrease in fire incidents caused by the action of this factor. On the other hand, [31] has noted that by 1946 the number of forest fires on the railroad in Canada has doubled due to the development of delivery and industrialization. In 1955 [32], a decrease in the number of forest fires on the railway was again noted. In 2007, it was noted that forest fires on the railway are still an unsolved problem [33]. In [29], in continuation of work [34], the occurrence of forest fires has been investigated; furthermore, the area covered by the fires, and the activity of the railway have been analyzed. It is noted that the transition from solid fuel (coal) to liquid (diesel) has not provided a complete cessation of forest fires on the railway. The authors of [35] cite the main causes and the sources of ignition of forest combustible materials on the railway: the action of brake pads (40.7%), sparks from the exhaust pipe of a locomotive (21.4%), metal cutting on the railway (4.8%), butts of railway employees, etc. passengers (4.5%), fires from fuses and torches (3.5%), fires on railway lines (3.7%), mechanical equipment (2.6%) and a number of other reasons. 6.1% of forest fires have not been identified due to the fire reasons. The assessment of the reliability of buildings and structures is one of the main tasks of modern industry [36]. In recent years, various methods have been developed to assess the reliability of structures [37]-[43].

An integral property of synthetic polymeric materials is their flammability [44]-[46]. The classic way to reduce the flammability of such materials is to add flame retardants to the composition of these materials. It has been shown that combustion retarders reduce the speed of flame propagation and the severity of the fire [47].

Various standard methods are used to test the fire danger of polymers [48]-[50]. In addition, several mathematical models have been developed to study the pyrolysis of materials, for example, Fire Dynamic Simulator [51]-[53], ThermaKin [54]-[56], Gpyro [57]-[59]. These mathematical models have been used to obtain the characteristics of pyrolysis of various combustible materials [60]-[63]. All these models require the use of the full set of material properties in order to calculate the formation of pyrolysis products [44]. These models use chemical kinetics, thermodynamics, and transport of pyrolysis products. At the same time, other studies are known to develop a systematic methodology for assessing the pyrolysis of combustible materials [60]-[71]. It should be noted that composite materials with high flammability are widely used in civil engineering and transport in the form of sandwich panels [72]-[75].

In addition, sandwich panels are used in conjunction with wood and metal materials [76]-[83]. Thermal stresses are the main cause of glass breakage in windows when exposed to fire or radiant heat flux [84]-[87].

Previously published papers show the results of glass destruction when exposed to solar radiation [88], [89]. The impact of fire or intense radiant heat flux on glass leads to its non-uniform heating and subsequent destruction [84]. There is an unambiguous similarity in glass shattering when exposed to solar radiation and fire. However, under conditions of exposure to fire, the density of radiant heat flux is much higher than under exposure to solar radiation. Research on the destruction of glass under the influence of fire has been carried out earlier, both theoretically and experimentally [90]-[95]. When assessing the destruction of glass under fire conditions, both convective and radiant heat fluxes from the fire flame should be taken into account. This should be taken into account when simulating the direct problem of heat conduction. The second process is mechanical destruction of glass. Various works use the Pagni criterion [94]-[99], when it is taken into account that the voltage is directly proportional to ΔT. ΔT is the temperature difference between the heated area of the glass and the cold edge of the glass. The theoretical value ΔT = 80 °C is the limit at which glass breakage begins [97]. When the Pagni criterion is used, temperature is an important parameter for assessing the time when glass breaks. There are restrictions on the use of the Pagni criterion. First, this criterion has been developed for the uniform effect of elevated temperature or radiant heat flux on glass [100]. The second limitation is that the Pagni criterion does not use glass characteristics, which can be different in the production of glass of the same brand or type.

III. Research Object

The object of the study is a passenger carriage, typical for the rolling stock of Russian Railways. Figure 1 shows the appearance of a typical passenger carriage. Figure 2 shows a plan of a passenger carriage of Russian Railways. In Figure 2, numbers indicate [102]: 1 - enclosed platform; 2 - boiler room; 3 – wareroom; 4 – passage; 5 - staff coupe; 6 - conductor coupe; 7 – coupe; 8 – window; 9 – passage; 10 – WC; 11 - second enclosed platform. The subject of the study is heat transfer in the structures of a passenger carriage due to the effect of radiant heat flux from the forest fire front. The paper considers the following types of forest fires: low- and high-intensity surface forest fires, and crown forest fires [103]. The scenario of a low-intensity surface forest fire is described by the following parameters [104]: T_f=900 K, v_f=0.015 m/s. The scenario of a surface forest fire of high intensity is described by the following parameters: T_f=1000 K, v_f=0.05 m/s. The scenario of a crown forest fire is described by the following parameters: T_f=1100 K, v_f=0.33 m/s.

IV. Mathematical Statement

Figure 3 shows a diagram of the solution area. The mathematical model is built taking into account the following physical assumptions:

- Heat transfer in the building envelope is due to conduction, because monolithic structures have been used in computational experiment;
- The only damaging factor of a forest fire is considered, namely, radiant heat flux, due to insufficient distance to take into account convection movement of flame;
- A two-layer structure of the carriage wall is considered due to Pagni criterion limitations;
- The glass unit is considered as a single-layer system, because monolithic structures have been used in computational experiments;
- Thermophysical characteristics of materials do not depend on temperature due to the averaged parameters used to simulate heat transfer;
- The wall of the carriage is considered to be made of metal with internal finishing with polymeric materials, because this structure is described in technical documentation on passenger carriages;
- The monolithic structure of all the elements of the enclosing structure is considered to simplify the computation procedure and to satisfy Pagni criterion;
- The optical characteristics of the surface of the carriage wall are not taken into account;
- Parametric modeling of the propagation of a forest fire front at a given speed is considered to decrease significantly the total computation time.

Fig. 1. External view of a passenger carriage of JSC Russian Railways [101]

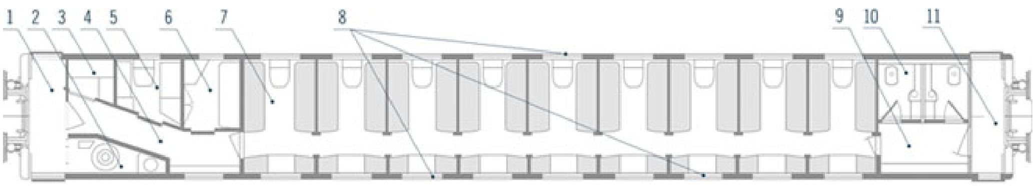


Fig. 2. Scheme of a passenger carriage [102]

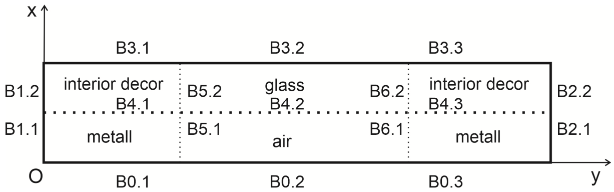


Fig. 3. Solution area diagram

Mathematically, the heat transfer process is described by a system of non-stationary nonlinear differential equations of heat conduction with the corresponding initial and boundary conditions. The finite difference method is used to solve partial differential equations.

