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TEMPERATURE EFFECT ON THE THERMAL-PHYSICAL PROPERTIES OF FIRE-PROTECTIVE MINERAL WOOL CLADDING OF STEEL STRUCTURES UNDER THE CONDITIONS OF FIRE RESISTANCE TESTS

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The value of the thermal conductivity coefficient depending on the temperature of the samples of steel rod fragments with fire-retardant cladding has been determined in the present research.

The thermal conductivity coefficient of mineral wool fire-retardant cladding was determined; special patterns of its dependence on temperature were revealed. This is explained by the thermal decomposition with the release of thermal energy of inclusions between the fibers of mineral wool and its fibers at a temperature of 750 °C. The apparent minimum of the thermal conductivity factor for fire-retardant mineral wool cladding with a thickness of more than 50 mm is observed at a temperature of about 100 °C. This happens due to the fact that at this temperature the free moisture contained between the fibers of the mineral wool evaporates.

Generalized temperature dependence of the thermal conductivity coefficient of mineral wool fire-retardant cladding has also been derived, in a tabular form. It can be used for calculating the temperature in steel structures with such fire protection. The thickness range for application is up to 80 mm for the specific heat capacity of 1,000 J/(kg °C) and a density of 200 kg/m^3.

It is shown how the obtained dependence can be used for predicting heating in steel structures with fire-retardant mineral wool cladding. The relative error between the calculated and experimental data was calculated. The Cochrane, Student, and Fischer criteria for the results of temperature calculation in steel structures with fire-retardant mineral wool cladding between the calculated and experimental data accept values that do not exceed the tabular quantities. This means that the results of the calculation using the obtained temperature dependence of the thermal conductivity coefficient are adequate

Keywords: thermal conductivity coefficient, thermal-physical parameters, steel constructions, fire protection cladding, fire protection test

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1. Introduction

Steel structures are widely used in modern construction in various structural forms. In particular, steel structures are common in quick prefabricated buildings. These are industrial and agricultural facilities (woodworking shops, warehouses of building materials, granaries, poultry farms, greenhouse), garages for special equipment, sports and recreation complexes, exhibition and entertainment centers, shopping pavilions, office buildings, etc.

One of the drawbacks of steel structures is low fire resistance. Given the high thermal conductivity of the metal and the small cross-sectional dimensions of steel structures, they are heated rapidly. At a temperature of 450 °C to 600 °C, steel enters a plastic state [1]. I this case, there is the complete destruction of a structure. To increase the fire resistance of steel structures, fire protection means are used.

In Ukraine, there is a normative document [2] that regulates experimental methods for determining the fire-retardant capacity for the construction load-bearing structures with fire-retardant coatings. Calculation methods are often used in Europe and globally. The main document for steel structures is Eurocode 3 [3].

The use of fire-retardant cladding remains an effective means of ensuring the designed fire resistance of steel structures. Mineral wool boards are a promising material for fire-retardant cladding because their application provides benefits when performing installation operations, cost-effectiveness, as well as the ability to increase fire resistance without dismantling the main structures.

Given this, it is a relevant task to study the fire resistance of steel columns with fire-retardant cladding made from the mineral wool coating.

2. Literature review and problem statement

Experimental and estimation papers reported studying the thermal conductivity coefficient of building materials [4–16].

Work [4] describes four options for assessing the fire protection of steel structures. Alternatives to the use of unprotected steel based on the method of geometric average methodological and analytical hierarchy are also shown. However, the use of mineral wool as fire protection means is not considered.

Paper [5] studied the realistic behavior of steel structures under the effect of fire. However, the behavior of fire-retardant structures was not studied.

Work [6] reports the results of testing steel elements protected by swelling coatings. The experiments were performed at the laboratory of the National Fire Service of Italy. No testing of steel structures protected by mineral wool was performed.

Paper [7] investigated the effect of expanded vermiculite as a modified filler to improve the fire protection of fire-resistant coatings. But the issue of the effect from mineral wool as a fire-retardant coating was not examined.

Article [8] outlines the essence of the published Brazilian standards for the design of fire-retardant steel structures. One of the options suggested for fire protection is the use of mineral wool cladding. However, no requirements for the thickness and quality of the cladding were given.

