Both numerical and experimental separation of heat transfer mechanisms in porous refractory thermal insulation materials

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Abstract. The results of estimation of three heat transfer mechanisms in porous refractory thermal insulating materials on example of exfoliated vermiculite at temperatures near 626, 773 and 910 K using experimental data by additive approach are presented.

1. Introduction
Currently, to obtain the thermal insulating properties of materials can be added natural porous substances, for example, an exfoliated vermiculite (hereinafter - vermiculite) obtained by roasting of vermiculite concentrate. His prospects are ensured by small density (80-120 kg/m³), low effective thermal conductivity (hereinafter - ETC) (λ_eff<0,12 W/(m*K) at T = 300 K), melting point up to 1700 K. Besides it is chemically inert, ecologically safe and does not decompose [1].

Authors of this paper have not yet found any published data of spectral absorption coefficient (hereinafter - AC) χ_ν and ETC at T > 773 K of vermiculite, which can be used to calculate the solution of heat transfer problem inside the material. So, authors conducted preliminary studies to determine the mentioned parameters [2], [3], which showed that vermiculite is a semi-transparent substance [4], and determined its ETC for different fractions and temperature ranges, taking into account the orientation of the particles and its states after calcination at T = 1273 K.

2. Method of numerical and experimental determination of components of ETC of material under consideration
As rising temperatures T > 773 K a proportion of heat transferred by radiation increases and free convective processes intensify. In this regard, a complex heat transfer must be considered for porous materials and it should be taken into account three heat transfer mechanisms: phonon (molecular), radiation and convection. Based on their independent nature, it can be assumed these components to be additive: q = q_rad. + q_cond. + q_conv. In this work it is attempted to make a separation of these heat transfer types based on the results of experimental data obtained. If there are no internal heat sources in a steady state:
\[ q = -\frac{dT}{dx} (\lambda_{\text{cond.}} + \lambda_{\text{rad.}} + \lambda_{\text{conv}}) = \text{const} = -\lambda_{\text{eff}} \frac{\Delta T}{h} \]  

\[ \text{(1)} \]

Where \( \lambda_{\text{eff}} \) is ETC, \( h \) - sample layer thickness, \( \Delta T \) is a temperature residual of hot and cold thermocouple junctions (Figure 1), \( \lambda_{\text{cond.}} \) is conductive (hereinafter - C) or (“phonon”) TC, which can be determined as \( \lambda_{\text{cond.}} = \lambda_{\text{eff}} - \lambda_{\text{rad.}} - \lambda_{\text{conv}} \). CTC is caused by the motion (vibration) and interaction of molecules (particles).

Because vermiculite is a dispersed (porous and multiphase) object, an inner heat transfer, in intermediate medium and on its boundaries is carried out by means of: (1) TC inside a separate particle - an element of solid state of the material, (2) heat transfer by TC from one solid particle to an adjacent one in the direct contact spots, (3) molecular TC of medium filling the gaps between particles (air), (4) heat transfer on boundaries of solid particles and medium, (5) emissions from particle to particle, (6) convection of gas (air) and moisture. The first four constituents of heat transfer were contained in CTC, the fifth and sixth cases were studied separately. Moisture has not been taken into account due to relatively high temperatures (\( T > 373 \) K).

As will be shown later, a convection heat transfer contribution can be neglected. Vermiculite was considered as thermally conductive, nonscattering (homogeneous) and radiative medium. In this paper a vermiculite layer thickness was taken the same as in experiment [3]: \( h = 33.5 \) mm. Cold side of sample was in contact with a copper calorimeter wall. The hot side is influenced by radiation heat source, which were 6 SiC-cylinders (Figure 1) “KENAPS” (manufactured by “Podolskogheupor”, OJSC according to “TU-1598-0001-00187046-97”) with 8 mm heating part diameter and its 150 mm length. The sample cell dimensions were 114x114 mm. The temperatures \( T_1, T_2 \) and \( T_3 \) were measured by 3 thermocouples located at distance \( d = 15 \text{ mm} (1^{st} \text{ and } 3^{rd}), 2^{nd} \text{ and } 3^{rd} \) and \( d = 30 \text{ mm} (1^{st} \text{ and } 2^{nd}) \) and used as boundary or auxiliary conditions to calculate a present paper problem.

