Overview of thermal conductivity models of anisotropic thermal insulation materials

A V Skurikhin$^1$ and A V Kostanovsky$^1$

$^1$National Research University «Moscow Power Engineering Institute», Russia, 111250 Moscow, Krasnokazarmennaya, 14

Abstract. Currently, the most of existing materials and substances under elaboration are anisotropic. It makes certain difficulties in the study of heat transfer process. Thermal conductivity of the materials can be characterized by tensor of the second order. Also, the parallelism between the temperature gradient vector and the density of heat flow vector is violated in anisotropic thermal insulation materials (TIM). One of the most famous TIM is a family of integrated thermal insulation refractory material («ITIRM»). The main component ensuring its properties is the «inflated» vermiculite. Natural mineral vermiculite is ground into powder state, fired by gas burner for dehydration, and its precipitate is then compressed. The key feature of thus treated batch of vermiculite is a package structure. The properties of the material lead to a slow heating of manufactured products due to low absorption and high radiation reflection. The maximum of reflection function is referred to infrared spectral region. A review of current models of heat propagation in anisotropic thermal insulation materials is carried out, as well as analysis of their thermal and optical properties. A theoretical model, which allows to determine the heat conductivity «ITIRM», can be useful in the study of thermal characteristics such as specific heat capacity, temperature conductivity, and others. Materials as «ITIRM» can be used in the metallurgy industry, thermal energy and nuclear power-engineering.

1. Vermiculite and its application

Vermiculite is a mineral from the group of hydromica, which has a layered structure and is formed in natural conditions as a result of hydration and secondary changes in magnesian-ferruginous micasbriotite or phlogopite. When heated from the lamellar crystal of vermiculite, wormlike columns or threads of golden or silver color with a transverse division into the finest scales are formed. In its layered structure, which determines its unique properties (inertness, safety, low bulk density (80-120 kg/m$^3$), low thermal conductivity (0.04-0.12 W/(m*K)), relatively high melting point (1240 -1430 °C)), expanded vermiculite is used in various areas of the national economy [1]. This is an effective fire-retardant and heat-insulating material that is a component of building mixtures, fireproofing panels, paints for heat insulation of thermal aggregates, furnace lining, buildings, for soundproofing of premises. So, It is also used for casting steel, for filtering water, as a smoke sorbent and poisonous gases, for sewage treatment, for reducing soil and water pollution. In addition, the material is used in agriculture: it is used as a bedding material in poultry farming; Normalization of pH, improving its water-air properties, in plant growing, as a carrier of mineral fertilizers and environment for the initial stages of growing vegetables and flowers in hydroponics.
2. Linking the application of the thermal insulation properties of expanded vermiculite with long-term directions of development of Russia

One of the tasks of the «Energy Strategy of Russia until 2030» (ES) [2] is to increase the energy and environmental efficiency of the Russian economy and energy, including through structural changes and activation of technological energy conservation. During the period of implementation of the ES, the Russian economy will depend on the energy sector to be reduced due to the outstripping development of innovative low-energy sectors of the economy and the implementation of the technological potential for energy saving, which will result in a reduction by 2030 (compared to 2005): the specific energy intensity of the gross domestic product - more than 2 times. It is expected that it is the low energy-intensive industries that specialize in the production of high-tech and science-intensive products under the influence of market demand will develop at a faster rate (figure 1). Due to this, it is expected that by 2030 the share of such branches (machine building, light industry, food industry, etc.) in the structure of industrial production will grow by 50-60 % and will make up more than half of its total volume in the country against 33 % at present.

Figure 1. Targeted vision of the development of the fuel and energy complex and the macroeconomics of Russia, one of the main goals of which is to reduce the energy intensity of the economy, until 2030.

The need to increase energy efficiency and reduce the energy intensity of the economy to the level of countries with similar climatic conditions (Canada, Scandinavian countries) due to radical renewal and diversification of the economy structure in favor of less energy-intensive industries, stimulating the transition of the Russian energy sector to accelerated innovation development and a new technological order is one of the ES policy statements.

Along with the expected structural changes in the economy, intensive implementation of organizational and technological measures to save fuel and energy is also envisaged, that is, a targeted energy-saving policy. The result of such structural changes in the economy and the implementation of energy-saving policies should be a significant reduction by 2030 of the energy intensity and electrical capacity of the Russian economy, which will adequately affect the dynamics of domestic demand for primary energy and electricity.

One of the main strategic objectives of the long-term state energy policy is the energy efficiency of the economy. In accordance with this, the dominant of the second stage will be a general increase in energy efficiency in the fuel and energy sector and the economy as a whole.
The strategic goal of the state energy policy in the sphere of increasing the energy efficiency of the economy is to maximally rational use of energy resources on the basis of ensuring the interest of their consumers in energy saving, increasing their own energy efficiency and investing in this sphere.

