Fire Testing on the Polymeric Bituminous Roof Covering with Heat Insulation

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Analysis of experience of other countries in the field of fire testing and analysis of the documents prepared by CEN resulted in the review of real fires and test methods used in Lithuania. As a consequence of that the fire test method for roof covering with insulation material exposed to external fire is proposed. The combustible roof covering with insulation materials is tested. The maximum lengths of affected surfaces of polymeric bituminous and insulation material were measured, the maximum temperatures of burning products were estimated as well as the speed of flame spread. It has been determined, that the temperatures along the specimen of the roof covering system become dangerous in relation to the combustibles.

Keywords: heat transfer, radiation, fire tests, roofing, combustibility.

INTRODUCTION

A special attention is being devoted to the new fire insulating materials, which, due to their good building temperature insulation qualities, are widely used. However, these materials are not equally viable due to combustibility, flame spread and toxicity properties in fire conditions [1 – 4]. The market of such materials in Lithuania has formed only in the recent decades, therefore in the sense of combustibility they are sorted, as were sorted other building materials, according to methods indicated in sources [5, 6] into the non-combustible, low combustible and combustible. These methods are not always suitable for the research of the heat insulation materials. It should be noted, that legal documents, regulating fire safety [7, 8] in Lithuania had been drafted before the thermal insulation process started in the country. Therefore, there were no fire safety requirements established for the thermal insulation systems, including roof covering with thermal insulation.

As there are many discussions and problems about the field of application of insulating materials in roofing systems, the experience of other countries in the field of fire testing of roofing systems was analysed. It was found out, that at present in the other countries there prevails a research direction oriented to accessing the practical information about the fire safety of covering constructions [9]. In the October of 1994 European Committee for Standardisation CEN/TC 127 prepared a test method for external fire exposure to roofs [10]. However, this project has not been approved. Furthermore, it was supplemented with two testing methods [11], which do not have any correlation with each other. Therefore, such research is very urgent at present, since the existing techniques and criteria are not yet fully standardised.

The research results analysed in work [12] showed, that fire tests in Lithuania are based only on establishing the combustibility characteristics and do not evaluate the other properties of insulation materials or evaluate them only partially. It was determined that products of polystyrene foam (density 15 – 25 kg/m^3) according to combustibility accounted for 66 percent of low combustible material. Other polystyrene products same density obtained lower groups of combustibility (24 %).

European Union resolution was adopted in September, the 6th, by 2001/553/EC (Official Journal OJ L235/19-22, 2000-09-19), which established the list of roof covering products/materials, which according to their specifications and existing national laws, in the case of external fire, may be classified as safe materials in the respect of fire safe.

Considering the above-mentioned facts, the most important attention should be devoted to the research of the most dangerous – combustible and low combustible materials.

This work is the attempt to fill a lack of information due to the mentioned problem and to work up the method for fire testing of roof coverings with thermal insulation. In order to achieve this, the tests with external fire exposure were carried out on the most dangerous flat roof specimens with different thermal insulation materials, and the results were summarised.

THEORETICAL ELEMENTS OF THE COMBUSTIBILITY TEST ON THE ROOF FRAGMENT

Consistent patterns [13] with some corrections could be referred to when describing the conditions of initial test phase. It could be summed up, that projected actual fire and test fire conditions are similar to two flat fields that have different temperature, thermal interaction, as it is shown in Fig. 1. We can analyse two absolutely black bodies, the isothermal surfaces of which F_1 and F_2 are characterised by temperatures T_1 and T_2 (see Fig. 1). Let us presume, that the air medium does not absorb heat and the heat flux Q has to be determined, when $T_1 > T_2$.

We will distinguish in the specimen under analysis of two infinitely small elements dF_1 and dF_2, compared with the distance r between their centres O_1 and O_2. The angles

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comprised by the normal going between the fields and O_1 and O_2 shall be marked as φ_1 and φ_2.

