Assessment of the influence of the structural characteristics of granular systems of microsilicon on the properties of thermal insulation materials

[1*]Sangulova I.B., [2]Selyaev V.P., [3]Kuldeev E.I., [4]Nurlybaev R.E., [4]Orynbekov Ye.S.

[1]*"International Educational Corporation", Almaty, Kazakhstan*
[2]*Ogarev Mordovia State University, Mordovia, Russia*
[3]*Satbayev University, Institute of Metallurgy and Ore Beneficiation, Almaty, Kazakhstan*
[4]*«SAVENERGY» Limited Liability Partnership, Almaty, Kazakhstan*

* Corresponding author email: e-mail: indiraberkinbaykyzy@gmail.com

ABSTRACT

The article discusses experimental studies of the size and shape of structured particles of microsilica small angle x-ray scattering method and a photophonon theoretical description of the heat transfer process in complex heterogeneous structures to assessment of the structural characteristics of granular systems for the properties of thermal insulating materials. The mechanism of heat transfer in granular, porous systems is quite complex, since heat exchange occurs in a material consisting of two phases (solid and gas) and at the phase boundary. Heat transfer in liquid thermal insulation coatings can be carried out from one solid particle to another. In this case, the thermal conductivity will depend on: the chemical and elemental composition of the material; particle granulometry; surface topology - the presence of inhomogeneities, defects on the surface; the number of touches and the contact area between the particles. The heat transfer of gas in the pores is carried out when gas molecules collide. Thermal conductivity will be determined by the ratio of the free path of molecules and linear pore sizes, temperature and dynamic viscosity of the gas phase, the nature of the interaction of gas molecules with the solid phase. Heat transfer by radiation depends on the nature of the particles, the dielectric, magnetic permeability and the degree of blackness of the particle surface. Based on the analysis of possible mechanisms of heat transfer in granular systems, it can be argued that the effective thermal conductivity of the system depends, all other things being equal, on the structure of the pore space of granular materials, topology and the number of particle touches. Considering idealized models of the structure of granular materials in the form of ordered folds of perfectly smooth balls, we can obtain several variants of structures: with tetrahedral; hexagonal; cubic packing of balls.

Keywords: x-ray diffractometer, microsilicon, thermal conductivity, diatomite, structure, filler.

	Information about authors:
Sangulova Indira Berlinbayevna	*Head of the Laboratory, Faculty of Construction Technologies, Infrastructure and Management, Limited Liability Partnership "International Educational Corporation", Almaty, Kazakhstan. Email: indiraberkinbaykyzy@gmail.com, https://orcid.org/0000-0002-4066-8238*
Selyaev Vladimir Pavlovich	*Doctor of Technical Sciences, Professor, Head of the Department of Building Structures of the Mordovian State University, Mordovia, Russia. Email: ntorm80@mail.ru, https://orcid.org/ 0000-0003-3343-094X*
Kuldeev Erzhan Itemenovich	*Candidate of Geological and Mineralogical Sciences, Vice-Rector for Corporate Development and Strategic Planning, Satbayev University, Institute of Metallurgy and Ore Beneficiation, Almaty, Kazakhstan. Email: kuldeev_erzhan@mail.ru, https://orcid.org/ 0000-0001-8216-679X*
Nurlybaev Ruslan Ergalievich	*Doctor of PhD, Director of Limited Liability Partnership "SAVENERGY", Almaty, Kazakhstan. Email: rusya_nre@mail.ru, https://orcid.org/0000-0003-0161-6256*
Orynbekov Yelzhan Serikovich	*Candidate of Technical Sciences, Scientific Consultant of Limited Liability Partnership "SAVENERGY", Almaty, Kazakhstan. Email: eljan_79@mail.ru, https://orcid.org/0000-0003-2131-6293*

Introduction

To determine the main structural parameters that affect the thermal conductivity of filled polymer binders, let us consider the mechanisms of heat transfer in solid, liquid, gaseous media.

It is customary to distinguish between three main mechanisms of heat transfer: thermal conductivity (conduction); convection; radiation [[1], [2], [3], [4], [5]].

The conduction mechanism of heat transfer occurs due to the exchange of kinetic energy when

moving molecules collide with each other or with the surfaces of a solid or liquid phase that limits space.