![Figure 1. Experimental installation scheme.](image1)

To estimate convection and radiation components, a preliminary study of fine (2-0,7 mm) and coarse (8-4 mm) vermiculite fractions by mercury porosimetry method on “Pascal 240” in “BKO”, JSC were carried out (Table 1, Table 2).

| Pore size distribution | Total specific area of pores, m²/g | Porosity, % | Apparent density, g/cm³ | Fraction, mm |
|------------------------|-----------------------------------|-------------|--------------------------|--------------|
| Pore diameter, µm      |                                   |             |                          |              |
| 130..100               | 2,14                              | 3,578       | 0,2                      | 8-4          |
| 100..20                | 14,34                             | 43,43       | 0,02                     | 2-0,7        |
| 20...5                 | 40,09                             | 55,75       | 28,56                    |              |
| <5                     | 43,43                             | 66,35       | 54,32                    |              |

Table 1. General measurement results of porosimetry.

![Figure 2. Flat layer of vermiculite, to the problem statement: “+” (sign “plus”) is attributed to rays along the positive direction of X axis, the “-“ (sign “minus”) – in opposite direction](image2)
Table 2. Vermiculite pore volume fraction p*, %.

| d1, μm | 110 | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 15 | 10 | 5 | 3 | 1 |
|--------|-----|-----|----|----|----|----|----|----|----|----|----|----|---|---|---|
| d2, μm | 100 | 90 | 80 | 70 | 60 | 50 | 40 | 30 | 20 | 15 | 10 | 5 | 3 | 1 | 0,1 |

| Fraction |     |     |    |    |    |    |    |    |    |    |    |    |   |   |   |
|----------|-----|-----|----|----|----|----|----|----|----|----|----|----|---|---|---|
| 8-4 mm   | 2.1 | 1.0 | 1.1 | 1.3 | 1.3 | 1.6 | 1.9 | 2.4 | 3.8 | 3.8 | 8.9 | 27.4 | 7.7 | 29 | 6.7 |
| 2-0.7 mm | 0.0 | 1.9 | 1.5 | 1.5 | 1.7 | 1.9 | 2.3 | 2.6 | 3.8 | 3.0 | 5.8 | 19.8 | 9 | 45.3 | 0.2 |

*a d1 and d2 specify the maximal and minimal pore size in the considered range. For example, the volume fraction of pores for fraction 8-4 mm from 100 to 110 μm is 2.1 %, from 90 to 100 μm – 1.0 %, etc.

3. Solution of ETC constituents.

3.1. Radiant constituent of ETC.

3.1.1. Exact solution.

3.1.1.1. Problem formulation.

Equation of radiative energy transfer in a non-scattering absorbing medium [4]:

\[
\frac{dI_\nu}{dL} = j_\nu - \chi_\nu I_\nu
\]

(2)

Where \( j_\nu(T) = \chi_\nu n_\nu^2 I_{b,\nu}(T) \), \( I_{b,\nu} \) – Planck function, \( \chi_\nu \) - spectral AC, \( n_\nu \) is a spectral refractive index, \( L \) is a path length along the radiation direction. When integrating equation (2) it follows a radiation transfer equation in integral form (\( L_0 \) is taken as an origin):

\[
I_\nu(L) = I(L_0)e^{-\int_{L_0}^{L} \chi_\nu dL} + \int_{L_0}^{L} j_\nu(L') e^{-\int_{L'}^{L} \chi_\nu dL''} dL'
\]

(3)

Separately for emission luminance \( I_\nu^+ \) and \( I_\nu^- \) (Figure 2) in non-dimensional coordinates (spectral optical width): \( \tau_\nu = \int_0^\tau \chi_\nu d\xi \):