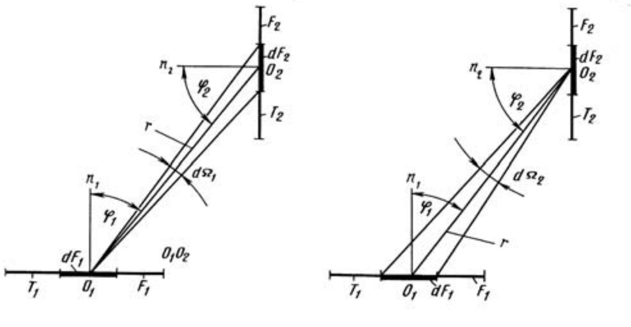

Fig. 1. The scheme of heat exchange by means of thermal radiation between two fields haphazardly located in space

Solid angle by which the small element dF_2 is seen from point O_1 is equal $d\Omega_1 = \cos\varphi_2\, dF_2 / r^2$. Solid angle by which the small element dF_1 is seen from the point O_2 is equal $d\Omega_2 = \cos\varphi_1\, dF_1 / r^2$. Then, according to Lambert's Law, the elementary incident radiation flux from dF_1 to dF_2 is equal:

$$d^2Q_1 = E_{01} d\Omega_1 dF_1 \cos\varphi_1 / \pi , \tag{1}$$

where E_{01} is the heat radiation flux of the first field.
Finally [11]:

$$d^2Q_1 = C_0\left(\frac{T_1}{100}\right)^4 \frac{\cos\varphi_1 \cos\varphi_2}{\pi r^2} dF_1 dF_2 , \tag{2}$$

where C_0 is the radiation coefficient of an absolutely black body, equal to 5,75 W/m^2K^4.

Analogically [11] the elementary radiation flux, directed from field dF_2 to field dF_1 is calculated:

$$d^2Q_2 = C_0\left(\frac{T_2}{100}\right)^4 \frac{\cos\varphi_1 \cos\varphi_2}{\pi r^2} dF_1 dF_2 . \tag{3}$$

Heat flux, conveyed from field dF_1 to field dF_2 is equal to:

$$d^2Q = d^2Q_1 - d^2Q_2 = C_0\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \frac{\cos\varphi_1 \cos\varphi_2}{\pi r^2} dF_1 dF_2 . \tag{4}$$

Stefan-Boltzman's law as referred in [14] and by integrating this expression according to fields F_1 and F_2, we get:

$$Q_{1,2} = \varepsilon_s C_0\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] H , \tag{5}$$

where

$$H = \int_{F_1} dF_1 \int_{F_2} \frac{\cos\varphi_1 \cos\varphi_2}{\pi r^2} dF_2 . \tag{6}$$

H is the interaction factor of 1 and 2 walls by radiation, ε_s – is calculated power of the wall's blackness:

$$\varepsilon_s = 1/+[1 + (1/\varepsilon_1 - 1)\psi_{1,2} + (1/\varepsilon_2 - 1)\psi_{2,1}] . \tag{7}$$

Quantity H can be expressed through the irradiance coefficient:

$$H = F_1\, \psi_{12} = F_2\, \psi_{21}, \tag{8}$$

where ψ_{12} and ψ_{21} are average surface irradiance coefficients respectively from plane 1 on plane 2 and from plane 2 on plane 1. These coefficients depend on the shape, dimensions, interrelated position in space of these bodies and they indicate which part of the effective radiation of one body falls on the other body [13, 14].

The equation (5) would be correct in the case of two absolutely black bodies with different temperatures. As this equation indicates, in order to locate the heat flux Q the most important thing is to calculate the irradiance coefficients. In most general case they are calculated using the expression (6). In practice, in most cases the calculation techniques are to be found in the reference books. However, as the surfaces are complex, calculations become very difficult or impossible. In these cases the method of experiment is used.

In our case the fields of interacting planes are not located haphazardly. The plane of the specimen makes an angle of 30° with the plane of irradiance screen. Therefore, the distance r is not the fixed quantity throughout the surface of the tested plane. Consequently, the value of irradiance of the specimen changes, and it is very difficult to calculate it. Therefore, it is expedient to determine it empirically.

As in practice and in our case the system is not infinite, we assume $F_1 > F_2$ as $F_2 \to 0$ (that means that we are interested in the irradiance of the small element of the surface of combustible construction, which, as a rule, is a point source of ignition), and then the formula (5) divided from F_2 gives [12]:

$$q_{1,2} = \varepsilon_s C_0\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \psi_{2,1} \tag{9}$$

This formula is derived with the condition that the heat flux density is independent on the direction. $\psi_{2,1}$ could be determined using measurements presented below (Fig. 2) and the data from reference books.

