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STUDY OF THERMAL CONDUCTIVITY OF A WASTE TEXTILE MATERIAL WITH AIR CONTAMINATION

When assessing the fire resistance limit of building structures and materials, thermal conductivity analysis plays an important role. Thermal insulation materials with air-filled cavities, as a rule, have the lowest thermal conductivity. The presence of air cavities reduces the weight of such materials and reduces thermal conductivity due to the fact that the thermal conductivity of air is very low, and convective heat exchange in the cavities is impossible. The relationship between the fire resistance of a material and thermal conductivity significantly depends on the properties and structure of a particular material.

Materials with low thermal conductivity are able to withstand high temperatures without significant heating and destruction. Low thermal conductivity slows down the spread of heat in the material, which helps to maintain its structural integrity, prevents its heating and ignition, and prevents the spread of fire. Waste textile materials can combine high fire resistance and low thermal conductivity due to their multilayer structure and air pockets. This combination slows down the spread of heat, as air is a poor heat conductor, and helps maintain the structural integrity of the material, preventing its rapid heating and ignition. These materials can combine high fire resistance and low thermal conductivity by creating a multilayer structure, similar to sandwich panels [1,2].

In such structures, with the right choice of material, design and installation, a specially folded fabric, waste textile material, with air gaps can be used to increase the fire resistance of the structures. The air pockets created between the layers of the waste textile material act as a thermal insulator. Air is a poor conductor of heat, so it slows down the spread of fire and heat through the structure, and the fabric itself, especially if it is made of fire-resistant materials, can delay or even prevent the structure from catching fire. The following requirements are imposed on the fabric. First, the fabric must be tightly folded to provide maximum thermal insulation, and secondly, it must be multi-layered - the more layers of fabric with air gaps, the higher the fire resistance of the structure. (Fig. 1) [1]

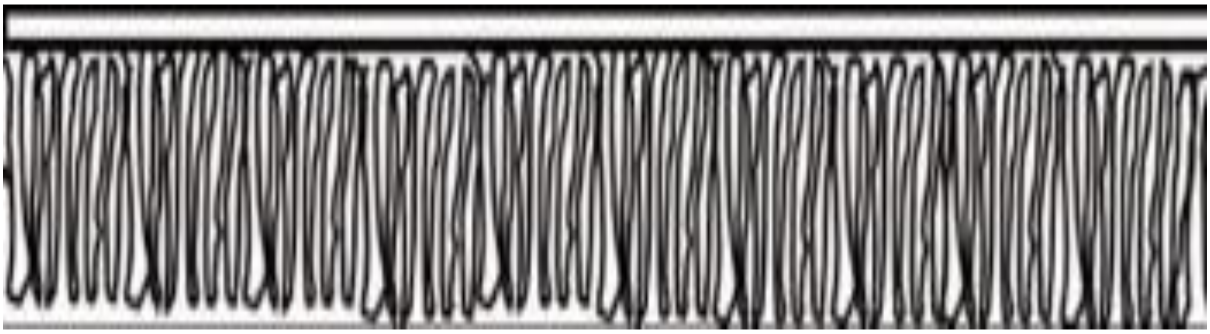

Figure 1 – Configurations of the layer of thermal insulation fabric material (waste textile material) used to increase the fire resistance of sandwich panels

In this regard, it is necessary to calculate the optimal ratio of fabric layers and air gaps to create the most effective thermal insulation and fire resistance.

Calculating the thermal conductivity of a multilayer heat-insulating wall during a fire is a complex task that requires taking into account many factors [3]. During a fire, the ambient temperature and, consequently, the temperature of the material constantly change over time. Under conditions of non-stationary heat exchange, the temperature at different points of the material will also change over time. Unlike calculating thermal conductivity under normal conditions, during a fire it is necessary to take into account the non-stationary nature of heat exchange, the change in temperature over time, and the possible change in the properties of materials at high temperatures. Let us consider some factors that determine the features of calculating a multilayer wall for heat-insulating, fire-resistant structures:

1. Under the influence of high temperatures, the thermal insulation properties of materials may decrease, which must be taken into account in the calculations.

2. Since during a fire the temperature is constantly increasing, the heat flow and temperature at different points of the wall change over time. 3. Since heat exchange is non-stationary, for calculation, use methods that take into account the non-stationary nature of heat exchange, for example, the finite element method. This is the most accurate method, allowing for complex geometric shapes and changes in material properties at high temperatures, which, however, requires the use of specialized software.