Difference analogs of differential equations have been solved by the marching method [105], [106]. The mathematical model is presented below. The system of transient heat transfer equations is:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_1 \frac{\partial T_1}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_1 \frac{\partial T_1}{\partial y}\right) \quad (1)$$

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_2 \frac{\partial T_2}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_2 \frac{\partial T_2}{\partial y}\right) \quad (2)$$

$$\rho_3 c_3 \frac{\partial T_3}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_3 \frac{\partial T_3}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_3 \frac{\partial T_3}{\partial y}\right) \quad (3)$$

$$\rho_4 c_4 \frac{\partial T_4}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_4 \frac{\partial T_4}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_4 \frac{\partial T_4}{\partial y}\right) \quad (4)$$

Initial conditions:

$$T_i\big|_{t=0} = T_{i0} \quad (5)$$

Boundary conditions:

$$B0.1: -\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x=0} = q_{ff} \quad (6)$$

$$B0.2: T_4 = T_e \quad (7)$$

$$B0.3: -\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x=0} = q_{ff} \quad (8)$$

$$B1.1: -\lambda_1 \frac{\partial T_1}{\partial y}\bigg|_{y=0} = 0 \quad (9)$$

$$B1.2: -\lambda_2 \frac{\partial T_2}{\partial y}\bigg|_{y=0} = 0 \quad (10)$$

$$B2.1: -\lambda_1 \frac{\partial T_1}{\partial y}\bigg|_{y=0} = 0 \quad (11)$$

$$B2.2: -\lambda_2 \frac{\partial T_2}{\partial y}\bigg|_{y=0} = 0 \quad (12)$$

$$B3.1: -\lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x=0} = \alpha_{in}\left(T_{in} - T_2\right) \quad (13)$$

$$B3.2: -\lambda_3 \frac{\partial T_3}{\partial x}\bigg|_{x=0} = \alpha_{in}\left(T_{in} - T_3\right) \quad (14)$$

$$B3.3 - \lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x=0} = \alpha_{in}\left(T_{in} - T_2\right) \quad (15)$$

$$B4.1: -\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x=xb} = -\lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x=xb}, \quad T_1 = T_2 \quad (16)$$

$$B4.2: -\lambda_4 \frac{\partial T_4}{\partial x}\bigg|_{x=xb} = -\lambda_3 \frac{\partial T_3}{\partial x}\bigg|_{x=xb}, \quad T_4 = T_3 \quad (17)$$

$$B4.3: -\lambda_1 \frac{\partial T_1}{\partial x}\bigg|_{x=xb} = -\lambda_2 \frac{\partial T_2}{\partial x}\bigg|_{x=xb}, \quad T_1 = T_2 \quad (18)$$

$$B5.1: -\lambda_1 \frac{\partial T_1}{\partial y}\bigg|_{y=xb} = -\lambda_4 \frac{\partial T_4}{\partial y}\bigg|_{y=xb}, \quad T_1 = T_4 \quad (19)$$

$$B5.2: -\lambda_2 \frac{\partial T_2}{\partial y}\bigg|_{y=xb} = -\lambda_3 \frac{\partial T_3}{\partial y}\bigg|_{y=xb}, \quad T_2 = T_3 \quad (20)$$

$$B6.1: -\lambda_4 \frac{\partial T_4}{\partial y}\bigg|_{y=xb} = -\lambda_1 \frac{\partial T_1}{\partial y}\bigg|_{y=xb}, \quad T_4 = T_1 \quad (21)$$

$$B6.2: -\lambda_3 \frac{\partial T_3}{\partial y}\bigg|_{y=xb} = -\lambda_2 \frac{\partial T_2}{\partial y}\bigg|_{y=xb}, \quad T_3 = T_2 \quad (22)$$

The computational formula to determine q_{ff} for surface forest fire influenced on carriage surface [104] is:

$$q_{ff} = \left(q_{fd} + \frac{xf}{50d} q_{fh}\right)/2 \quad (23)$$

The computational formula to determine q_{ff} for crown forest fire influenced on carriage surface [104] is:

$$q_{ff} = \left(q_{fd} + \frac{t_{\exp} xf}{10d} q_{fh}\right)/2 \quad (24)$$

These equations have been obtained as a result of data processing on incident heat flux from forest fire resulted in [10]. These equations are the best fit to experimental data [10].

The computational part to determine heat flux depends on distance to forest fire [10]:

$$q_{fd} = 1000 \times 326.37 \exp\left(-0.2791 xf\right) \tag{25}$$

The computational part to determine heat flux depends on height of forest fire [10]:

$$q_{fh} = 1000 \times \left(16.636 xf + 29.772\right) \tag{26}$$

A brief description of computational procedure is done as the following instructions [107]. The first stage is a setting-up of parameters (thermophysical, geometrical and thermochemical characteristics) and initial data. At present, air temperature can be used as initial temperature for all three layers of birch leaf. In addition, at this stage time exposure and forest fire front temperature can be defined. This stage is also used to determine spatial and temporal step for computational mesh.

At present time uniform discretization is used both for spatial and temporal coordinate. The next stage is computational circle within time exposure consisting of two sub-circles to compute in x and z directions, while another coordinate is fixed. Thus, each sub-circle has computed a set of one-dimensional tasks of heat conductivity in x and z directions. Each one-dimensional task can be described as a sequence of forward and backward run for marching method. Forward run begins from the computation of the first run-through coefficients using left boundary conditions, then the computation of all the coefficients is processed. Backward run begins from computational right temperature using right boundary conditions, then computation of all the temperature distribution on definite direction is processed.

It should be taken into account that a simple iteration method is used to resolve nonlinear terms of equations at each sub-circle. After computational procedure is complete, the results are written in data files.

Computational procedure is realized in RAD Studio Software using Delphi high level programming language [108]. Then these data files are analyzed and visualized using Origin Pro software [109].