For \( \mu \in [-1; 0] \) (\( \mu = \cos \alpha \)) from equation (3):

\[
I_\nu^- (\tau, \mu) = I_\nu^- (\tau_0) e^{-\tau_\nu \mu} + \int_{\tau_0}^{\tau} n_\nu^2(\tau') I_{b,\nu}(\tau') e^{-\tau_\nu \mu} \frac{d\tau'}{\mu}
\]

(4)

Similarly for \( \mu \in [0; 1] \):

\[
I_\nu^+ (\tau, \mu) = I_\nu^+ (0) e^{-\tau\mu} + \int_0^{\tau} n_\nu^2(\tau') I_{b,\nu}(\tau') e^{-\tau\mu} \frac{d\tau'}{\mu}
\]

(5)

From [5] for the case under consideration, the resulting radiation:

\[
q_\nu^* = 2\pi \left( \int_0^1 I_\nu^+(\mu) \mu d\mu - \int_0^1 I_\nu^-(-\mu) \mu d\mu \right)
\]

(6)

After substitution equations (4) and (5) into equation (6) we get:
\[ q_\nu^+ = 2\pi \left( I_\nu^+(0)E_3(\tau_\nu) + \int_{0}^{\tau_\nu} n_1^2 I_{b, b, v} E_2(\tau_\nu - \tau_\nu')d\tau_\nu' - I_\nu^-(\tau_{0v})E_3(\tau_{0v} - \tau_\nu) - \int_{\tau_{0v}}^{\tau_\nu} n_1^2 I_{b, b, v} E_2(\tau_\nu' - \tau_\nu)d\tau_\nu' \right) \]  

(7)

Where \( E_n(\tau) = \int_0^1 \mu^{n-2} e^{-\frac{\tau}{\mu}} d\mu \) - integro-exponential functions of \( n \)th order, \( \tau_{0v} = \int_0^h \chi_v d\xi \) is an optical layer thickness for monochromatic radiation. Assuming the radiation intensity on boundaries to be independent on the direction and integrating over all frequencies:

\[ q^+(\tau) = \int_0^\infty q_\nu^+(0)dv = 2\pi \int_0^\infty E_3(\tau_\nu)dv - 2\pi \int_0^\infty E_3(\tau_{0v} - \tau_\nu)dv \]

\[ + 2\pi \int_0^\infty dv \int_0^{\tau_\nu} n_1^2 I_{b, b, v} E_2(\tau_\nu - \tau_\nu')d\tau_\nu' - 2\pi \int_{\tau_\nu}^{\tau_{0v}} n_1^2 I_{b, b, v} E_2(\tau_\nu' - \tau_\nu)d\tau_\nu' \]

(8)

\[ I^+(0) = \frac{\int_0^\infty I_\nu^+(0)E_3(\tau_\nu)dv}{\int_0^\infty E_3(\tau_\nu)dv} \]

(9)

\[ I^-(\tau_0) = \frac{\int_0^\infty I_\nu^-(\tau_{0v})E_3(\tau_{0v} - \tau_\nu)dv}{\int_0^\infty E_3(\tau_{0v} - \tau_\nu)dv} \]

(10)

Earlier [2] authors obtained an vermiculite spectral AC array from 9000 cm\(^{-1}\) (\(\nu_\lambda = 2.7 \times 10^{14}\) Hz) to 370 cm\(^{-1}\) (\(\nu_\lambda = 1.1 \times 10^{13}\) Hz) with a step approximately 0.96 cm\(^{-1}\). Due to considerable range of \([\nu_\lambda; \nu_\lambda] \) upper and lower limits of integration were replaced by \(\nu_\lambda\) and \(\nu_\lambda\) respectively.