Convection - heat transfer by a moving environment, air or liquid streams.

Radiation - emission of electromagnetic energy emitted by some kind of heat, such as the sun.

In quantum theory, heat transfer in solids by thermal conductivity is considered as a process of nonequilibrium phonon distribution, and thermal conductivity is determined by the deviation of the phonon distribution from the equilibrium state at a given temperature gradient.

Considering the transfer of heat in the gas phase of the composite (in pores, hollow spheres), the molecular kinetic theory assumes the presence of two mechanisms of heat transfer by gas - due to the collision of molecules and radiation.

The efficiency of molecular heat transfer in pores, spheres of liquid heat-insulating coating further (LTC), depends on temperature, pressure, geometry of the pore space, the nature of interaction at the boundary of a solid with gas.

Experimentally established, that the effective thermal conductivity of heterogeneous finely dispersed granular systems, even at atmospheric pressure, may turn out to be lower than the thermal conductivity of the gas filling the pores.

To describe the process of heat transfer in continuous media and determine the coefficient of thermal conductivity, the most often used methods are based on the application of the principle of generalized conductivity, which is based on the analogy (similarity) between the differential equations of stationary heat flux, temperature, mass, current, etc.

It is possible to use topological models, when solving more complex problems to determine the thermal conductivity coefficient. However, they do not take into account the features of the quantum mechanisms of heat transfer through the main matrix of the material [[5], [6], [7]].

Analysis of modern research in this area

To assess the effect of the structural characteristics of granular microsilica systems on the properties of heat-insulating materials, a comprehensive analysis showed that the only mechanism for heat transfer for granular systems would be:

- *heat transfer through a flat, two-layer and multi-layer plate.*

In the works of Krainov A.Yu. To calculate the heat transfer through a flat plate, the value of the heat flux through a plate of thickness L, having a thermal conductivity coefficient λ, the walls of which have a constant temperature T0 and T1, is determined. The mathematical formulation of the problem consists of a stationary one-dimensional heat equation with boundary conditions of the first kind [8].

- *heat transfer of coatings with a coefficient of thermal conductivity that depends on the temperature of the environment.*

In the works of V.A. Maksimov, S.R. Vitaly. the values of the thermal conductivity coefficient of some ultrathin liquid composite heat-insulating coatings have been experimentally determined. The calculation of the measurement error has been performed. As a result of the work done, the thermal conductivity coefficient of ultra-thin liquid composite heat-insulating coatings was experimentally determined for sample No. 1 λ = 0.086 W / (m · ° C), for sample No. 2 λ = 0.091 W / (m · ° C). But, the real thermal conductivity coefficient of the samples under study in practice turned out to be higher than the declared one.

According to the authors, this discrepancy is possible due to the fact that manufacturers of liquid coatings in laboratory determination of thermal conductivity either used some "ideal" conditions, or the coefficient was obtained by theoretically solving the problem of thermal conductivity in liquid composite heat-insulating environment.

Despite this, the authors consider such liquid thermal insulation coatings to be of great interest for builders, since they allow insulating objects of complex geometric shapes (valve bodies, complex units, etc.), which in some cases makes them practically irreplaceable. Correct consideration of the thermal properties of paints will allow avoiding excessive increases in heat losses of insulated pipelines with a coolant or building enclosing structures, and will also protect them from possible defrosting during periods of negative temperatures [9].

- *heat transfer of a plate with a coefficient of thermal conductivity depending on the coordinate.*

The work of Kolmychkov V.V., Mazhorova O.S. is devoted to the numerical study of convective structures arising near the stability threshold in a non-Bussinesq fluid, the thermal diffusivity of which depends on the vertical coordinate. The main attention is paid to the study of the existence and

stability of a flow in the form of square cells for various values of the Prandtl number [10].

- phonon-photon model for the theoretical description of the process of heat transfer in complex heterogeneous structures.

In the works of Gladkov S.O. for an arbitrary type of porous structures, a theoretical approach is proposed for calculating their thermal conductivity coefficient κ as a function of porosity ξ, temperature T, density ρ, and a number of other parameters. The general calculation algorithm is based on the theory of nonequilibrium processes. Its modification in the language of the gas-kinetic approximation allows one to obtain compact formulas for κ and easily estimate the corresponding dependences. On a specific example of such a very important in practical terms refractory substance, like concrete, the theoretical formulas are compared with experimental results and their good agreement is shown [11].