V. Results and Discussion

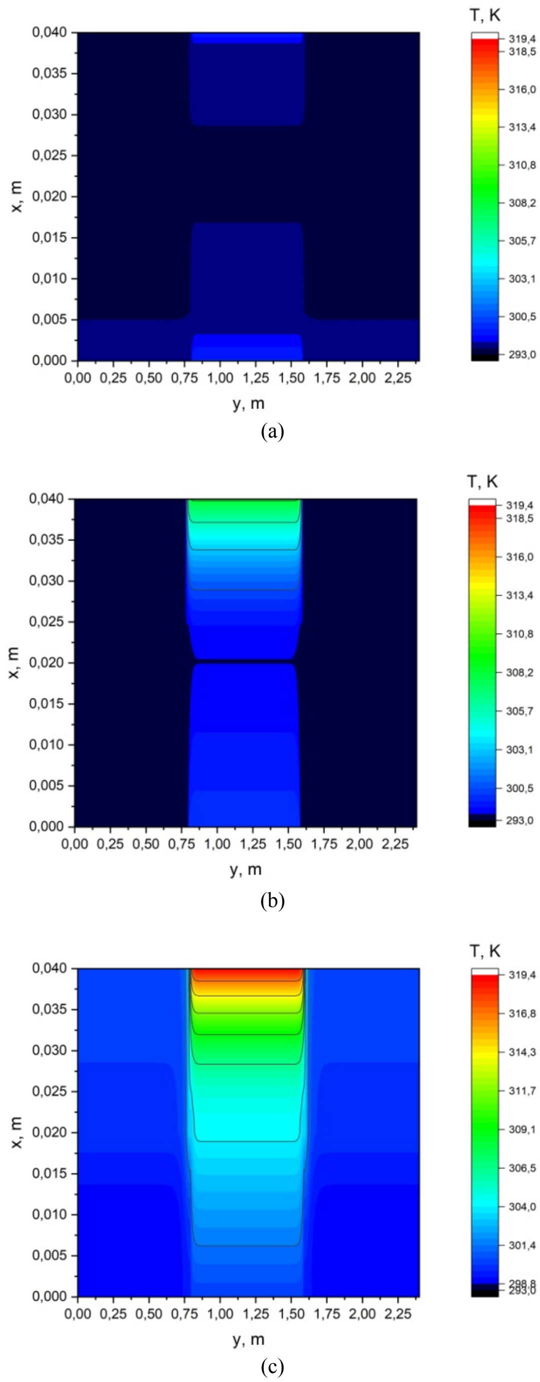
In this work, a scenario simulation of the impact of forest fires on the structure of a passenger carriage is carried out.

Scenario 1: the impact of a low-intensity surface forest fire, taking into account the meteorological conditions typical for the summer forest fire danger.

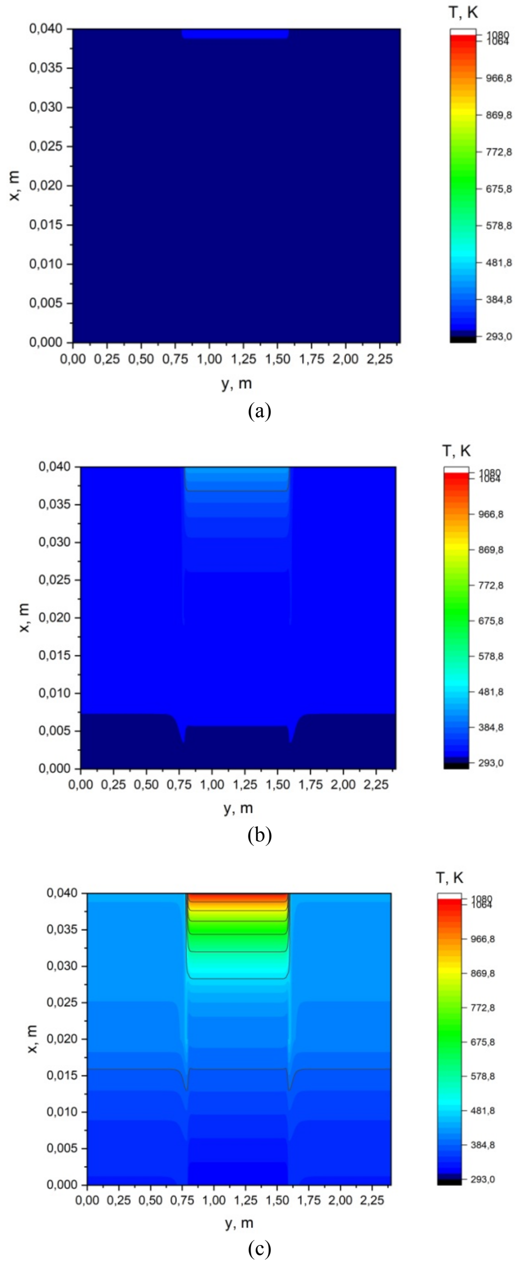
Figures 4 show the temperature fields in the enclosing structure of a passenger carriage for the scenario of the impact of a low-intensity surface forest fire.

Scenario 2: the impact of a surface forest fire of high intensity, taking into account the meteorological conditions typical for the summer period of forest fire danger. Figures 5 show the temperature fields in the enclosing structure of a passenger carriage for the scenario of the impact of a high-intensity surface forest fire.

Scenario 3: the impact of a crown forest fire, taking into account the meteorological conditions typical of the summer forest fire danger. Figure 6 shows the temperature field in the enclosing structure of a passenger carriage for the scenario of the impact of a crown forest fire.



Figs. 4. Temperature fields in the enclosing structure of a passenger carriage for the scenario of the impact of a low-intensity surface forest fire: (a) 125 s; (b) 300 s; (c) 425 s



Figs. 5. Temperature fields in the enclosing structure of a passenger carriage for the scenario of the impact of a high-intensity surface forest fire: (a) 125 s; (b) 300 s; (c) 425 s

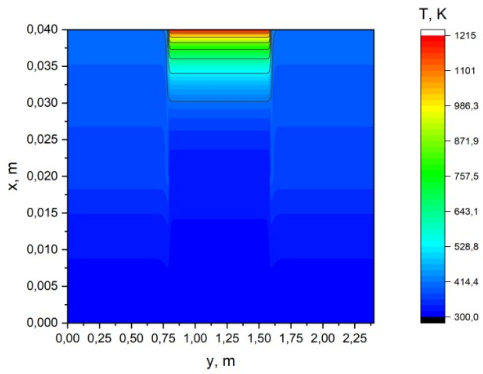


Fig. 6. Temperature field in the enclosing structure of a passenger carriage for the scenario of the impact of a crown forest fire at 75 s exposure