Study [9] compared, based on the international recommendations, the results of the experimental study and numerical calculation of temperature inside the thermally protected steel structures under the action of fire. However, the models were not verified.

The effect of hybrid nanoparticles (FGNP-TPP) on the improvement of fire-retardant properties of fire-retardant mixtures was studied in [10]. However, the change in the value of the thermal conductivity coefficient that accompanies it was not studied.

The properties of another type of passive fire protection of steel structures were studied in [11]. Steel plates were coated with composites based on geopolymers. However, the tests were performed only at the standard fire temperature.

Research [12] focuses on the study of a fire-retardant coating for steel structures based on the epoxy emulsion. But the results obtained were not compared to the effectiveness of other means.

Experimental, numerical, and analytical studies are described in study [13]. The reactions of stainless steel or galvanized steel structures to a temperature rise were tested. At the same time, the issue of fire protection of these structures was not considered.

The problems and shortcomings of the traditional method, based on experiments on fire-resistant design of steel structures, are indicated in work [14]. A modern method based on analysis is proposed. The efficiency of computational methods was not considered.

Work [15] established the dependence of the limit values of building structures' fire resistance on temperature dispersion at their heating surfaces. Paper [16] analyzed the temperature regimes of fire that are different from the standard one. Given this, it is possible to choose correctly the measuring equipment for the experiment and an appropriate temperature mode. However, the issues of structure fire protection were ignored.

The above studies paid no attention to investigating the thermal-physical properties of the mineral wool cladding of steel structures under conditions of fire resistance tests. Therefore, examining it will contribute to the development of this area.

3. The aim and objectives of the study

The work aims to identify the dependence of the thermal conductivity coefficient of mineral wool fire-retardant cladding on temperature under conditions of testing structures for fire resistance.

To achieve this aim, the following tasks were solved:

– to determine patterns in the change of the effective coefficient of thermal conductivity of the mineral wool fire-retardant cladding of the steel beam when heated to the standard fire temperature;

– to investigate the reliability of temperature calculation data for fragments of steel structures with mineral wool fire-retardant cladding under conditions of fire resistance tests obtained on the basis of the revealed regularities of the thermal conductivity coefficient.

4. Procedure for estimating results of testing the fire-resistance of steel structures with the fire-retardant cladding

According to [3], there should be two identical samples of steel columns with a fire-retardant coating for testing. The thickness of each one, together with the fire-retardant coating, is not less than 1,000 mm. Considering the requirements from [2, 3], 4 pairs of the samples of steel columns were made for testing. They were made from the I-beam cross-section profile No. 20, a consolidated metal thickness of 3.4 mm, a shelf width of 100 mm, a distance between the outer surfaces of the shelves of 200 mm, a height of 2,000 mm. The fire-retardant cladding was made of mineral wool boards manufactured according to TU U V.2.7-26.8-35492904-004:2010 from rock wool based on rocks from the basalt group. The data are summarized in Table 1.

Table 2

The thermal-physical characteristics of building structures' materials

Thermal conductivity coefficient $\lambda(\theta)$, Wt/(m °C)	Volume specific thermal capacity, $c_p(\theta)\cdot\rho$, J/(m^3 °C)	Density, kg/m^3
Steel EN 1993-1-2:2012 Eurocode 3 [3]		
$54-3.33\cdot10^{-2}\theta$ at 20 °$C\leq\theta\leq$800 °C, 27.3 at $\theta>$800 °C	$425+0.773\theta-1.69\ 10^{-2}\theta^2+2.22\ 10^{-6}\theta^3$ at 20 °C$\leq\theta\leq$600 °C, $666-13{,}002/(\theta-738)$ at 600 °C$<\theta\leq$735 °C, $545+17{,}820/(\theta-731)$ at 735 °C$<\theta\leq$900 °C, 650 at 900 °C$<\theta\leq$1,200 °C	7,850