Simplified methods can be used for an approximate assessment of thermal conductivity, which, unfortunately, do not take into account all the factors affecting heat exchange during a fire.

The most accurate of the simplified calculation methods for cases where the layers of material have different values of thermal conductivity and thickness is the thermal resistance method

$$R_\Sigma = R1 + R2 + ... + Rn \qquad (1)$$

where: R_Σ - total thermal resistance of a multilayer wall; R1, R2, ..., Rn - thermal resistance of each layer

Thermal resistance of each layer is calculated using the formula:

$$R = d / \lambda \qquad (2)$$

where: d - layer thickness; λ - thermal conductivity of the layer

After calculating the total thermal resistance, the total thermal conductivity of the wall can be calculated using the formula:

$$\lambda_\Sigma = d_\Sigma / R_\Sigma \qquad (3)$$

where d_Σ- total wall

If the material is folded in such a way that air-filled voids are formed between its layers, it is of interest to determine the thermal conductivity of such a layer and the effect of its packing density on the overall thermal conductivity of the layer [4]. If the design of the thermal insulation layer consists of three layers of material and two air layers (Fig. 2)

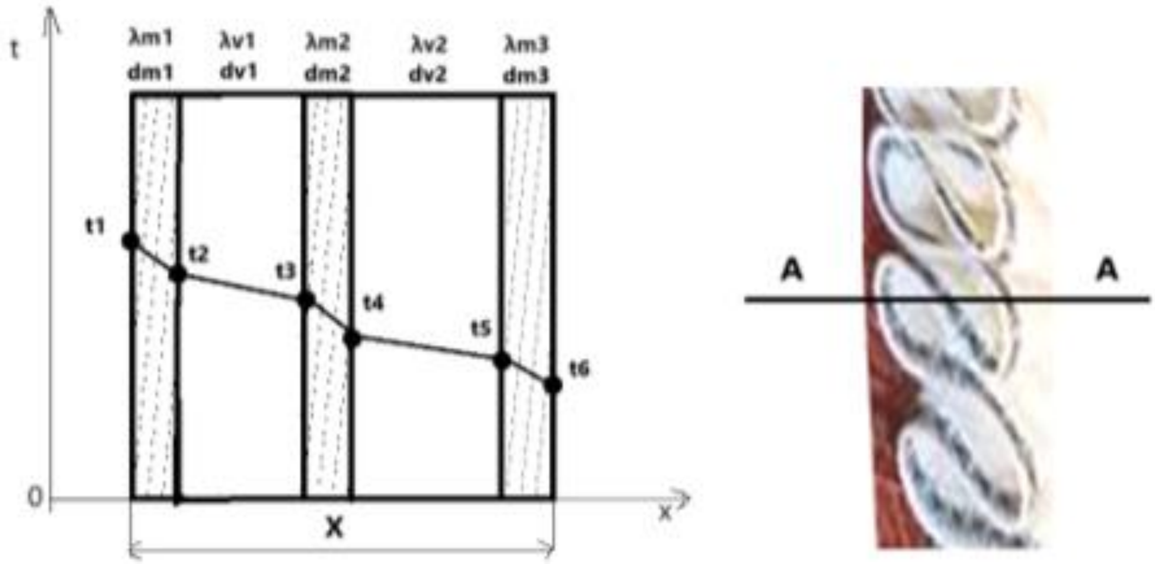

Figure 2 – Thermal conductivity through a layer with an air gap (section AA of the layer)

If we assume that $\lambda m1 = \lambda m2 = \lambda m3 = \lambda m$ and $dm1 = dm2 = dm3 = dm$ and $\lambda v1 = \lambda v2 = \lambda v$

The total thermal resistance of such a layer will consist of the sum of the thermal resistances of thermal conductivity

$$R_\Sigma = dm/\lambda m + dv1/\lambda v + dm/\lambda m + dv2/\lambda v + dm/\lambda m = 3^* dm/\lambda m + dv1/\lambda v + dv2/\lambda v \quad (4)$$

Otherwise, we can write the thermal resistance of a layer consisting of i - layers of material and *j* - air layers, assuming that the air layers are the same thickness

It will be equal to

$$R_\Sigma = \Sigma dmi/\lambda m + \Sigma dvj/\lambda v, \quad (5)$$

from which it is possible to determine the required layer thickness *(Σdmi + Σdvj)* or interlayers *dmi* and *dvj,* given by known values