Spectral refractive index (hereinafter - RI) was calculated by using Kramers-Kroning relations [8], for absorption of various types of carriers:

\[ (n^2 - k^2)_a = 1 + \frac{2}{\pi} \int_0^\infty \frac{\omega a - 2n_{a}k_{a}}{\omega^2 - a^2} d\omega \]

(11)

\[ (2nk)_a = - \frac{2a}{\pi} \int_0^\infty \frac{n^2 - k^2 - (n^2 - k^2)_a}{\omega^2 - a^2} d\omega \]

(12)

\[ n_a - 1 = \frac{c}{2\pi a} \int_0^\infty \frac{d\chi_v}{d\omega} \left| \frac{\omega + a}{\omega - a} \right| d\omega \approx \frac{c}{2\pi a} \int_{\nu_\lambda}^{\nu_a} \frac{d\chi_v}{d\omega} \left| \frac{\omega + a}{\omega - a} \right| d\omega \]

(13)

Where \( k \) is an absorption rate, \( \chi_v \) is the spectral AC, \( \omega = 2\pi \nu \) is the cyclic frequency, \( n_a \) is RI at a given frequency \( a \). Outside of the range \([\nu_\lambda; \nu_\lambda] \) AC was considered to be equal a zero. RI \( n_\nu \) was calculated for each frequency \( \nu = \frac{h\nu_0}{\lambda} \). Additionally, taking into account dielectric losses [7]:

\[ n(a) = \sqrt{\varepsilon_0 + \frac{2\nu_0}{\pi} \int_0^\infty k(\nu) d\nu} \approx \sqrt{\varepsilon_0 + \frac{2\nu_0}{\pi} \int_{\nu_\lambda}^{\nu_a} k(\nu) d\nu} \]

(14)

\[ k(a) = - \frac{2a}{\pi} \int_0^\infty n_\nu - \sqrt{\varepsilon_0} \frac{d\nu}{\nu^2 - a^2} d\nu \approx - \frac{2a}{\pi} \int_{\nu_\lambda}^{\nu_a} n_\nu - \sqrt{\varepsilon_0} \frac{d\nu}{\nu^2 - a^2} d\nu \]

(15)

Where the static dielectric permittivity \( \varepsilon_0 \approx 2.4 \) was found based on published data [1].
3.1.1.2. Results of Precise Solution.

Figure 3 shows a plot of a resulting radiant flux density $q(x)$ at different sample points calculated by equation (8) using $T_1$, $T_2$ and $T_3$. Figure 4 shows a plot of sample ETC and its radiant component, calculated as $\lambda(T) = -q \frac{h}{\partial T}$ and averaged over the sample layer and hereinafter at mean temperatures $626$ K, $773$ K and $910$ K.

![Figure 3](image1.png)  
**Figure 3.** The resulting radiant flux density at different mean temperatures.

![Figure 4](image2.png)  
**Figure 4.** Plot of radiant component $\lambda_{rad}$ and ETC $\lambda_{eff}$ itself vs. mean temperature.

3.1.2. Approximate methods of radiant component estimation.

Radiation diffusion approximation is used in cases of sufficiently large AC, so that an average free path (penetration depth) of a thermal photon is small compared to a distance of a significant temperature change or a layer thickness. In this case, the medium can be considered as optically thick, and Rosseland equation [6] is valid, so in an one-dimensional case ($\frac{\partial n}{\partial x} \ll 1$):

$$q_{rad}(x) = -\frac{4}{3} \sigma \frac{\partial (n^2 T^4)}{\partial x} = -\frac{8}{3} n \frac{\sigma T^3}{\chi(T)} \left(2n + T \frac{\partial n}{\partial T}\right) \frac{\partial T}{\partial x} \approx -\frac{16}{3} n^2 \frac{\sigma T^3}{\chi(T)} \frac{\partial T}{\partial x} \approx -\lambda_{rad}(x) \frac{\Delta T}{h}$$  \hspace{1cm} (16)

Where $\chi(T)$ is a Rosseland AC [6]:

$$\int_0^\infty \frac{1}{X_v} \frac{\partial e_{vb}}{\partial e_b} dv = \frac{1}{\chi(T)} \int_0^\infty \frac{\partial e_{vb}}{\partial e_b} dv$$  \hspace{1cm} (17)

$$\frac{\partial e_{vb}}{\partial e_b} = \frac{\lambda^3(\frac{2\pi C_1}{e^2 c_0^2})^\frac{1}{2}}{\lambda^6 T^2 (e^2 c_0^2)^\frac{1}{2}}$$  \hspace{1cm} (18)