In this article, a parametric modeling of a forest fire has been used. The calculation of the distance from the forest fire front to the outer surface of the passenger carriage wall is carried out. The calculation time is selected over 50 seconds. It is considered that this is a sufficient calculation time interval in order to take into account the movement of a passenger carriage along the railway at different speeds. The analysis of the results in Figures 4 shows that when exposed to a low-intensity surface forest fire, the radiant heat flux from the edge of the fire does not lead to any dangerous heating of the structures of a passenger carriage during its typical movement along the perpendicular to the line of movement of the carriage. Even on the surface of the carriage, the temperature by the end of the impact does not exceed 300 K. Therefore, under the scenario of the impact of a low-intensity surface forest fire, there is no danger of thermal injuries or the fire of the inner lining of the carriage. This is a relatively safe scenario for the impact of a forest fire on a passenger carriage. The analysis of temperature distributions shows that the Pagni criterion is not met and the glass remains undisturbed at various times of exposure to radiant heat flux from the front of a low-intensity surface forest fire. The analysis of the results in Figures 5 shows that when exposed to a high-intensity surface forest fire, the radiant heat flux does not lead to dangerous heating of the passenger carriage structures for the indicated period of exposure.

Only on the surface of the wall of a passenger, a carriage temperature of 380-400 K is reached. However, it should be noted that the speed of advancement of the front of a surface forest fire of high intensity is relatively low and this determines the fact that there is no significant heating of the structural materials of the passenger carriage. In the event of a strong deceleration of the train movement or its complete stop, the period of exposure to a surface forest fire of high intensity may be higher and, accordingly, the temperatures in the structure of constructional materials of a passenger carriage will also be higher. Therefore, it should be considered that the scenario of the impact of a high-intensity surface forest fire is potentially dangerous. When exposed to a radiant heat flux from the front of a forest fire for a short time, no glass breakage is observed. At times above 125 seconds, the temperature difference ΔT is already greater than 80 K and, accordingly, the destruction of the glass material in the passenger carriage should be observed.

The analysis of the results in Figure 6 shows that in the event of a crown forest fire, the structural materials of the passenger carriage warm up quite well along the depth of the wall. Moreover, in the near-surface layers, they reach temperatures at which wood-glued and polymer materials are subject to thermal decomposition.

This, at least, can lead to the poisoning of passengers and employees serving the carriage during this period. In case of prolonged exposure and damage to the windows in the passenger carriage, a fire may develop. Therefore, the scenario of the impact of a crown forest fire is dangerous and the passengers of the train should be evacuated. In the scenario of a crown forest fire, the thermal effect will always be accompanied by glass breakage. Thus, the analysis of the results of the work done makes it possible to establish three levels of danger of the impact of forest fires on a passenger carriage on the railway. The safest scenario is the impact of a low-intensity surface forest fire, when structural materials and glass in the passenger carriage warm up slightly and there is no danger of a fire inside the passenger carriage.

In this case, other damaging factors of the forest fire, for example, the formation of soot particles, can pose a danger. However, this is the subject of a separate study.

The scenario of the impact of a surface forest fire of high intensity is a potentially dangerous scenario, since with prolonged exposure to a radiant heat flux from the front of a high-intensity surface forest fire, there may be significant heating temperatures for the interior of the carriage. This can lead to their thermal decomposition and, as a result, to the poisoning of passengers and railway employees who are in the passenger carriage. In addition, with prolonged exposure to radiation, glass in the passenger carriage may break and, accordingly, the radiant heat flux will directly affect the people in the passenger carriage. It is also possible that the convective heat flow and the burning particles escaping from the forest fire front directly affect the structural materials inside the passenger carriage and the people in the carriage. The scenario of the impact of a crown forest fire is unambiguously dangerous and it is accompanied by both thermal destruction of the interior trim of the passenger carriage and the destruction of glass in the carriage window. As a result, passengers and employees of the railway in a passenger carriage will be exposed to the whole range of damaging factors of a forest fire. Only evacuation can help preserving the health and life of passengers and railway employees in the carriage in this scenario of the impact of a crown forest fire. This work opens in the future a whole block of studies on the impact of damaging factors of forest fires on the structural materials of a passenger carriage and the people in it. The results obtained in this work and the ones expected in future studies will create a physical basis for the development of software for fire safety systems for rolling stock on the railway. In addition, it is necessary to develop physical and mathematical models for analyzing fire safety when forest fires affect other types of cars in the rolling stock of the railway. In particular, it is necessary to develop such models for cars that are used to transport potentially dangerous goods and flammable liquids and materials. It is necessary to conduct a critical analysis of the results obtained and the proposed mathematical model of heat transfer in the structure of a passenger carriage. First, it should be noted that the indisputable advantage of this work is the fundamental possibility of simulating the impact of various forest fires on a passenger carriage. No similar works have been found in scientific periodicals. This is because there are no mathematical models that would take into account the processes occurring in the forest fire front when it affects a passenger carriage. In this work, the analytical dependences [104], which have made it possible to calculate the parameters of the thermal effect of a forest fire on a passenger carriage, are used. The use of the specified parameterization of a forest fire is also an advantage of this mathematical model, since the time for calculating the parameters of a forest fire does not have a noticeable effect on the total time for calculating heat transfer in the structure of a passenger carriage. For example, the general mathematical model of a forest fire [7] is known.

Simplified mathematical models derived from this mathematical model require a sufficiently powerful calculator for their software implementation. Thus, the proposed mathematical model opens up prospects for the development of information and computing systems for fire safety of rolling stock on the railway. It is also necessary to discuss the limitations of the proposed mathematical model of heat transfer in the structure of a passenger carriage when exposed to forest fires. The proposed mathematical model uses the Pagni criterion to assess the destruction of a glass unit in the wall of a passenger carriage. The limitations of the proposed mathematical model follow from the limitations of the Pagni criterion used. This criterion cannot be applied in cases where the density of the radiant heat flux incident on the wall of the passenger carriage is locally not uniform. Thus, now it is impossible to apply the developed mathematical model in a three-dimensional setting, since it is necessary to generalize the Pagni criterion for the case of non-uniform thermal effects. The second limitation is related to the application of formulas for parameterization of a forest fire [104]. These formulas are valid only in the range of distance from the forest fire front to the object from 0 to 20 meters. For other values of the distance from the forest fire front to the object, the formulas will give an incorrect result in terms of the magnitude of the radiant heat flux.