If the total layer thickness is *X*, then given the number of layers of material i, it is possible to calculate the thickness of the air interlayers *Σdv*

Knowing the heat flux by radiation to the surface ($q_{\text{žareni}}$), described by the Stefan-Boltzmann equation (Fig. 3), equating it with the specific heat conduction flux ($q_{\text{tepelna vodivost}}$), we can determine the required thickness of the air layer at a given temperature t1

$$\sigma^*((Ts)^4-(t1+273)^4) = (t1-t6)/ R_\Sigma, \text{ kde } R_\Sigma = [\sigma^*((Ts)^4-(t1+273)^4)]/ (t1-t6) \quad (6)$$

and from equation 4 we find the thickness of the interlayer

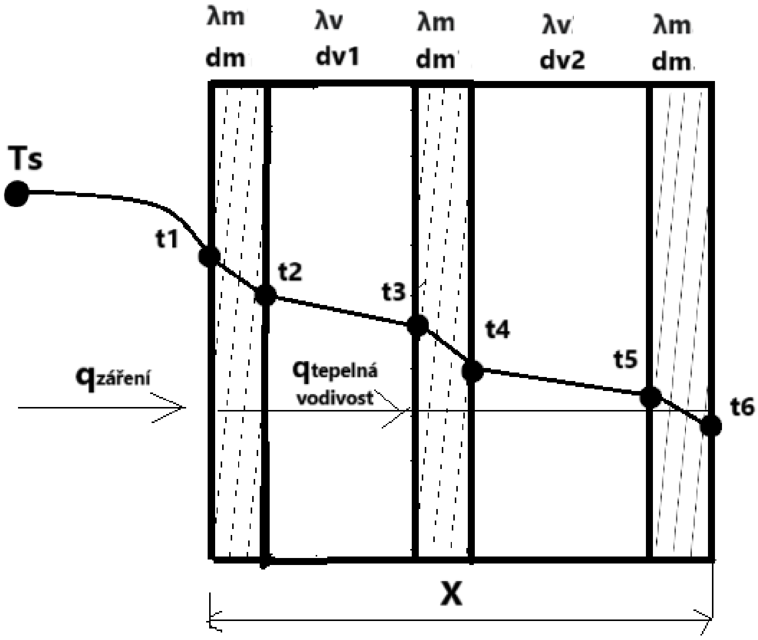

Figure 3 – Heat flows in a layer with an air gap

These studies confirm that a clear understanding of the thermal behavior of textile waste and the factors affecting it allows not only for an effective evaluation of the materials but also for the development of accurate models to predict their properties, particularly the influence of air inclusions on thermal conductivity. It is these features that make such materials effective for fire protection and thermal insulation.

Conclusion

1. The determination of the thermal conductivity coefficient can solve two problems: structural analysis for figuring out the layer thickness and thermal analysis of the temperature field in the layer for a given thickness and layer configuration.

2. Calculation of thermal conductivity is necessary for designing effective fire protection structures, such as fire curtains, doors, and partitions.

3. The analysis of thermal conductivity allows you to compare different configurations of the material and air gap by their fire protection properties and select the most suitable for specific operating conditions.

4. The prediction of thermal conductivity taking into account non-stationarity allows you to foresee how quickly the material will heat up during a fire and how long it will be able to perform its fire protection functions.

Referenses

1 X. Xiong, M. Venkataraman, D. Liederhausová, T. Yang, R. Mishra, J. Militký, M. Petrů, An experimental evaluation of convective heat transfer in multi-layered fibrous materials composed by different middle layer structures, Journal of Industrial Textiles, SAGE PUBLICATIONS INC, 1, p. 362-379, 18 pages, ISSN: 1528-0837, n. 3, [Online], 2021

2. Luo Z, Li W, Li S, et al. Lattice Boltzmann Modeling of the Effective Thermal Conductivity for Complex Structured Multiphase Building Materials. Applied Mechanics and Materials 2014; 541: 694–698. https://www.sciencedirect.com/science/article/abs/pii/S1290072906002122

3 Farnworth B. Mechanisms of heat flow through clothing insulation. *Textile Res J* 1983; 53: 717–725.
https://journals.sagepub.com/doi/full/10.1177/1528083719878845#core-bibr1-1528083719878845-1

4 Majumdar, A. (2010). Thermal behaviour of textiles: A review. Journal of the Textile Institute, 101(2), 163-182. https://www.researchgate.net/publication/288786487