Several methods can be used to evaluate the results of fire resistance experiments of steel structures with fire protection cladding in accordance with [2]. They are based on solving the differential equation of thermal conductivity with constant or variable values of the thermal conductivity coefficient. The initial expression of the differential equation of thermal conductivity describes determining the temperature gain over time and takes the form:

$$\Delta\theta_{a,t}=\frac{\lambda_p A_p}{V d_p c_a}\cdot\frac{\left(\theta_{g,t}-\theta_{a,t}\right)}{\left(1+\phi/3\right)}\cdot\Delta t-\left(e^{\phi/10}-1\right)\cdot\Delta\theta_{g,t}, \qquad (1)$$

($\Delta\theta_{a,t}\geq0$ at $\Delta\theta_{g,t}>0$),

where $\varphi=\frac{c_p\rho_p}{c_a\rho_a}\cdot\frac{d_p A_p}{V}$, $\frac{A_p}{V}$ are the cross-section coefficients for steel constructions, insulated by fire-protective material; c_a is the specific thermal capacity of steel that depends on temperature, (J/(kg °C)); c_p is the specific thermal capacity of the material that does not depend on temperature (J/kg·K)); d_p is the thickness of fire-retardant material (m); $\Delta t\leq30$ is the period (interval) of time (s), for calculation at a value of Δt larger than 30 s, taken to equal 30 s; $\Delta\theta_{a,t}$ is the steel temperature at moment t (°C); $\theta_{g,t}$ is the temperature of ambient gas at moment t (°C); $\Delta\theta_{g,t}$ is the temperature increase of ambient gas over time interval Δt (°C); $\lambda_p=0.2$ is the thermal conductivity coefficient of the fire-retardant system (Wt/(m °C)); $\rho_a=7{,}850$ is the steel density, (kg/m^3); $\rho_p=1{,}355$ is the density of the fire-retardant material (kg/m^3).

When a method with λ_p as a variable applied, we first calculate the effective thermal conductivity of the coating for each sample, which is represented as a function of time $\lambda_{p\cdot t}$ (t) in the following expression:

$$\lambda_{\rho,t}(t)=\left[d_p\cdot\frac{V}{A}\cdot c_a p_a\cdot\left(1+\frac{\phi}{3}\right)\cdot\frac{1}{\left(\theta_t-\theta_{a,t}\right)\Delta t}\right]\times$$

$$\times\left[\Delta\theta_{a,t}+\left(e^{\frac{\phi}{10}}-1\right)\Delta\theta_t\right]. \qquad (2)$$

To solve equation (2), it is necessary to set the temperature dependences of the thermal-physical steel characteristics. Table 2 gives the specified thermal-physical characteristics.

According to the recommendations set by DSTU-N B EN 1991-1-2:2012 Eurocode 1 [17], and the conditions of application of the method set by Annex D DSTU B.V. 1.1.7–17:2007 [2], heat capacity is considered constant and is equal to c_p=1,000 J/(kg °C). The density of the fire-retardant coating is also considered constant and is equal to ρ=200 kg/m^3 according to reference data [18].

5. Results from the estimation and experimental methods for determining a fire-retardant capacity

5. 1. Investigating the pattern of change in the effective thermal conductivity coefficient

Fig. 1 shows the diagrams of average temperature indicators for each sample. The indicators were acquired from three thermocouples mounted on a metal surface. The dependences are coordinated with the time of testing. These diagrams also show the deviations in the measured temperature indicators from the mathematically expected value, that is, the average temperature of the three thermal couples.

Analyzing the diagrams in Fig. 1 one can see that the measurements were performed correctly. The conclusion is evidenced by that the deviations of the indicators and the spread of measurement results are insignificant.

Considering the data in Table 2, and using formula (2), the thermal conductivity coefficient of the mineral wool cladding was calculated. The obtained results are represented in Fig. 2 in the form of diagrams of the dependences of the thermal conductivity coefficient depending on the test time.

The derivation of the total dependence of the thermal conductivity coefficient involved the standard averaging over all obtained dependences. They were determined discretely for temperature values in the interval of 50 °C.

The obtained dependence of the thermal conductivity coefficient is given in the form of a diagram in Fig. 3.

Thus, the dependence of the thermal conductivity coefficient of mineral wool fire-retardant cladding up to 80 mm thick was obtained. It corresponds to the previously accepted values of the specific thermal capacity and density.