Having completed heat flux measurements at the certain positions on the surface of specimen area (see Fig. 5) the distribution of the density of heat flux, subject to distance, estimated from the starting point of the irradiation area on the surface of specimen was determined (see Fig. 2):

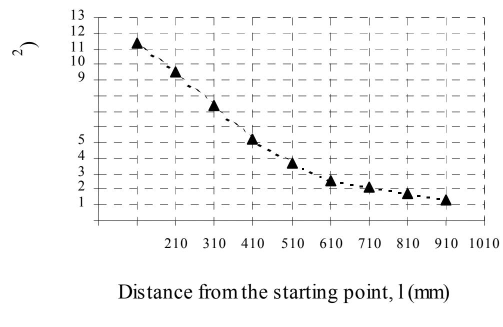

Fig. 2. The distribution of the density of heat flux, subject to distance, estimated from the starting point of the irradiation area on the surface of specimen

The established distribution of the heat flux from the source of radiation will hold at the beginning of the experiment, the equation (9) theoretically in the course of the experiment should describe the process only for some time, because in the next phase the condition $T_1 > T_2$ will not be fulfilled, especially if the construction material of the specimen of the experiment is combustible. It is likely then, that $T_1 = T_2$, and after some time, such condition is possible:

$$T_1 < T_2. \tag{10}$$

Thus, from the presented theoretical reasoning there flows a clear conclusion about the doubtless relation between the temperature and time. The descriptions of the similar relation can be found, variously interpreted, in the source [15]. In this case there is only attempt to expand on generally known theory [13], which does not completely reflect the projected conditions of the experiments and the possibilities of the evaluation of objective combustibility.

EQUIPMENT USED AND THE CHARACTERISTICS OF THE TESTED MATERIALS

For testing specimens of maximum thickness of 50 mm were used, the affected surface area of the specimen was 1050 mm in length and 200 in width. The specimen was installed in the frame of stainless steel, the frame had scale for measuring the spread of the flame on the surface of the specimen. On the middle axis of the specimen there were 5 thermocouples: the first thermocouple was located 100 mm from the starting point of the specimen, other four thermocouples were installed every 100 mm one after the other in the 2 mm apertures so that the hot joint would be on the touching plane of the non combustible foundation and heat insulation (see Fig. 3). The non- combustible foundation was 10 mm thick asbestos-cement slab.

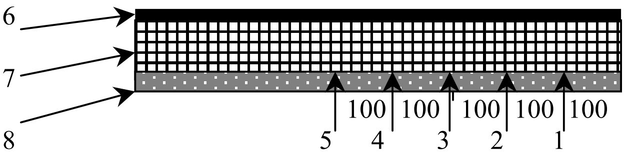

Fig. 3. Principal scheme of fragment tested: 1 – 5 – thermocouples, set in the non-combustible foundation, 6 – roof covering, 7 – thermal insulation, 8 – non-combustible

During the experiment, in order to estimate the maximum temperature of the combustion products, produced in the course of the experiment, one thermocouple was installed in the vent pipe.

The basic scheme of the equipment, presented in the Figure 4 is produced as given in [16]. Temperature was registered by 12 channel digital self-recording EUROTHERM 4100, the data was processed with a personal computer.

The essence of the experiment was to affect the tested fragment, made from the certain tested material with established thermal radiation flux and gas burner.

Before the experiment, the density of the heat flux, emanating from the electric irradiance screen (450 mm × 300 mm), was established by non-combustible calibration slab (Fig. 5), in the centre of which there were apertures, situated 100 mm from each other. For measurements the heat flux gage “Termogage 1000” (producer “Vatell

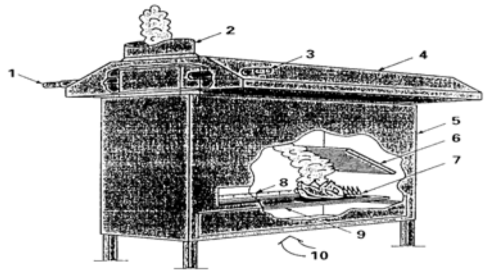

Fig. 4. Basic scheme of the equipment: 1, 3 – aperture (if projected); 2 – vent pipe; 4 – vent hood; 5 – test chamber; 6 – the screen surface of heat flux radiation; 7 – flame controlling burner; 8 – scale; 9 – specimen holder with the specimen; 10 – environment air suction through the bottom of the chamber