Therefore, it is only possible to carry out scenario modeling on the impact of a forest fire on a passenger carriage. It is impossible to organize continuous monitoring with constant tracking of the movement of the forest fire front from its place of ignition to the object. It is necessary to verify the results obtained in this work. A direct comparison of the results obtained with previously published results is impossible, since similar results on the study in the wall of a passenger carriage under the influence of a forest fire have not been published so far. As already mentioned, one of the main reasons is the impossibility of simulating the conditions of the thermal effect of a forest fire on a passenger carriage. However, a qualitative comparative analysis of the results of modeling heat transfer in the wall of a passenger carriage and in the enclosing structures of a wooden building can be carried out [104]. A comparative analysis of the results shows that there is a qualitative agreement of the results, both in spatial coordinates and in time. The quantitative differences are due to different thermophysical characteristics of wood-glued materials and structural materials used in the manufacture of a passenger carriage. Thus, this paper presents the results of mathematical modeling of heat transfer in the structures of a passenger carriage. The scenarios of the impact of low and high intensity surface forest fires, as well as crown forest fires are considered. Modeling has shown that a low-intensity surface forest fire represents a relatively safe forest fire impact scenario, while a high-intensity surface forest fire impact is a potentially dangerous impact scenario. The scenario of the impact of a crown forest fire is unambiguously dangerous. An important point is the fact that in some cases it is possible to break glass in the window of a passenger carriage.

This leads to the fact that people inside the carriage can be exposed to the whole range of damaging factors of a forest fire. Further comprehensive work is required to create physical and mathematical models of the impact of forest fires on other types of cars in the rolling stock of the railway. The results obtained can be used to create software for monitoring and predicting the fire safety of rolling stock in case of forest fires near the railway.

VI. Conclusion

In this work, a new physical and mathematical model of heat transfer in the wall of a passenger carriage under the influence of a forest fire is proposed. A parametric modeling of the front propagation of various types of forest fires has been carried out. Three types of fires are considered: surface forest fires of low and high intensity, as well as a crown forest fire. The main advantage of the proposed mathematical model is the ability to simulate heat transfer conditions in the wall of a passenger carriage when exposed to a forest fire. The conditions and the degree of fire safety of the impact of forest fires on the structure of a passenger carriage have been established. The most dangerous scenario is the impact of a crown forest fire, when both direct thermal effects and emissions of pollutants pose an immediate danger to passengers.

The Pagni criterion has been used to assess the conditions for the destruction of a glass unit in the wall of a passenger carriage. The limitations of the criterion lead to the limitations of the proposed mathematical model, namely, the impossibility of using the mathematical model in a three-dimensional setting.

The proposed mathematical model of heat transfer in the wall of a passenger carriage opens up prospects for the development of information and computing systems for predicting, assessing, and monitoring the fire safety of railway rolling stock under the influence of forest fires.

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References

[1] Baranovskiy N.V. (2020). Predicting, Monitoring, and Assessing Forest Fire Dangers and Risks. *IGI Global*. doi: http://doi:10.4018/978-1-7998-1867-0

[2] Martynyuk I.V., Shevchenko A.I., Denisov V.V. Features of ensuring the stability of the transportation process on railway transport in conditions of natural disasters, *Science and technology of transpor*t. 2020. N 1. P. 108-116. (In Russian)

[3] Brushlinsky N.N, Ahrens M, Sokolov S.V, Wagner P. World fire statistics // *International Association of fire and rescue services*, 2019, №24, 68p.

[4] Baranovskiy N.V. (2020) Mathematical Simulation of Anthropogenic Load on Forested Territories for Point Source. In N. Baranovskiy (Ed.), *Predicting, Monitoring, and Assessing Forest Fire Dangers and Risks*. (pp. 64-88). Hershey, PA: IGI Global. doi:10.4018/978-1-7998-1867-0.ch003

[5] Ilyavin M.V., Katin V.D. On the problem of ensuring fire safety during the reform of the Transsib // In the collection: Transsib: at the forefront of reforms. *Materials of the international scientific and practical conference*. Irkutsk State University of Railways; Transbaikal Institute of Railway Transport. 2016. P. 254-259. (In Russian).

[6] Loehle C. Historical forest changes in the western united states // *Forestry Chronicle*. 2020. Vol. 96, pp. 36-49.

[7] Grishin A. M. *Mathematical modeling of forest fire and new methods of fighting them*. Russia. Tomsk: Publishing House of the Tomsk State University, 1997. 390 P.

[8] Balbi J.H., Chatelon F.J., Morvan D., Rossi J.L., Marcelli T., Morandini F. A convective-radiative propagation model for wildland fires // *International Journal of Wildland Fire*. 2020. Vol. 29, pp. 723-738.

[9] Frangieh N., Accary G., Morvan D., Méradji S., Bessonov O. Wildfires front dynamics: 3D structures and intensity at small and large scales // *Combustion and Flame*. 2020. Vol. 211, pp. 54-67.

[10] Valendik E.N., Kosov I.V. Effect of thermal radiation of forest fire on the environment. *Contemporary Problems of Ecology*. 2008, 1, p. 399–403. doi:10.1134/S1995425508040012

[11] Pais C., Carrasco J., Elimbi Moudio P., Shen Z.-J.M. Downstream protection value: Detecting critical zones for effective fuel-treatment under wildfire risk // *Computers and Operations Research*. 2021. Vol. 131, Article N 105252.

[12] Francos M., Úbeda X. Prescribed fire management // *Current Opinion in Environmental Science and Health*. 2021. Vol. 21, Article N 100250.

[13] Elimbi Moudio P., Pais C., Shen Z.-J.M. Quantifying the impact of ecosystem services for landscape management under wildfire hazard // *Natural Hazards*. 2021. Vol. 106, pp. 531-560.

[14] Dillon W.W., Hiatt D., Flory S.L. Experimental manipulation of fuel structure to evaluate the potential ecological effects of fire // *Forest Ecology and Management*. 2021. Vol. 482. Article N 118884.

[15] Baranovskiy N.V. *Mathematical modeling of the most probable scenarios and conditions for the occurrence of forest fires*. PhD Thesis. Tomsk: Tomsk State University, 2007. 153 P. (In Russian).

[16] Kosov I.V., Yakubailik O.E. Development of the prototype of a geo-information web system for dynamic visualization of forest fire hazard // *IOP Conference Series: Earth and Environmental Science*. 2021. Vol. 677. Article N 032102.

[17] Jamal S., Bappy T.H., Shahariar Azad Rabby A.K.M. Brazilian Forest Fire Analysis: An Unsupervised Approach // *Advances in Intelligent Systems and Computing*. 2021. Vol. 1248, pp. 423-435.