Table 1

The parameters and width of cladding on samples

Profile	Type	Consolidated thickness, δ, mm	Consolidated box thickness, Δb, mm	Box cross-section coefficient Amk/V, m^{-1}	Mineral wool density, kg/m^3	Cladding thickness, d, mm	Mineral wool thickness (nom.) dw, mm	Sample No.
No. 20	Column 2 m	3.4	4.5	222.2	154	24	20	6
						25		5
						35	30	2
						36		1
						52	30+15	8
						55		7
						73	30+30	4
						75		3

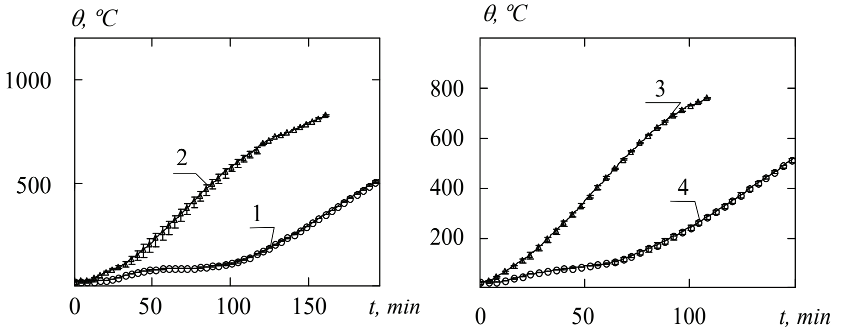

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Fig. 1. Diagrams of the indicators of the average temperature for each sample based on the indicators from three thermocouples installed on the metal surface depending on the time of testing: *a* — Samples No. 1–4 (1 — Samples No. 1, 2; 2 — Samples No. 3, 4); *b* — Samples No. 5–8 (3 — Samples No. 5, 6; 4 — Samples No. 7, 8)

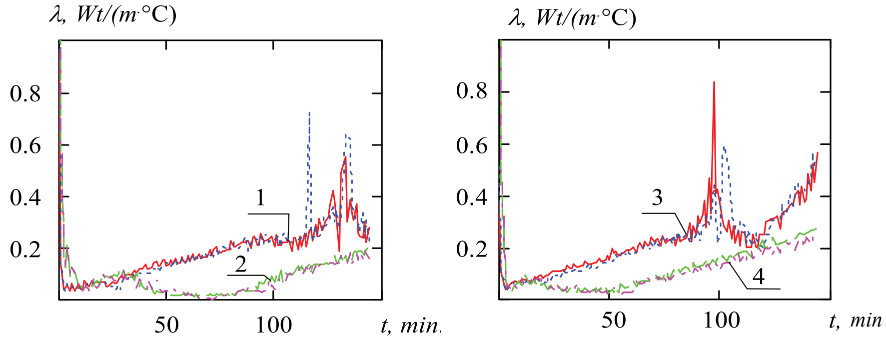

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Fig. 2. Diagrams of the dependences of the thermal conductivity coefficient of the mineral wool cladding of the fragments of samples of steel rods depending on testing time: *a* — Samples No. 1–4 (1 – Samples No. 1, 2; 2 — Samples No. 3,); *b* — Samples No. 5–8 (3 — Samples No. 5, 6; 4 — Samples No. 7, 8)

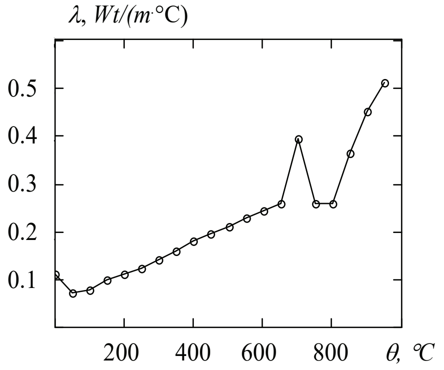

Fig. 3. The dependence of the average value of the thermal conductivity coefficient on the temperature of samples of the fragments of steel rods with the fire-retardant cladding

5. 2. Studying the validity of data on the calculation of temperature for the fragments of steel structures with mineral wool fire-retardant cladding

Data on the thermal-physical characteristics (Table 1) of fire-retardant mineral wool cladding were used. They were obtained based on the results of fire tests of the fragments of steel rods. The temperature modes of heating the tested fragments were also calculated. Dependence (2) was used for calculating the heating temperature modes.