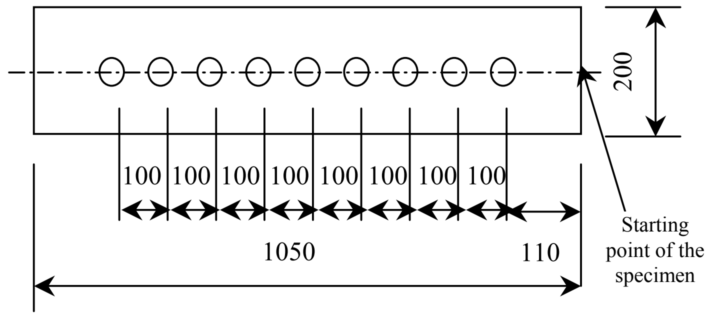

Fig. 5. Calibration slab with apertures for heat flux density measurement

Corp.” USA) was used, the accuracy of the device was 3 %. In such way the distribution of the heat flux on the surface of the specimen was ensured, as well as initial testing conditions on the test of each fragment were established. The thermal flux slab made up angle of 30° with the horizontal plane of the specimen and the slanting angle of it was removed from the specimen by 140 mm.

To ignite the volatile gases and steams that were released from the surface of the specimen during the experiment the burner of 1 mm in diameter was used, the height of flame was ca 4 – 5 cm. The burner used liquid mixture of propane- butane gas. The burner was ignited before the experiment and would begin affecting the specimen at its starting point (see Fig. 5) after period of 30 seconds after the specimen was placed in the chamber. The maximum temperature of combustion product was measured during the experiment, as well as the distribution of temperatures on the not affected side of the specimen, the lengths of damage on the roof covering and insulation fragments and the average speed of fire spread. The latter indicator was calculated in the range of 100 mm from the starting point of the specimen until the point of 550 mm, because the spread was even in all experiments. The experiment was ended when the flame extended over the whole length of the specimen, when it was extinguished and did not reach the end of the specimen or after 30 minutes after the start of the experiment. The latter condition for ending the experiment was chosen due to the fact, that more than 60 % of fires in the country are eliminated within 30 minutes [17].

According to the chosen technique, the fragments of flat roofs made of polymeric bituminous roof covering with different thermal insulation were used:

1) Polymeric bituminous covering of PYE-PV160S4s type with mineral sift. For modification of the bituminous mass the thermoplastic elastomers (styrene – butadiene – styrene) of the type SBS was used, the 25 % of ground sand was used for filling. The covering was formed of foundation of polystyrene re. Producer – "Gargždų Mida", joint stock company. Thickness – 4.2 mm, the weight of the plane – 5.2 kg/m^2, combustible, medium ignitable;

2) Mineral stone wool slabs F110, binder content up to 3 %. Producer – "Paroc", Joint Stock Company. Thickness – 50 mm, density 110 kg/m^3, non-combustible;

3) Polystyrene foam slabs PS-E-FS 15 with non-combustible add-ons. Producer – Polish factory "Fabryka styropiany sklad budowlany podbielski". Thickness – 100 mm, density – 15 kg/m^3, combustible and low ignitable;

4) Polyurethane foam slab. Thickness – 100 mm, density – 45 kg/m^3, combustible and low ignitable.

All roof fragments were made up from the above-mentioned materials, the thermal insulation and its thickness was being changed. The composition and thickness of fragments are presented in Table 3.

EXPERIMENTAL RESULTS AND DISCUSIONS

After the tests of burning the maximum lengths of affected surfaces of polymeric bituminous and insulation material were measured, the maximum temperatures of burning products were estimated as well as the speed of flame spread. Findings are presented in the Table 4. The data of the direct temperature rise are presented in Figures 7 – 14. The results show (see Fig. 7 – 14) that the change of temperatures during the experiments is very complex. It depends on the qualities of the insulation material, localisation of thermocouples and burning products from the bituminous polymeric covering. During experiments on all fragments it was established, that the polymeric bituminous covering is changing its aggregate condition, that is, it is getting more liquid and evaporates due to the heat radiation flux. The gas burner ignited the issuing steam and gas. As he burning process got more intensive it was determined, that before the front of the flame the strip of liquidised polymeric bituminous covering was formed (see Table 4).

When the thermal insulation was stone wool, the characteristic increase of temperature was observed as the thickness of the wool decreased (see Table 3 and Fig.7–9), but it obviously did not have influence on the length of the damage on the specimen, the damage length did not exceed 57 cm (1.1 – 1.3 fragments, Table 4, Fig. 6). The difference between releases of the burning products in 1.1 – 1.3 fragment systems could be explained by the release of the binder. The thinner stone wool insulation layer heated up quicker, at the same time the release of the binder quantities got more intensive. The thicker stone wool layer heated up more slowly (see Fig. 7 – 9). After the bituminous covering got burnt out, the blue coloured flame was observed, characteristic of burning of binder.