Where $C_1 = h c_0^2$, $C_2 = \frac{h c_0^2}{k}$, $k$ is a Boltzmann constant, $h$ is a Planck constant, $c_0$ is a light velocity, $\lambda$ is a wavelength, $e_{vb}$ is the Planck function, $T = \left(\frac{e_k}{\sigma}\right)^\frac{1}{2}$ is an absolute temperature according Stefan-Boltzmann’s law. An average Planck RI at temperature $T$ [7]:

$$n(T) = \frac{\int_0^\infty n_v e_{b,v}(T) dv}{\int_0^\infty e_{b,v}(T) dv} \approx \frac{\int_{v_d}^{v_u} n_v e_{b,v}(T) dv}{\int_{v_d}^{v_u} e_{b,v}(T) dv}$$  \hspace{1cm} (19)

RI outside $[v_d; v_u]$ is considered to be negligibly small. Dielectric emissivity with a negligibly small absorption rate can be determined by Dunkle formula [5]:
\[ \varepsilon_v = \frac{4n_v + 2}{3(n_v + 1)^2} + \frac{2n_v^3(n_v^2 + 2n_v - 1)}{(n_v^2 + 1)(n_v^4 - 1)} - \frac{8n_v^4(n_v^4 + 1)}{(n_v^2 + 1)(n_v^4 - 1)^2}\ln(n_v) - \frac{n_v^2(n_v^2 - 1)^2}{(n_v^2 + 1)^3}\ln\left(\frac{n_v - 1}{n_v + 1}\right) \]  

(20)

And its average Planck value at temperature \( T \) can be found by the same way [7]:

\[ \varepsilon(T) = \int_{\nu_{	ext{m}}}^{\nu_{	ext{u}}} \varepsilon_v e_{\nu_v}(T) d\nu \int_{\nu_{	ext{m}}}^{\nu_{	ext{u}}} e_{\nu_v}(T) d\nu \]  

(21)

Basing on obtained from [2] data the diffusion approximation might be acceptable to determine \( \lambda_{\text{rad}} \).

**Table 3.** Results of \( \lambda_{\text{rad}} \) calculation by equation (16) for fraction 8-4 mm [3].

| T, K | \( \lambda_{\text{rad}}, C^0 \) | ETC, C\textsuperscript{b} | T, K | \( \lambda_{\text{rad}}, O^c \) | ETC, O\textsuperscript{b} | T, K | \( \lambda_{\text{rad}}, R^d \) | ETC, R\textsuperscript{d} |
|------|------------------------------|------------------|------|-------------------------------|------------------|------|-------------------------------|------------------|
| 626  | 0.041                        | 0.223            | 633  | 0.042                         | 0.214            | 628  | 0.041                         | 0.242            |
| 921  | 0.139                        | 0.370            | 923  | 0.140                         | 0.441            | 924  | 0.141                         | 0.433            |

* Unit of measure of radiant component of ETC \( \lambda_{\text{rad}} \) and ETC is W/(m*K) in this table.
* Filling after calcination in muffle furnace (3 h, 1273 K).
* Original (or initial) filling.
* Filling after repeated measurements.

**Table 4.** Results of \( \lambda_{\text{rad}} \) calculation by equation (16) for fraction 2-0.7 mm [3].

| T, K | \( \lambda_{\text{rad}}, C^0 \) | ETC, C\textsuperscript{b} | T, K | \( \lambda_{\text{rad}}, O^c \) | ETC, O\textsuperscript{b} | T, K | \( \lambda_{\text{rad}}, R^d \) | ETC, R\textsuperscript{d} |
|------|------------------------------|------------------|------|-------------------------------|------------------|------|-------------------------------|------------------|
| 620  | 0.0394                        | 0.1802           | 627  | 0.0411                        | 0.1278           | 621  | 0.0395                        | 0.1043           |
| 891  | 0.1270                        | 0.2446           | 882  | 0.1236                        | 0.1741           | 905  | 0.1330                        | 0.2147           |

* Unit of measure of radiant component of ETC \( \lambda_{\text{rad}} \) and ETC is W/(m*K) in this table.
* Original (or initial) filling.
* Filling after repeated measurements.
* Filling after calcination in muffle furnace (3 h, 1273 K).