The results of the calculation are represented in the form of diagrams of the temperature regimes of heating a steel element of the fragments together with the diagrams built experimentally. The constructed diagrams of temperature modes are shown in Fig. 4.

The diagrams in Fig. 4 show a slight discrepancy between the experimental and calculated data. The calculations were performed based on the generalized temperature dependence of the thermal conductivity coefficient of fire-retardant mineral wool cladding.

To assess the adequacy (acceptability) of the obtained data on the thermal conductivity coefficient, the adequacy criteria should be calculated based on [2]. The heating temperature of the steel structure's element was calculated from formula (2) under the conditions of the standard fire temperature mode. The calculation results are given in Table 3.

When calculating, in the case of non-compliance with the adequacy criteria (acceptability), a safety factor was introduced into the calculation. It must be multiplied by the obtained temperatures to meet the reliability criteria. The obtained safety factors were used to determine the appropriate coating thickness to ensure the required fire resistance class.

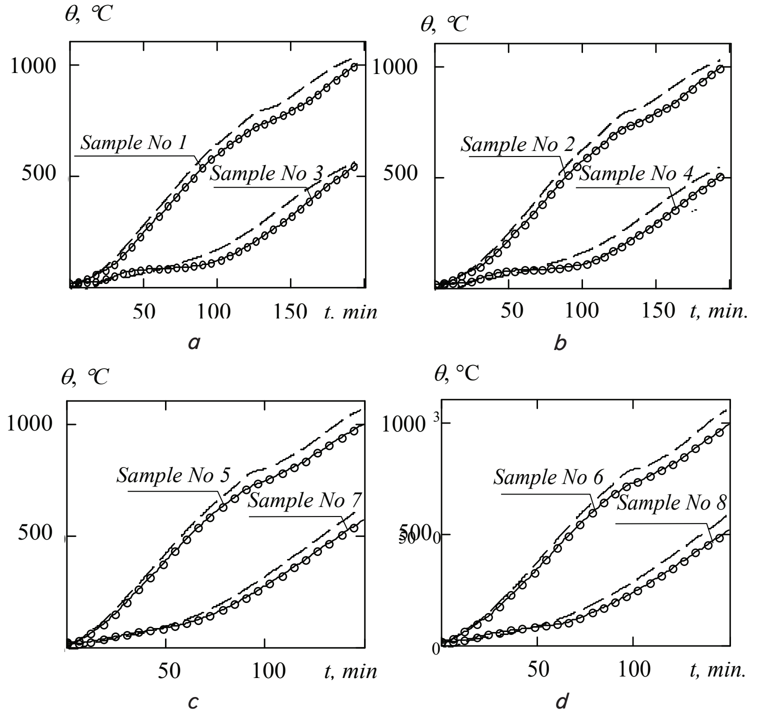

Fig. 4. Diagrams of temperature modes of heating for the dependences of steel rod elements with mineral wool fire-retardant cladding: *a* — samples No. 1, 3; *b* — samples No. 2, 4; *c* — samples No. 5, 7; *d* — samples No. 6, 8 (○-○-○ — experimental data; – – – – — calculated data)

The data in Table 3 were obtained when using a safety factor K=1.05, which is multiplied by the temperature obtained by direct calculation according to formula (2). Under such conditions, the criteria of adequacy (acceptability) according to [2] coincide.

Statistical characteristics of the obtained estimated indicators were calculated. The aim was to test the reliability of the temperature calculation. It also confirms the acceptability of the results from determining the parameters of the thermal effect of fire on the fragments of steel rods with fire-retardant mineral wool cladding. The indicators of the average absolute deviation, the average relative deviation, the standard deviation, when compared for the calculated and experimental values, are given in Table 4.

The data in Table 4 showed that the error, when comparing the calculated and experimental temperature indicators, has no significant effect on the accuracy of temperature calculation. This is because the relative error does not exceed 14.2 **%**. The magnitude of the standard deviation does not exceed 16.7 °C. This means that the obtained dependence of the thermal conductivity can be used as general for predicting the heating in steel structures with fire-retardant mineral wool cladding.