The main problem in this area is a significant unrealized potential for organizational and technological energy saving, accounting for up to 40 % of the total domestic energy consumption. According to existing estimates, the specific weight of some of the different components in the total value of this potential is characterized by the following data:

- Residential buildings: 18 - 19 %;
- Electric power, industry, transport: 13-15 %;
- Heat supply, provision of services, construction: 9-10 %;
- Agriculture: 3-4 %.

In support of strategic initiatives, the stimulation of the development and use of new energy technologies, which create products with qualitatively new consumer properties, is declared [2].

Thus, the basic development document of the energy sector in Russia reveals the need to reduce energy intensity and increase energy efficiency, which can be realized through the use of thermal insulation materials for construction, industrial production, heat supply, agriculture, etc. One of such materials can be a family of heat-insulating materials Brand ITIR, the qualitative characteristics of which are due to the presence in its composition of expanded vermiculite in an amount from 20 to 60 %. It should be noted that in Russia the production and use of vermiculite and vermiculite-containing materials is at the stage of formation.

3. Characteristics of expanded vermiculite, affecting its structure

On the example of vermiculite of the world’s largest Kovdor deposit with reserves of more than 40 million tons (Murmansk region), we will consider the properties of the expanded material obtained. Similar properties can be found in expanded vermiculites from other deposits.

The average values of the volumetric mass of expanded materials obtained from Kovdor concentrate are given in Table 1 [3].

| Size, mm | from 5 to 8 | from 2 to 5 | from 0.6 to 2 | to 0.6 |
|----------|-------------|-------------|---------------|-------|
| Kovdor expanded vermiculite, kg/m³ | from 80 to 98 | from 95 to 112 | from 110 to 135 | from 230 to 285 |

The porosity coefficient for vermiculite is 0.365, this approximate value is obtained on the basis of the configurational similarity of particles [4]. The porosity depends on the thermal conductivity and sound absorption. The shape of the grains of the expanded vermiculite occupies an intermediate position between the rounded-uneven expanded claydite and the cube-like rubble. Vermiculite grains in the transverse direction have a rounded shape, and in the longitudinal direction they are closer to rectangular.

The effective swelling of vermiculite is mainly due to its dehydration during rapid heating, but some other factors also have an effect. At the moment, there is no direct relationship between the degree of hydration and the degree of swelling. Numerous experiments have also established that even vermiculite plates from the same sample, with the same thickness and transverse dimensions, swell unequally. When the content of chemically bound water was only 4.5 to 5 %, the degree of swelling from 12 to 16 was given, while other samples from this batch increased in volume only from 3.5 to 4 times. Other factors include: the structure of the mineral, the type of exchange ions, the presence and location of other mineral inclusions in the mineral, and the content of adsorbed gases.

In mica, incl. in vermiculite, a significant amount of carbon monoxide, which forms continuous layers of molecules, is adsorbed. The amount of water removed from heating and adsorbed gases is related, on average, to 2:1. Therefore, the swelling work is also performed by gas layers.
Between the vermiculite plates there are various mineral inclusions forming intergrowths and silicate bridges, forming the strength and elasticity of the particles and limiting the opening of the layers. These factors, including interlayer water, contribute to the dependence of the degree of swelling on the natural hydration of vermiculite.

In the process of temperature influence on various varieties of vermiculite ores the following patterns are noted [5]:

- As you heat in the temperature range from 100 to 150 °C, up to 30 % of the water contained in the mineral leaves the material. At the same time, swelling does not occur, which is due to the release of free interlayer water. Further heating up to 300 °C leads to the fact that about 30 % of the water leaves, but intensive swelling occurs. The second endothermic effect (about 270 °C) is accompanied by the release of chemically bound water. This stage is the main, has a «shock» character and is accompanied by a mechanical transformation of particles of vermiculite concentrate. The mass fraction of moisture is no more than 4-6 % for freshly expanded vermiculite;

- increased content of free water has a negative effect on the duration and degree of swelling;

- during studying the dependence of swelling and the volumetric mass of the expanded material on humidity, it is observed that as the concentrate moisture increases, the swelling time increases, and the bulk density also increases with equal duration;

- typical concentrates with a vermiculite content of about 90 % show the worst swelling;

- the degree of expansion increases with decreasing thickness. The samples with a thickness of 0.5 mm or less are more intensively swollen: for thicker particles, the surface layers isolate the internal (heat-shielding barrier), worsen the conditions for their heating, and slow the dehydration. Increasing the dimensions in the transverse direction also worsens the conditions of swelling;

- the direct influence of the configuration of vermiculite particles on the degree of its swelling is not established, however, as the dimension of the concentrate increases, the coefficient of swelling also increases;

- as the heating rate increases, the yield of water vapor increases: in the interlayer spaces a much higher pressure develops, which leads to a more complete swelling. Also, an increase in the rate of dehydration leads to an increase in the degree of swelling, thus making it possible to obtain a lighter material. The maximum speed of particle heating and the most complete expansion is provided in a suspended state when the particles to be expanded are introduced into a preheated furnace or flame torch;

- preheating vermiculite before roasting also has a great influence on the degree of swelling.