This approximation may not be valid at high temperatures (Table 3, Table 4): radiant component of ETC grows as cubic function of absolute temperature \( \lambda_{\text{rad}} \sim T^3 \) at \( \lambda \sim \text{const} \), whereas \( \lambda_{\text{eff}} \) depends on \( T \) linearly.

**3.1.3. Other methods of radiant contribution estimation to an ETC.**

In some papers devoted to study of thermal radiation heat transfer in dispersed materials, an expression to determine the radiant component of ETC [10] looks like:

\[ \lambda_{\text{rad}} = 4f\sigma T^3d \]  

(22)

where \( d \) is a particle size, \( f \) is a parameter, for example, by Loeb [14]: \( f = \Gamma_{\text{eff}} \), by Chudnovsky [9]: \( f = \frac{He_{\text{M}}}{2d} \). It was assumed that the average particle size \( d = 1.4 \) mm (for 2-0.7 mm fraction), the geometric factor \( \Gamma = 2/3 \) (for spherical pores), and \( \epsilon_{\text{M}} \) - pore surface emissivity at a temperature \( T \), \( H \) is a pore size (Table 2).

The parameter \( f \) differs dramatically (Table 5): by Chudnovsky \( \lambda_{\text{rad}} < 0.001 \) W/(m*K), i.e. radiant contribution is less than 1% of ETC, meanwhile by Loeb, radiation part is significant and varies from 24% (at \( T = 620 \) K, initial filling) to 72% (at \( T = 882 \) K, after repeated measurements).
Table 5. Calculated average $\lambda_{\text{rad}}$ by Loeb and Chudnovsky (fraction 2-0.7 mm) by equation (22).

| T, K | ETC, W/(m*K) | $\lambda_{\text{rad}}$ by Loeb, W/(m*K) | $\lambda_{\text{rad}}$ by Chunovsky, W/(m*K) |
|------|--------------|-------------------------------------|---------------------------------------|
| 620  | 0.1802       | 0.0438                              | 0.0003                                |
| 891  | 0.2446       | 0.1297                              | 0.0009                                |

Filling after repeated measurements

| T, K | ETC, W/(m*K) | $\lambda_{\text{rad}}$ by Loeb, W/(m*K) | $\lambda_{\text{rad}}$ by Chunovsky, W/(m*K) |
|------|--------------|-------------------------------------|---------------------------------------|
| 627  | 0.1278       | 0.0452                              | 0.0003                                |
| 882  | 0.1741       | 0.1261                              | 0.0008                                |

Filling after calcination in muffle furnace (3 h, 1273 K)

| T, K | ETC, W/(m*K) | $\lambda_{\text{rad}}$ by Loeb, W/(m*K) | $\lambda_{\text{rad}}$ by Chunovsky, W/(m*K) |
|------|--------------|-------------------------------------|---------------------------------------|
| 621  | 0.1043       | 0.0438                              | 0.0003                                |
| 905  | 0.2147       | 0.1362                              | 0.0009                                |

Vermiculite is a layered material consisting of sheets (walls) and its grain may be approximated as infinite plane-parallel plates (Figure 5). The radiation energy inside the plates is reflected (R), transmitted (D) or absorbed or emitted (A = e) in a steady state and according to energy conservation law: $R + D + A = 1$. Resulting output thermal radiation flux density for this model (Figure 6):

$$q^r = \sum_{k=1}^{N-1} w_k \varepsilon_k \sigma T_k^4 + (1 + w_N) \varepsilon_N \sigma T_N^4 + w_q q_i = q_c + w_0 q_i \approx q_c$$  \hspace{1cm} (23)

where $w_0$ and $w_k$ - incident radiation part and radiation part of $k^{th}$ wall respectively behind last wall, $q_i$ and $q_c$ – incident, $k^{th}$ wall and entire system radiant flux density respectively, N – number of walls.

Figure 5. Multi-wall vermiculite model for a stand-alone grain (blue - air gaps, brown - vermiculite walls with no pores inside).