[18] Daşdemir İ., Aydın F., Ertuğrul M. Factors Affecting the Behavior of Large Forest Fires in Turkey // *Environmental Management*. 2021. Vol. 67. pp. 162-175.

[19] Fonseca C E.R., Marcillo D., Jácome-Guerrero S.P., Gualotuña T., Cruz H. Identifying Technological Alternatives Focused on Early Alert or Detection of Forest Fires: Results Derived from an Empirical Study // *Advances in Intelligent Systems and Computing*. 2021. Vol. 1326, pp. 354-368.

[20] Müller M.M., Vilà-Vilardell L., Vacik H. Towards an integrated forest fire danger assessment system for the European Alps // *Ecological Informatics*. 2020 Vol. 60. Article N 101151.

[21] Eskandari S., Amiri M., Sãdhasivam N., Pourghasemi H.R. Comparison of new individual and hybrid machine learning algorithms for modeling and mapping fire hazard: a supplementary analysis of fire hazard in different counties of Golestan Province in Iran // *Natural Hazards*. 2020. Vol. 104, pp. 305-327.

[22] Laneve G., Pampanoni V., Shaik R.U. The daily fire hazard index: A fire danger rating method for mediterranean areas // *Remote Sensing*. 2020. Vol. 12. Article N 2356.

[23] Grishin A.M., Dolgov A.A., Zima V.P., Subbotin A.N., Tsvyk R.S.H. Experimental and theoretical investigation of the effect of radiation and combined heat transfer on initiation and spread of surface forest fires // *Heat Transfer Research*, 2002, Vol. 33, pp. 502-514.
doi: 10.1615/heattransres.v33.i7-8.50

[24] Perminov V.A., Marzaeva V.I. Mathematical Modeling of Crown Forest Fire Spread in the Presence of Fire Breaks and Barriers of Finite Size // *Combustion, Explosion and Shock Waves*, 2020, Vol. 56, pp. 332-343.
doi: 10.1134/S0010508220030107

[25] Strokatov A.A. *Physical modeling of fire and heat tornadoes*. Abstract of Ph.D. Thesis. Tomsk: Tomsk State University, 2007. 20 p. (In Russian)

[26] Grishin A.M., Golovanov A.N., Kolesnikov A.A., Strokatov A.A., Tsvyk R.Sh. Experimental investigation of the thermal and fire tornadoes // *Doklady Akademii Nauk*, 2005, Vol. 400, pp. 618-620.

[27] Badmaev N., Bazarov A. Correlation analysis of terrestrial and satellite meteodata in the territory of the Republic of Buryatia (Eastern Siberia, Russian Federation) with forest fire statistics // *Agricultural and Forest Meteorology*, 2021, Vol. 297, Article N 108245.
doi: 10.1016/j.agrformet.2020.108245

[28] Badmaev N.B., Bazarov A.V., Sychev R.S. (2020). Forest Fire Danger Assessment Using Meteorological Trends: Case Study. In Baranovskiy, N. V. (Ed.), *Predicting, Monitoring, and Assessing Forest Fire Dangers and Risks* (pp. 183-208). IGI Global.
doi: http://doi:10.4018/978-1-7998-1867-0.ch008

[29] Grunstra M.R., Martell D.L. A history of railway fires in Ontario's forests // *The Forestry Chronicle*. 2014. Vol. 90. P. 314 – 320.

[30] Leavitt C. Railway fire protection in Canada // *The Forestry Chronicle*. 1928. Vol. 4. P. 10 – 19.

[31] Beall H.W. Wartime influence on forest fires in Canada // *The Forestry Chronicle*. 1946. Vol. 22. P. 25 – 29.

[32] Beall H.W. Theme address- - fire highlights in the development of forest fire protection in Canada // *The Forestry Chronicle*. 1955. Vol. 31. P. 332 – 337.

[33] CIFFC. Railway fire prevention task team, Canadian Interagency Forest Fire Centre. Wildland fires resulting from railway operations – a public safety threat submission to the Advisory Panel, Railway Safety Act Review. (Accessed 06 March 2021). Available: http://www.tc.gc.ca/media/documents/rsa-lsf/ciffc.pdf

[34] Grunstra M.R., Martell D.L. Along a rickety road: one hundred years of railway fire in Ontario's forests // *Forestory*. 2013. Vol. 4. P. 5 – 10.

[35] Pottharst E., Mar B.W. Wildfire prevention engineering systems // *Canadian Journal of Forest Research*. 1981. Vol. 11. P. 324 – 333.

[36] Beskopylny A., Veremeenko A., Kadomtseva E., Anysz H. Monitoring of metal structures with the dynamic methods // *AIP Conference Proceedings*. 2019. Vol. 2188. Article 060012.

[37] Chen Y., Bescou N.D., Qian J. Soil dynamics and earthquake engineering. 2018. Vol. 107. P. 292 – 302.

[38] Beskopylny A., Veremeenko A., Shilov A. Diagnostics of steel structures with the dynamic non-destructive method *MATEC Web of Conferences*. 2019. Vol. 279. Article 02003.

[39] Serov A. Cognitive Sensor Technology for Structural Health Monitoring, *Procedia Structural Integrity*. 2017. Vol. 5. P. 1160 – 1167.

[40] Sung Y.-Ch., Lin T.-K., Chiu Y.-T., Chang K.-Ch., Chen K.-L. Chang Ch.-Ch. *Engineering Structures*. 2016. Vol. 126. P. 571 – 585.

[41] Hosseinaei S., Ghasemi M.R., Etedali S. Optimal design of passive and active control systems in seismic-excited structures using a new modified tlbo // *Periodica Polytechnica Civil Engineering*. 2021. Vol. 65, pp. 37-55.

[42] Liu Z., Jiang N., Zhou C., Ji L., Luo X. Damage effect of terrorist attack explosion-induced shock wave in a double-deck island platform metro station // *Periodica Polytechnica Civil Engineering*. 2021. Vol. 65, pp. 215-228.

[43] Giaccu G.F., Solinas D., Briseghella B., Fenu L. Time-Dependent Analysis of Precast Segmental Bridges // *International Journal of Concrete Structures and Materials*. 2021. Vol. 15. Article N 13.

[44] Ding Y., Stoliarov S.I., Kraemer R.H. Pyrolysis model development for a polymeric material containing multiple flame retardants: Relationship between heat release rate and material composition // *Combustion and Flame*. 2019. Vol. 202. P. 43 – 57.

[45] Wong J.F., Chan J.X., Hassan A., Mohamad Z., Othman N. Thermal and flammability properties of wollastonite-filled thermoplastic composites: a review // *Journal of Materials Science*. 2021. Vol. 56, pp. 8911-8950.