The distribution of particles of expanded vermiculite (also by the example of the Kovdor deposit) by their size is shown in figure 2.

![Figure 2. Granulometric composition of expanded vermiculite (Kovdor vermiculite sample).](image-url)
Thermal conductivity of the expanded vermiculite of the Kovdor deposit as a function of its density (ρ): $\lambda = (0.0526 + 0.000128\times\rho) \pm 0.012 \text{ W/(m*K)}$ [6]. At the same density, as the temperature increases, the thermal conductivity grows faster in coarse-grained material, as compared with fine-grained material, since convective heat transfer in coarse-grained material is greater. An increase in humidity by 1 % causes an increase in thermal conductivity, on average, by 4-5 %, but with the humidity of the expanded vermiculite 20-30 %, the increase in thermal conductivity decreases [4].

Figure 3. Image of particles of expanded vermiculite [7].

Vermiculite, expanded at a temperature below 700 °C, reaches a maximum of reflectivity in the red part of the spectrum (wavelength 750 nm), which adjoins the infrared radiation region. The melting point of the vermiculite of the Kovdor field is 1320-1410 °C, the density is approx. 90 kg/m$^3$ [5].

Thermal conductivity, when the particles are oriented by cleavage planes perpendicular to the heat flux, is practically an order of magnitude lower (figure 3).

Thus, the thermal conductivity of expanded vermiculite is explained not only by its low density and humidity, but also by the ability of its surface to reflect thermal radiation.

4. Description of the model for the propagation of heat of expanded vermiculite

It is assumed that when radiating heat in the vermiculite contribute to the radiation and convective components. Since the characteristic mean free path of air molecules under normal conditions is about 50 nm, and the thickness of the air gap between the mica layers (at the molecular level) in the vermiculite cell is an order of magnitude smaller, the main contribution to heat conduction is made by heat transfer due to radiation. Calculation rationale. The angles of the tilting of the mica cells (orientation to the perpendicular to the outer surface) have an arbitrary distribution, as well as the distance between the layers of mica bags (figure 4), which creates multiple reflections of the radiant energy inside the material.

Materials of the family «ITIRM» contain a ceramic base with inside particles of expanded vermiculite («raisins with raisins»). In this case, the particles themselves have a layered structure, which is suitable for the model of «sandwich» or «book with sheets»: a ceramic base with particles of expanded vermiculite distributed inside it.

One of the approaches to the determination of the thermophysical properties (TPP) of various materials are methods based on solving inverse coefficient problems (the inverse heat conduction problem is IHCP). These methods are based on numerical modeling of heat transfer, with the mandatory
use of experimental data obtained either on a relatively simple experimental setup or on industrial equipment. Thus, this approach to the investigation of TPP materials contains four stages:

1. Development of a numerical methodology for solving IHCP and also by solving numerically direct three-dimensional thermoelectric problems by working out the most suitable variants of experimental installations.
2. Production of an experimental setup and the commissioning of field experiments, the data of which are processed with the help of well-established numerical models of the IHCP solution.
3. Analysis of the calculated and experimental data obtained and the introduction of certain changes, both in the technique of carrying out the full-scale experiment, and possibly in the numerical solution of IHCP.
4. The final conclusion about the advisability of using IHCP for determining TPP for this class of materials.

This approach was used to determine the TPP of a heat-insulating charge in the temperature range up to 1600 °C [9-12], but it is logical to assume that it can be used to study the properties of vermiculite and to explain the mechanism of heat propagation within a given material. In this paper, we review the publications published over the last few years on the construction of a model for the propagation of heat in media containing expanded vermiculite.

Swelling is characterized as the process of mechanical transformation of planar particles into voluminous expanded grains with a complex scaly structure occurring in the thermal shock mode caused by the dehydration of chemically bound water (up to 20 % of the initial mineral mass).

During swelling (500-800 °C), the structure and properties of vermiculite vary considerably. Such a transformation entails a significant change in its optical properties. The author has not encountered publications over the past decade devoted to the search for experimental values of absorbing, reflective, radiative and transmissive capacities, which perhaps indicates that no one sets a goal to determine them. In [14], a static analytical model was obtained describing the absorptive-reflectivity of a single-layered array of intumescent vermiculite under conditions of thermal radiation with the assumption that the lateral surfaces are absolutely black, and the end surfaces completely reflect radiant energy. With this in mind, the corresponding absorption and reflection coefficients were determined by the proportion method based on the number of grains located on the end and on the side. The main result of the article was the formula for describing a single-layer dense intumescent vermiculite flow: $\alpha + \rho + \tau = 0.768 + 0.232 + 0 = 1$.