Table 3. The characteristics of roof fragment systems

Fragment No.	Thermal insulation	
	Type	Thickness mm
1.1	Stone wool F110	10
1.2	Stone wool F110	30
1.3	Stone wool F110	50
2.1	Polyurethane	10
3.1	Polystyrene PS-E-FS15	10
3.2	Polystyrene PS-E-FS15	20
3.3	Polystyrene PS-E-FS15	30
4.1	Absent	Absent

Note. Length and width were equal for all tested fragment systems (1.05×0.2; surface area 0.2 m^2). Polymeric bituminous covering with 4.2 mm thickness was used for all tested fragment systems.

Table 4. The results of experiments on roof fragments

Frag-ment No.	Covering damage length, cm	Thermal insulation damage length, cm	Maximum tempera ture of burning product, °C	The liquidised strip of covering before the fire front, cm	Average speed of flame spread, cm/min
1.1	57	Not damaged	229	10÷12*	5.9
1.2	56	Not damaged	212	9÷10*	4.6
1.3	53	Not damaged	190	8÷10*	3.8
2.1	85	105	268	15÷20*	19.6
3.1	48	55	154	10÷15*	2.8
3.2	75	80	231	10÷15*	8.3
3.3	105	105	429	10÷15*	14.8
4.1	52	-	105	10÷13*	2.7

Note. *Indicator was observed in the initial stage of the experiments (up to 10 min from the start of the experiment).

Fig. 6. The image of Fragment System 1.1 after the burning test

In the case of polystyrene foam the polymeric bituminous covering got liquid, sank into the polystyrene foam and ignited it, polystyrene foam would collapse due to the heat flux at the front of the fragment (ca 10 – 15 cm). Characteristic rise of temperature during the experiment

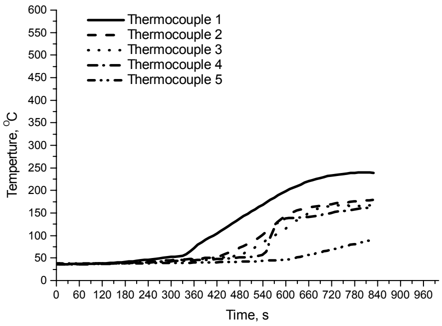

Fig. 7. Fragment 1.1 temperature changes

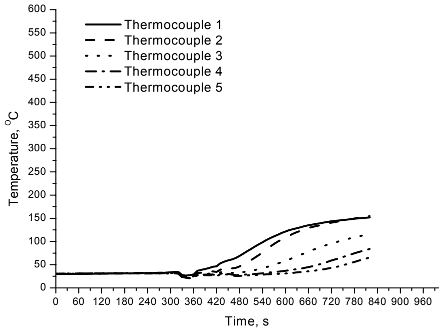

Fig. 8. Fragment 1.2 temperature changes

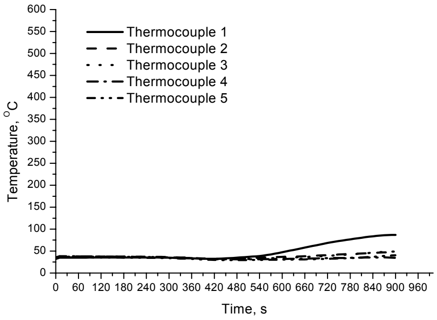

Fig. 9. Fragment 1.3 temperature changes

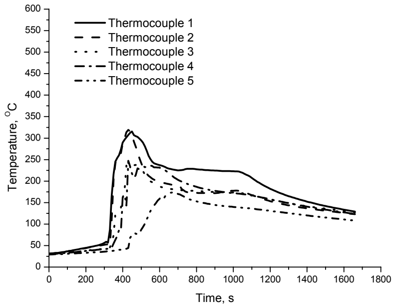

Fig. 10. Fragment 2.1 temperature changes

(Fig. 11 – 13) for the fragments 3.1 – 3.3 (Table 3) could be explained by the destruction of polystyrene foam and continuing oxidation. The damage length of bituminous covering depended on the thickness of polystyrene foam (3.1 – 3.3 fragments, Table 4). Analogous dependence was confirmed in the work [18], where the fire tests were carried out on building facade insulating with foam polystyrene. It means that the fire load affected the