[46] Khuntia T., Biswas S. An investigation on the flammability and dynamic mechanical behavior of coir fibers reinforced polymer composites // *Journal of Industrial Textiles*. 2020 (Article in Press)

[47] Weil E.D., Levchik S.V. *Flame retardants for plastics and textiles: practical applications*. Carriagel Hanser Verlag GmbH Co KG. 2015.

[48] ASTM E1354-15 Standard test method for heat and visible smoke release rates for materials and products using oxygen consumption calorimeter. 2007.

[49] Tests for flammability of plastic materials for parts in devices and appliances. Underwrit. Lab. Inc. 2015.

[50] ASTM E2058-13a Standard test methods for measurement of material flammability using a fire propagation apparatus (FPA). 2013.

[51] McGrattan K., Hostikka S., McDermott R., Floyd J., Weinschenk C., Overholt K. Sixth edition fire dynamic simulator technical reference guide volume 1: mathematical model. *NIST special publication*. 2017. 147 P.

[52] Elhelw M., El-Shobaky A., Attia A., El-Maghlany W.M. Advanced dynamic modeling study of fire and smoke of crude oil storage tanks // *Process Safety and Environmental Protection*. 2021. Vol. 146, pp. 670-685.

[53] Salamonowicz Z., Krauze A., Majder-Lopatka M., Dmochowska A., Piechota-Polanczyk A., Polanczyk A. Numerical reconstruction of hazardous zones after the release of flammable gases during industrial processes // *Processes*. 2021. Vol. 9. Article N 307, pp. 1-17.

[54] Stoliarov S.I., Lyon R.E. Thermo-kinetic model of burning for pyrolyzing materials // *Fire Safety Science*. 2008. Vol. 9. P. 1141 – 1152.

[55] Gong J., Zhu H., Zhou H., Stoliarov S.I. Development of a pyrolysis model for oriented strand board. Part I: Kinetics and thermodynamics of the thermal decomposition // *Journal of Fire Sciences*. 2021. Vol. 39, pp. 190-204.

[56] Swann J.D., Stoliarov S.I. Determination of pyrolysis and combustion properties of poly(vinylidene fluoride) using comprehensive modeling: Relating heat transfer to the intumescent char's porous structure // *Fire Safety Journal*. 2021. Vol. 120, Article N 103086.

[57] Lautenberger C., Fernandez-Pello C. Generalized pyrolysis model for combustible solids // *Fire Safety Journal*. 2009. Vol. 44. P. 819 – 839.

[58] Vermesi I., Richter F., Chaos M., Rein G. Ignition and Burning of Fibreboard Exposed to Transient Irradiation // *Fire Technology*. 2021. Vol. 57, pp. 1095-1113.

[59] Roenner N., Yuan H., Krämer R.H., Rein G. Computational study of how inert additives affect the flammability of a polymer // *Fire Safety Journal*. 2019. Vol. 106, pp. 189-196.

[60] Li J., Gong J. Stoliarov S.I. Gasification experiments for pyrolysis model parameterization and validation // *International Journal of Heat and Mass Transfer*. 2014. Vol. 77. P. 738 – 744.

[61] Li J., Gong J., Stoliarov S.I. Development of pyrolysis models for charring polymers // *Polym. Degrad. Stab*. 2015. Vol. 115. P. 138 – 152.

[62] Vermesi I., Roenner N., Pironi P., Hadden R.M., Rein G. Pyrolysis and ignition of a polymer by transient irradiation // *Combustion and Flame*. 2016. Vol. 163. P. 31 – 41.

[63] Linteris G.T., Lyon R.E., Stoliarov S.I. Prediction of the gasification rate of thermoplastic polymers in fire-like environments // *Fire Safety Journal*. 2013. Vol. 60. P. 14 – 24.

[64] Li J., Stoliarov S.I. Measurement of kinetics and thermodynamics of the thermal degradation for non-charring polymers // *Combustion and Flame*. 2013. Vol. 160. P. 1287 – 1297.

[65] Li J., Stoliarov S.I. Measurement of kinetics and thermodynamics of the thermal degradation for charring polymers // *Polym. Degrad. Stab*. 2014. Vol. 106. P. 2 – 15.

[66] McKinnon M.B., Stoliarov S.I., Witkowski A. Development of a pyrolysis model for corrugated carriagedboard // *Combustion and Flame*. 2013. Vol. 160. P. 2595 – 2607.

[67] McKinnon M.B., Stoliarov S.I. Pyrolysis model development for a multilayer floor covering // *Materials*. 2015. Vol. 8. P. 6117 – 6153.

[68] McKinnon M.B., Ding Y., Stoliarov S.I., Crowley S., Lyon R.E. Pyrolysis model for a carriagebon fiber/epoxy structural aerospace composite // *Journal of Fire Science*. 2017. Vol. 35. P. 36 – 61.

[69] Lautenberger C., Rein G., Fernandez-Pello C. The application of a genetic algorithm to estimate material properties for fire modeling from bench-scale fire test data // *Fire Safety Journal*. 2006. Vol. 41. P. 204 – 214.

[70] Chaos M., Khan M.M., Krishnamoorthy N., De Ris J.L., Dorofeev S.B. Evaluation of optimization schemes and determination of solid fuel properties for CFD fire models using bench-scale pyrolysis tests // *Proceedings of Combustion Institute*. 2011. Vol. 33. P. 2599 – 2606.

[71] Kim E., Dembsey N. Parameter estimation for comprehensive pyrolysis modeling: guidance and critical observations // *Fire Technology*. 2015. Vol. 51. P. 443 – 477.

[72] Toubia E.A., Sihn S., Pitz J., Vernon J.P., Flores M., Parks S. Thermal response and edgewise compression failure of thermally degraded sandwich composite structures // *Composite Structures*. 2021. Vol. 256. Article 113070.

[73] Upasiri I.R., Konthesigha K.M.C., Nanayakkara S.M.A., Poologanathan K., Gatheeshgar P., Nuwanthika D. Finite element analysis of lightweight composite sandwich panels exposed to fire // *Journal of Building Engineering*. 2021. Vol. 40, Article N 102329.

[74] Wang H., Li S., Liu Y., Wang P., Jin F., Fan H. Foam-filling techniques to enhance mechanical behaviors of woven lattice truss sandwich panels // *Journal of Building Engineering*. 2021. Vol. 40, Article N 102383.