Methods for determining the structural characteristics of granular systems

1. To study the properties of microdispersed materials, a Hecus S3 - MICRO small-angle X-ray diffractometer was used.

The most important feature of this method is the ability to analyze the internal structure of disordered systems - particles, pore space, interfaces between heterogeneities of heterogeneous substances.

As the scattering coordinate, we used the magnitude of the scattering vector modulus s = 4π sinθ / λ, where 2θ is the scattering angle, λ = 1.5418 Å is the wavelength of the radiation used. Scattering intensities were recorded in the range of s values from 0.0094 to 0.40 Å-1, which made it possible to study inhomogeneities with linear dimensions L ~ (2 π) / S, in the range of 2 ... 60 nm.

2. One of the most important parameters that determine the thermal insulation properties of materials based on microstructured mineral powders (silica, diatomite) is thermal conductivity. Knowing a number of characteristics of dispersed systems, such as the size, thermal conductivity of the material of primary particles, the method of filling and some other characteristics, it is possible to theoretically calculate the thermal conductivity of granular systems based on the polystructural theory and, as a result, it is possible to assess the structural characteristics of granular systems for

the properties of heat-insulating materials [[12], [13], [14], [15], [16], [17]].

Assessment of the structural characteristics of granular systems to the properties of heat-insulating materials

For the theoretical description of the process of heat transfer in complex heterogeneous structures, a photophonon model was used, according to which the general expression for the thermal conductivity of a porous system is written in the form of an additive function [[12], [13], [14], [15], [16], [17]].

$$\lambda = \left(1 - \frac{m}{m_p}\right)^2 \lambda_{00} + \frac{m}{m_p}\left(1 - \frac{m}{m_p}\right)\lambda_{01} + \frac{m}{m_p}\left(1 - \frac{m}{m_p}\right)\lambda_{10} + \left(\frac{m}{m_p}\right)^2 \lambda_{11} \qquad (1)$$

where m – porosity of the structure;
λ_{00} - thermal conductivity of the main matrix;
λ_{11} - thermal conductivity of pores;
λ_{01} - phonon-photon thermal conductivity at the interface between pores and the main matrix;
λ_{10} - photon-phonon thermal conductivity;
m_p - percolation threshold for the basic matrix model.

Using the gas-kinetic approximation, we represent the thermal conductivity of the main matrix in the form:

$$\lambda_{00} = \frac{1}{3} c_{fon} v^2 \tau_{fon} \qquad (2)$$

where c_{fon} - phonon heat capacity per unit volume of the main matrix;
v - average speed of sound in the material;
τ_{fon} - phonon relaxation time, which is associated with phonon scattering by structural inhomogeneities and at the boundaries of contact of pores with the main matrix.

The phonon heat capacity is determined by the formula (at T >> θ_D)

$$c_{fon} = \frac{3k}{a^3} \qquad (3)$$

where k - Boltzmann constant;
a - average interatomic distance of the main matrix material.

The phonon relaxation time satisfies the expression [10]:

$$\tau_{fon} \approx \frac{m_p}{m} \frac{\rho\, a^4\, v \left(1 - \frac{m}{m_p}\right)}{k\,T} \qquad (4)$$

where ρ – base matrix material density;
T – absolute temperature (K).
Substituting (3) and (4) into (2), we obtain the expression

$$\lambda_{00} = \left(1 - \frac{m}{m_p}\right) \frac{\rho\, v^3\, a}{T} \frac{m_p}{m} \qquad (5)$$

Similarly, representing the photon flux as a photon gas, we can write

$$\lambda_{11} = \frac{1}{3} c_{fot} c^2 \tau_{fot} \qquad (6)$$

where c_{fot} - photonic heat capacity per unit pore volume;
c - speed of light in pores;
τ_{fot} - photon relaxation time within pores.
The work presents an expression for determining the photon heat capacity:

$$c_{fot} \approx k \left(\frac{k\,T}{\hbar\,c}\right)^3 \qquad (7)$$

($\hbar$ – Planck's constant), and the photon relaxation time for the case of vacuum or a low concentration of gas molecules in the pores:

$$\tau_{fot} = \frac{L}{c} \qquad (8)$$

L – linear pore sizes. Substituting (7) and (8) into (6), we obtain

$$\lambda_{11} = \frac{1}{3} \frac{k\,L}{c^2} \left(\frac{k\,T}{\hbar}\right)^3 \left(\frac{k\,T}{\hbar}\right)^3 \qquad (9)$$