As indicated earlier, expanded vermiculite has a layered structure, which emphasizes its anisotropy (figure 5). The deduced statistical formula for the description of a single-layer intumescent vermiculite
flow is only one of the components for compiling the mathematical model for the thermal conductivity of vermiculite.

![Figure 5](image_url)

**Figure 5.** Demonstration of the anisotropy of the optical properties of grains of expanded vermiculite [14].

Unfortunately, the methods for calculating the thermal conductivity through elementary cells [13] are not suitable due to the chaotic distribution of particles within the materials of «ITIRM» and the anisotropic structure of the most expanded vermiculite.

A direct solution that determines the radiative and conductive energy transfer through such a medium is obtained by numerical methods or approximate solutions are used.

5. Conclusion

1. Expanded vermiculite, possessing a number of unique properties: low apparent density and thermal conductivity makes it possible to obtain structural heat-insulating materials with high thermal insulation properties.

2. In publications there is no information on the developed methods for calculating the thermal conductivity of TIM on the basis of vermiculite.

3. Determination of thermophysical properties (TPP) of vermiculite TIM should be based on the methodology, solving the inverse coefficient problem (inverse heat conduction problem - IHCP).

References

[1] Skurikhin V V Integrated thermal insulation refractory materials based on vermiculite: the dissertation of a science degree of a Candidate of technical science (St.-Petersburg: St.-Petersburg State Technological Institute (Technical University)), 2004. p. 3.

[2] Energy strategy of Russia for the period until 2030. URL: [https://minenergo.gov.ru/](https://minenergo.gov.ru/)

[3] Nizhegorodov A I Vermiculite and vermiculite technologies: research, production, application / Al. Nizhegorodov. (Irkutsk: Publishing house Business-Story), - 2008. - 96 p.

[4] Nizhegorodov A I Technologies and equipment for the processing of vermiculite: optimal fractionation, electric roasting, additional enrichment. – (Irkutsk: Publishing House of INRTU), - 2011. - 172 p.

[5] Nizhegorodov A I Scientific substantiation of industrial application of technological systems for processing vermiculite concentrates and conglomerates. - The dissertation author abstract of a science degree of the doctor of engineering sciences (INRTU). - 36 p.

[6] Spirina V Y and Akhtyamov R Y Ceramic vermiculite products for lining of thermal units in the building materials industry. Analyte. overview. – (Moscow: VNIISMM). - 1991. - 54 p.

[3] Kovdor vermiculite. - Apatity: Kola branch of the USSR Academy of Sciences, 1966. - 370 p.

[4] Hemmerling G V et al. Thermal insulation materials and products based on vermiculite, mineral wool and cellular concrete: *Coll. of sci. papers / Ural Sci.-Res. & Des. Inst of Building Materials* (Chelyabinsk: UralNIStroMProekt), 1990. - 186 p.: ill. - 500 cop.

[5] Akhtyamov N A and Hemmerling G V On the direction of improving the vermiculite swelling // *Building materials and concretes*. – (Chelyabinsk: UralNIStromproekt), 1969. - 112 p.
[6] Fandeev A P, Vinogradov N A, Tataurov V P and Kuznetsov V A New Thermal Insulating Materials Based on Vermiculite and Diopside for Aluminum Cells. Problems of manufacturing of aluminum, magnesium and an electrode. Mater. / (St. Petersburg: All-Rus. Alum.-magn. In-t: JSC “VAMI”). 1992, p. 59-63.

[7] Moeller E Vermiculite // Mining Eng. (USA). - 2000. - 52, No. 6. - p. 66-67.

[8] Zvezdin A V et al. Analytical model of the absorbent-reflectivity of vermiculite under thermal radiation conditions // New Refractories. - 2017. - №1. Pp. 15-20.

[9] Nikitenko N I Conjugate and inverse problems of heat and mass transfer // (Kiev: Dumka). 1988. - 240s.

[10] Himmelblow D Applied nonlinear programming. – (Moscow: Mir), 1975.

[11] Berkovich E M and Golubeva A A On the numerical solution of some inverse problems for the heat equation. (Moscow: Scientific Labours of Moscow State University), 1974.

[12] Goryachev A A and Yudin V M Solution of inverse coefficient problem of heat conductivity. IFZ. 1982, vol. 43, No. 4.

[13] Dulnev G N and Zarichnyak Y P Thermal conductivity of mixtures and composite materials. Reference book. (Leningrad: Energy), 1974. 264 p. With ill.

[14] Zvezdin A V, Bryanskikh T B and Nizhegorodov A I Analytical model of the absorbent-reflectivity of vermiculite under thermal radiation conditions. New refractories, ISSN 1683-4518. No. 1, 2017