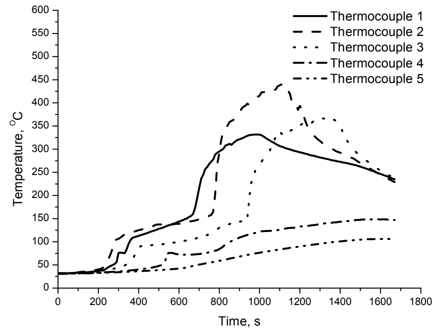

Fig. 11. Fragment 3.1 temperature changes

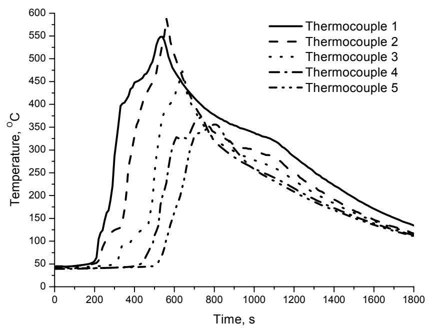

Fig. 12. Fragment 3.2 temperature changes

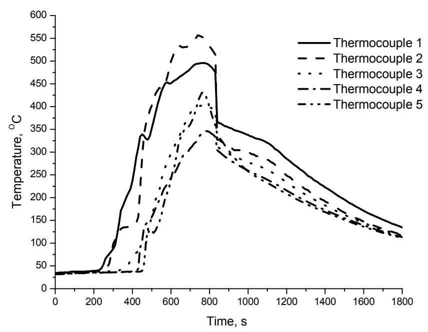

Fig. 13. Fragment 3.3 temperature changes

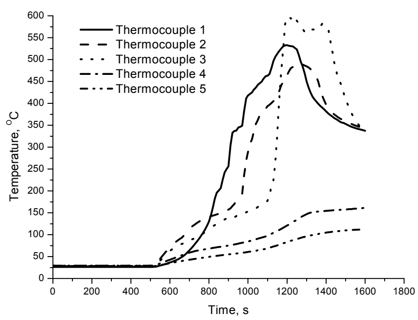

Fig 14. Fragment 3.4 temperature changes

burning process in intensive way. In all cases the length of damage of polystyrene foam was bigger than that of polymeric bituminous covering (Table 4). The characteristic image of fragment system 3.3 is presentedin Fig. 15. For comparison, the tests were carried out on non-combustible foundation with the polyurethane insulation fragment system (2.1, Table 4) and fragments system with only polymer bituminous roof covering (4.1, Table 4). The burning of the fragment 2.1 was very intensive, the increase of temperature was very sudden after the third minute of experiment (see Fig. 10). In the 3 minute of experiment the spread of polymeric bituminous covering made up from 15 to 20 cm (see Table 4), this resulted in a big fire spread on the surface.

Fig. 15. The image of fragment 3.3 after test with burning

Whole fragment was damaged during the experiment. Taking into consideration, that the density of polyurethane foam was 45 kg/m^3 (in the case of polystyrene - 15 kg/m^3), one can make a conclusion that fire load has influence on the length of the damage of the fragment.

In the case of fragment 4.1, the length of the damage was close to those observed the tests on fragment systems 1.1 – 1.3 (see Table 4).

Table 4 shows, that the spread of the flame is different. It was influenced also by the spread of liquid polymeric bituminous covering on the surface of insulation. The strip of spread before the flame front on the surface of the specimen was 8 ÷ 12 cm for fragment systems 1.1 – 1.3, 15 ÷ 20 cm for fragment system 2.1, 5 ÷ 10 cm for fragment systems 3. – -3.3, 10 ÷ 13 cm for fragment system 4.1. It was noticed, that with greater spread of liquid covering, the speed of flame spread increases.

CONCLUSIONS

1. The theoretical background for fire testing of roof covering was presented by expanding the concept of heat transfer between two fields

2. During the fire tests, the equipment provided stable conditions for testing of the heat flow and flaming, which is an essential factor in the test results.

3. There was determined the complex relation of temperature and time in the insulation layer of the fragment.

4. It was established that the process of combustion of the fragments tested depends on combustibles and fire load: the different thickness of stone wool in the polymeric bituminous roof covering fragments has no great influence on the length of damage on the covering, whereas this influence in the fragments with polystyrene foam was very significant.

5. Evaluating fire safety and possibilities of use of analogous systems, it would be expedient to test more different roof covering fragments which are dangerous in the respect of fire safety.

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