It is shown in the work that in formula (1) the terms containing λ_01 and λ_10 are small compared to other terms and can be discarded. Then expression (1) will look like this:

$$\lambda = \left(1 - \frac{m}{m_p}\right)^2 \lambda_{00} + \left(\frac{m}{m_p}\right)^2 \lambda_{11} \text{ , and}$$

given
(5) and (6):

$$\lambda = \left(1 - \frac{m}{m_p}\right)^3 \frac{\rho\, v^3\, a}{T} \frac{m_p}{m} +$$
$$\frac{1}{3}\left(\frac{m}{m_p}\right)^2 \frac{k\,L}{c^2} \left(\frac{k\,T}{\hbar}\right)^3$$

$$(10)$$

The resulting formula makes it possible to: estimate the dependence of the thermal conductivity of the LTP on the porosity of the material structure (m), linear pore size (L), density (ρ) on temperature and calculate the effective thermal conductivity of a dispersed porous substance, based only on the knowledge of some macro- and microscopic material parameters; to solve the inverse problem - by measuring the effective thermal conductivity of a dispersed powder by the method of stationary heat flux or by the method of laser flash, knowing the density, speed of sound and average interatomic distances, calculate the characteristic linear dimensions of its pores. At low temperatures, the thermal conductivity of a granular system is determined mainly by its phonon component. With an increase in temperature (T>>θ_D), this component decreases $\propto T^{-1}$, but radiant heat transfer (by photons of electromagnetic radiation) $\propto T^3$ increases. If the dependence of thermal conductivity on temperature (10) is represented in the form

$$\lambda(T) = \frac{A}{T} + B\,T^3 \qquad (11)$$

then the minimum value of the effective thermal conductivity λ (T) will be observed at a temperature.

$$T_{min} = \sqrt[4]{\frac{A}{3\,B}} \qquad (12)$$

In this case, the photon thermal conductivity (10) will be the smaller, the smaller the dimensions L of the pores of a given material. Consequently, formulas (10) and (12) make it possible, on the basis of the data obtained as a result of studying the structural characteristics of the pore space of dispersed powders, to reasonably recommend granular systems for use as a filler for LTM. It is proposed to determine and evaluate the structural characteristics of filler powders by the method of small-angle X-ray scattering (SAXS) [1]. The features of structural inhomogeneities of microsilica [[1], [18], [19]] and natural diatomite of the Utesai deposit, as well as a filler powder of the FRONT-VIP vacuum insulating panel from VACU - ISOTEC KG were investigated.

Experimental part

Small-angle X-ray scattering is a diffraction method widely used to study nanoobjects of

various physical nature and state of aggregation, including highly dispersed powders.

The experimental material was obtained in the form of small-angle X-ray scattering indicatrices for all investigated dispersed powders. As the scattering coordinate, we used the magnitude of the scattering vector modulus s = 4π sinθ/λ, where 2θ is the scattering angle, λ = 1.5418 Å is the wavelength of the radiation used. Scattering intensities were recorded in the range of s values from 0.0094 to 0.40 Å-1, which made it possible to study inhomogeneities with linear dimensions L ~ (2 π) / S, within 2 ... 60 nm. The character of the I (s) curves indicates that the studied materials contain scattering inhomogeneities (pores) of different linear sizes, and high values of the scattering intensity are due to the sharp contrast caused by the large difference between the density of silica particles and pores. Fig. 1 shows the experimental SAXS curves of the natural diatomite of the Utesayskoye deposit and the filler powder of the FRONT-VIP insulation panel. The scattering indices of the other three microsilica have a similar form to the FRONT-VIP SAXS curve.
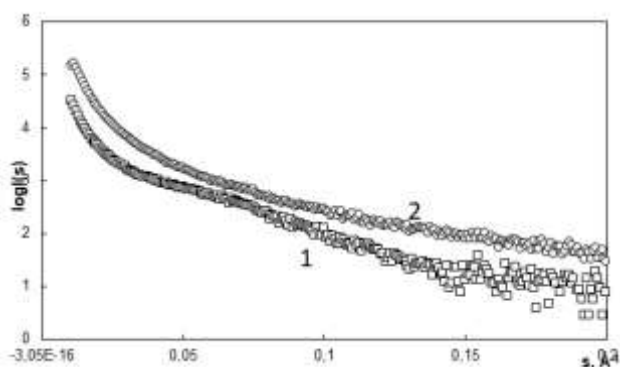