Data on the statistical criteria of temperature data for the corresponding test samples are given in Table 5.

The data from Table 5 showed that the indicators of the statistical criteria that characterize the scatter of temperature deviations in the studied samples do not exceed the tabular values. This means that the obtained dependence of the thermal conductivity coefficient can be used as general for predicting the heating in steel structures with fire-retardant mineral wool cladding.

Table 5

Statistical criteria of the temperature indicators of the corresponding test series

Sample No.	Cochran's criterion	Student's criterion	Fischer's criterion
1	0.465	0.633	0.846
2	0.446	0.660	0.861
3	0.615	0.748	0.945
4	0.623	0.765	0.984
5	0.794	0.816	1.008
6	0.746	0.881	1.004
7	0.581	0.645	0.901
8	0.622	0.687	0.904

6. Discussion of results of studying a thermal conductivity coefficient of the mineral wool cladding

The diagrams in Fig. 2 have certain features. They testify to the marked difference of the change in the character of a thermal conductivity coefficient for a thick and thin cladding layer. This difference implies the presence of a maximum in the curve of the thermal conductivity coefficient of the mineral wool cladding of small thickness. This occurs when such a maximum is absent for samples with a relatively thicker layer of mineral wool cladding. The presence of such a maximum can be explained by the fact that at a certain heating temperature of the fire-retardant mineral wool cladding, its inner layers undergo an oxidation reaction. It has an endothermic character, that is, the reaction releases additional heat.

Table 3

Adequacy (acceptability) criteria of the obtained values of the thermal conductivity coefficient

Sample No.	A discrepancy in the value of reaching the norm. range of temperatures, %								Average discrepancy, %	Share of value variations, %
	400 °C	450 °C	500 °C	550 °C	600 °C	650 °C	700 °C	750 °C		
1	–8.62	–5.88	–3.846	–2.273	–1.02	–0.93	0.86	0	–2.71	12.5
2	–10	–7.32	–7.447	–5.769	–6.90	–7.81	–5.22	–5.479	–6.99	0
3	–25	–25	–22.22	–21.67	–23.53	–21.62	–22.62	–15.96	–22.20	0
4	–8.97	–7.61	–6.731	–6.034	–5.47	–4.35	–3.38	–0.633	–5.40	0
5	–17.39	–11.53	–11.66	–10.60	–9.72	–10	–6.97	0	–9.73	0
6	–12.79	–8.82	–6.89	–3.90	–3.52	–1.94	0	0.56	–4.66	0
7	–6.25	–3.57	0	–1.42	–2.56	0	–1.06	6	–1.11	12.5
8	0	–13.04	–8.97	–5.29	–3.22	–0.5	0.46	0	–3.82	12.5
9	–17.74	–11.42	–6.41	–2.32	–1.06	0	–0.89	0	–4.98	0
10	–8.16	–6.14	–3.12	–2.11	–1.28	–0.58	0	1.90	–2.43	12.5
11	–13.04	–9.25	–8.87	–7.24	–5.92	–4.26	–2.84	0	–6.43	0

Table 4

Absolute deviations, relative deviations, rms deviations, for the experimental and estimated data according to the place of temperature control

Sample No.	Absolute deviations, °C	Relative deviations, %	Rms deviations, °C
1	44.6	13.2	16.7
2	32.8	11.4	9.8
3	26.3	9.9	6.3
4	42.8	14.2	15.4
5	16.4	5.9	4.9
6	22.1	8.9	8.6
7	41.6	12.6	15.1
8	24.4	9.4	8.3
Average values	31.4	10.7	10.6

For the case of fire-retardant mineral wool cladding with the smallest thickness (≈25 mm), after a partial decrease after the maximum, the thermal conductivity coefficient begins to increase again. This state can be explained by the fact that the substance of the inclusions contained between the fibers of the mineral wool is oxidized first. Such inclusions may be certain contaminants in the mineral wool material that remain due to the technological processes in its manufacture After the complete burnout of these inclusions, the thermal conductivity coefficient decreases. The increase in the thermal conductivity coefficient in the last stages of testing samples with a fire-retardant mineral wool cladding of the smallest thickness (≈25 mm) can be explained by that the fibers of the mineral wool material begin to decompose thermally. This effect is absent in the samples with a mineral wool fire-retardant cladding of thickness (≈36 mm), and there is not a maximum in the samples with a mineral wool fire-retardant cladding of thickness exceeding 50 mm. This is due to the fact that in such samples the temperature of thermal decomposition of inclusions and the fibers themselves is not reached.