[75] Xie H., Fang H., Li X., Wan L., Wu P., Yu Y. Low-velocity impact damage detection and characterization in composite sandwich panels using infrared thermography // *Composite Structures*. 2021. Vol. 269, Article N 114008.

[76] LaMalva K.J. *Structural fire engineering*. Reston, VA: American Society of Civil Engineering. 2018.

[77] Buchanan A.H., Abu A.K. *Structural design for fire safety*. John Wiley & Sons. 2017.

[78] Wang W., Kodur V., Yang X., Li G. Experimental study on local buckling of axially compressed steel stub columns at elevated temperatures // *Thin-Walled Struct*. 2014. Vol. 82. P. 33 – 45.

[79] Ryder N.L., Wolins S.D., Milke J.A. An investigation of the reduction in fire resistance of steel columns caused by loss of spray-applied fire protection // *Journal of Fire Protection Engineering*. 2002. Vol. 12. P. 31 – 44.

[80] Wang W.-Y., Li G.-Q. Behavior of steel columns in a fire with partial damage to fire protection // *Journal of Construct Steel Res.* 2009. Vol. 65. P. 1392 -1400.

[81] Birman V., Kardomateas G.A., Simitses G.J., Li R. Response of a sandwich panel subject to fire or elevated temperature on one of the surfaces // *Compos Part A: Appl Sxi Manuf.* 2006. Vol. 37. P. 981 – 988.

[82] Kardomateas G.A., Simitses G.J., Birman V. Structural integrity of composite columns subject to fire // *Journal of Compos Mater*. 2009. Vol. 43. P. 1015-1033.

[83] Toubia AE., Flores M., Rapking D. *A systematic experimental approach for damage quantification in sandwich structures under low-heat fire induced damage*. American Society for Composites. 2019. DEStech Publications, Inc.

[84] Dembele S., Rosario R.A.F., Wen J.X. Thermal breakage of window glass in room fire conditions – analysis of some important parameters // *Building and Environment*. 2012. Vol. 54. P. 61 – 70.

[85] Lester B.T., Long K.N. A constitutive model for glass–ceramic materials // *Mechanics of Materials*. 2021. Vol. 158. Article N 103849.

[86] Hu K., Li S., Fan Z., Yan H., Liang X., Cai Y., Zhu Q., Zhang Y. Contributions of mechanical bonding and chemical bonding to high-temperature hermeticity of glass-to-metal compression seals // *Materials and Design*. 2021. Vol. 202, Article 109579.

[87] Lin J., Lin P., Ao R., Xing L., Lin T., He P., Li J., Yang W. Microstructure evolution and mechanical properties of YAG/YAG joint using bismuth-borate glass // *Journal of the European Ceramic Society*. 2021. Vol. 41, pp. 2847-2854.

[88] Mai Y.W., Jacob L.J.S. Thermal stress fracture of solar control window panes caused by shading of incident radiation // *Mater Struct.* 1980. Vol. 13. P. 283 – 288.

[89] Pilette C.F., Taylor D.A. Thermal stresses in double-glazed windows // *Canadian Journal of Civil Engineering*. 1988. Vol. 15. P. 807 – 814.

[90] Emmons H.W. The needed fire science // *Proceedings of the First International Symposium of Fire Safety Science*. Berkeley, California. IAFSS. 1986. P. 33 – 53.

[91] Barth P.K., Sung H. *Glass fracture under intense heating. Senior project report.* Cambridge: Harvard University. 1977.

[92] Pagni P.J. Fire physics – promises, problems and progress // *Proceedings of the Second International Symposium on Fire Safety Science*. Tokyo, Japan: IAFSS. 1989. P. 49 – 66.

[93] Hassani S.K.S., Shields T.J., Silcock G.W.H.Thermal fracture of window glazing: performance of glazing in fire // *Journal of Applied Fire Science*. 1994. Vol. 4. P. 249 – 263.

[94] Pagni P.J. Thermal glass breakage // *Proceedings of the Seventh International Symposium on Fire Safety Science*. Worchester, MA, USA: IAFSS. 2002. P. 3 – 22.

[95] Chow W.K., Gao Y., Chow C.L. A review on fire safety in buildings with glass façade // *Journal of Applied Fire Science.* 2006-2007. Vol. 16. P. 201 – 223.

[96] Guzzillo B.R., Pagni P.J. Thermal breakage of double-pane glazing by fire // *Journal of Fire Protection Engineering*. 1998. Vol. 9. P. 1 – 11.

[97] Keski-Rahkonen O. Breaking of window glass close to fire // *Fire Materials*. 1988. Vol. 12. P. 61-69.

[98] Pagni P.J., Joshi A.A. Glass breaking in fires // *Proceedings of the Third International Symposium on Fire Safety Science*. Edinburg, UK: IAFSS. 1991. P. 791 – 802.

[99] Joshi A.A., Pagni P.J. Fire-induced thermal fields in window glass – I Theory // Fire Safety Journal. 1994. Vol. 22. P. 25 – 43.

[100] Shields T.J., Silcock GW.H., Flood M. Performance of a single glazing assembly exposed to fire in the centre of an enclosure // *Fire Materials*. 2002. Vol. 26. P. 51 – 75.

[101] Carriageriage. (Accessed 03 May 2021) Available: http://www.train-photo.ru/

[102] Carriageriage characteristics. (Accessed 03 May 2021) Available: http://www.tvz.ru/catalog/passenger/item_detail.php?ELEMENT_ID=180

[103] Grishin A.M. *Mathematical modeling of forest fires and new ways fighting them*. Novosibirsk: Science. 1992. 411 p. (In Russian)

[104] Baranovskiy N., Malinin A. Mathematical simulation of forest fire impact on industrial facilities and wood-based buildings // *Sustainability*. 2020. Vol. 12. Article 5475.

[105] Samarskii A.A. *The theory of difference schemes*. New York – Basel. Marcel Dekker, Inc, 2001, 761 P.

[106] Samarskii A.A., Vabishchevich P.N. *Computational Heat Transfer, Vol. 1. Mathematical Modeling* (Chichester, Wiley, 1995)

[107] Baranovskiy, N., Kirienko, V., Mathematical Simulation of Forest Fuel Element at the Crown Forest Fire Impact Taking Into

Account Multiphase Reactive Media Mechanics Fundamentals, (2020) *International Review of Mechanical Engineering (IREME)*, 14 (8), pp. 504-515.
doi: https://doi.org/10.15866/ireme.v14i8.19655
[108] RAD Studio Accessed: 2021-05-03: https://www.embarcadero.com/ru/products/rad-studio
[109] Origin Lab Official web-site Accessed: 2021-05-03: https://www.originlab.com/

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