Figure 6. Simulation result for a grain with number of walls N = 20 in a sample center (x = 15 mm).

3.2. Convection contribution evaluation to ETC.

Convection intensity in various processes is measured by parameter $\psi = \frac{\lambda_{\text{conv}}}{\lambda_{\text{eff}}} = A(Gr Pr)^n$, where $A$ is a material-dependent factor, $n$ for free convection is in range from 0.20 to 0.33 [9]. The difference between an effective thermal conductivity and a conductive part [9]:

$$\delta = \lambda(\psi - 1) = \lambda_{\text{eff}} - \lambda = \frac{2B_T(T_2 - T_1) \rho \beta^2 \nu^3 c_p x}{18 a^2 \mu} = -0.00016 Gr Pr \left(\frac{px}{d_{eq}}\right)^2 \lambda_{eq}$$ \hspace{1cm} (24)

Where $c_p$ is a specific heat (at constant pressure) (J/(kg*K)), $\mu$ is an air dynamic viscosity coefficient (Pa*s), $\lambda_{eq}$ - gas (air) thermal conductivity coefficient (W/(m*K)) [11]. The highest Grashof number ($Gr = \frac{\beta T_d a d_{eq}^3}{\nu^2}$) is achieved in the lower part of the sample, $\Delta T$ is a temperature difference at boundaries of a material layer of height $x$ open on both sides, $d_{eq} = \frac{4p}{a}$ is the equivalent layer thickness, $p$ is a porosity of material and the grain specific area per volume unit of the layer $a = F/\rho$, $F$ – specific area per...
unit mass unit (m$^2$/kg), $\rho$ – fraction density (kg/m$^3$), $p$ - porosity, $g$ = 9.81 m/s$^2$ - free fall acceleration, $v$ – air kinematic viscosity coefficient (m$^2$/s) [11], $\beta_0$ - volume expansion thermal coefficient (K$^{-1}$).

### Table 6. Calculation by equation (24) results of convective constituent in ETC.

| $T^a$, K | $T^b$, K | $|\beta^a|$, W/(m$^3$K) | $|\beta^b|$, W/(m$^3$K) | $|1-\rho^a|$ | $|1-\rho^b|$ | $x$, mm |
|----------|----------|------------------------|------------------------|-----------------|-----------------|---------|
| 1189     | 1150     | 3E-10                  | 4E-10                  | 1E-09           | 1E-09           | 5       |
| 1090     | 1028     | 2E-09                  | 1E-09                  | 6E-09           | 5E-09           | 10      |
| 976      | 906      | 4E-09                  | 5E-09                  | 2E-08           | 1E-08           | 15      |
| 848      | 784      | 1E-08                  | 1E-08                  | 4E-08           | 3E-08           | 20      |
| 704      | 663      | 2E-08                  | 2E-08                  | 9E-08           | 8E-08           | 25      |
| 546      | 541      | 5E-08                  | 3E-08                  | 2E-07           | 1E-07           | 30      |

* Fraction 2-0.7 mm, initial, chaotic filling, $d_{eq} = 3.14 \mu m$

* Fraction 8-4 mm, initial, flat parallel filling, $d_{eq} = 3.12 \mu m$

Contribution of convective component to the ETC is extremely small and does not exceed 0.005% (Table 6). To take a convection constituent into consideration it is required: $GrPr > 680$. In case of the present paper: $Gr < 10^3$, $Pr \approx 0.7$.

### 4. Conclusions

To find a radiant component of ETC a diffusion approach was accepted (due to specific sample physical properties), an exact solution was found and other techniques were used. According calculations a convection contribution in ETC can be neglected. Additive approach might be applied to find components of ETC at $T < 700$ K because $\lambda_{rad} \sim T^3$ and $\lambda_{eff} \sim T$ and at $T > 700$ K it might not work.

### Acknowledgements

Authors express their gratitude for assistance to conduct measurements to a leading engineer S.A. Markelov and a chief of physicochemical department A.A. Kovalenko of Technologies and Production Development Center of “BKO”, JSC.

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