There is also a feature related to the thermal conductivity coefficient of a fire-retardant cladding of thickness larger than 50 mm in the corresponding tested samples. It implies reaching a certain minimum in the initial stages, from minute 30 to minute 60. This feature is explained by that the samples with a greater thickness of the flame retardant cladding contain more moisture. Moisture is found among the fibers of the mineral wool. Under gradual heating of the cladding, the available moisture evaporates, which slows down the heating process. This affects the shape of the time curves of the thermal conductivity coefficient.

In the diagram shown in Fig. 3, there is a maximum at about 0.4 Wt/(m °C) of thermal conductivity in the range of 700 °C. This is explained by the presence of a local maximum of the used temperature curve of the heat capacity of steel at such temperature values. The presence of a maximum of the heat capacity affected the obtained temperature curve because the chosen procedure employed the effective thermal conductivity coefficient. It is temperature-dependent.

The obtained results of the experimental and estimation studies (Fig. 4) differ by an average of 10.7 % (Table 5). This is due to the accuracy of the constructed mathematical model. The equations of the thermal conductivity and stressed-strained state under heating conditions during the fire were accepted as the basis, as well as the Fourier thermal conductivity equations. When constructing it, a change in the value of the thermal conductivity coefficient was taken into consideration, according to the recommendations from [3].

A special feature of the obtained mathematical dependence is the possibility of its application for calculating the temperature in steel structures with fire-retardant mineral wool cladding. Papers [4, 5] reported the behavior of steel structures under the action of fire. However, the behavior of fire-retardant structures was not studied. The dependence obtained in the current study takes into consideration the mineral wool fire protection of steel.

The thickness range for the use in steel structures with such fire protection is up to 80 mm, for the specific heat capacity 1,000 J/(kg °C) and density 200 kg/m^3.

Although 14.2 % is an acceptable error, it is possible to lower it. One option is to use powerful software packages. Computational experiments employing them can reduce the error. However, the model may become more difficult to apply.

In this paper, only one type of steel and mineral wool has been considered. There are many different products with different thermal-physical parameters. They necessitate conducting separate studies. However, the procedure for obtaining the dependence can be used later by researchers in their further work. In addition, the use of estimation methods to assess the fire resistance of building structures has been further developed.

7. Conclusions

1. The thermal conductivity coefficient of mineral wool fire-retardant cladding has been determined in this work; patterns of its dependence on temperature have been revealed. This is explained by thermal decomposition with the release of thermal energy from inclusions among the fibers of mineral wool and the fibers of the mineral wool itself at a temperature of 750 °C. The minimum of the thermal conductivity coefficient of a fire-retardant mineral wool cladding with a thickness of more than 50 mm is observed at a temperature of about 100 °C. It occurs because at this temperature the free moisture that is contained between the fibers of the mineral wool evaporates. The generalized temperature dependence of the thermal conductivity coefficient of a mineral wool fire-retardant cladding in the tabular form has been derived. It can be used to calculate the temperature in steel structures with such fire protection. The thickness range for application is up to 80 mm, for the specific heat capacity 1,000 J/(kg °C) and density 200 kg/m^3.

2. It is proven that the obtained dependence of the thermal conductivity coefficient can be used as general for predicting the heating in steel structures with a fire-retardant mineral wool cladding. The magnitude of the relative error between the experimental and calculated data does not exceed 14.2 %, and the magnitude of the standard deviation is 16.7 °C. The statistical criteria by Cochrane, Student, and Fisher between the calculated and experimental data accept values not exceeding 0.8; 0.9; and 1.008; they do not exceed the tabular values. This means that the results of the calculation using the obtained temperature dependence of the thermal conductivity coefficient are adequate.

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