Figure 1 - Curves of small-angle X-ray scattering of dispersed powders: 1 - natural diatomite; 2 - filler powder FRONT- VIP
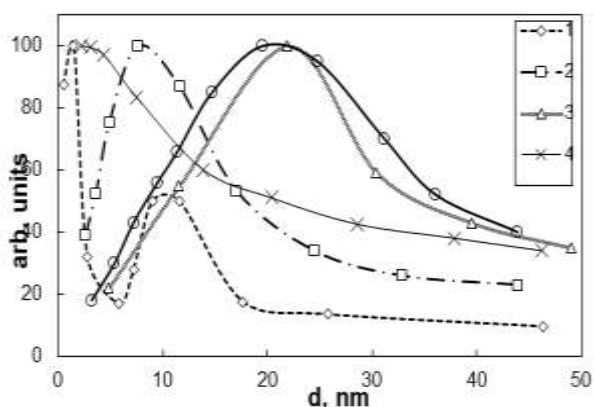

Figure 2 - Size distribution of scattering inho.mogeneities: 1 - natural diatomite; 2 -

microdispersed silica obtained from diatomite; 3 - condensed silica; 4 - white soot; 5 - FRONT-VIP filler powder.

To find the approximate size distribution functions of scattering inhomogeneities (for spherical particles), the SAXS curves were rearranged into coordinates $\ln I(s) - s^2$. Using the Kitaygorodsky method, we obtained the dependencies shown in Fig. 2. Pore size distribution curves of dispersed microsilica have pronounced maxima; a similar function of natural diatomite is bimodal. Table 1 shows the results of the analysis of distribution curves - the maxima of the distribution functions dᴃ; average values of the linear dimensions of the scattering inhomogeneities <d>; variances of distribution functions Δd.

Table 1 - Pore size distribution of dispersed microsilica

Powder type	dᴃ, nm		<d>, nm		Δd , nm
Natural diatomite	2	10	2	7	7 - 15
Dispersed microsilica obtained from diatomite	8		12		3 − 18
Condensed silica fume	22		26		10 − 34
White soot	2		13		2 - 21
FRONT-VIP	20		20		8 - 37

In general, the average linear dimensions of the scattering inhomogeneities of the investigated dispersed powders are ~ 10 - 30 nm, which, according to the classification of M.M. Dubinin, officially adopted by the International Union of Pure and Applied Chemistry (IUPAC), corresponds to mesopores. Capillary condensation of water molecules occurs in them, which are partially removed during heating (calcination) of dispersed powders [11].

The SAXS indicatrices were rearranged into double logarithmic coordinates $\lg I(s) - \lg s$. An analysis of these dependences showed that, in all investigated dispersed materials, a fractal character of scattering by structural inhomogeneities of the nanoscale level is observed. To determine the fractal dimensions of these inhomogeneities, a method was used, which consists in determining the slope of the corresponding linear section of the scattering curve plotted in the indicated coordinates. If the investigated structural elements of the nanoscale, such as pores, pore clusters, and interfaces of inhomogeneities are of a fractal nature, then in certain intervals of values of the modulus of the scattering vector, a power-law

decay of the scattering indicatrix I(s) ~ s$^{-\alpha}$ with a non-integer value of the exponent should be observed, and α < 4. At 1 ≤ α <3, the power-law decay of I(s) is characteristic of scattering from fractal clusters or aggregates of nanoparticles (mass fractals) with the dimension D = α. In the case when 3 <α <4, scattering from nanoparticles with a nonsmooth fractal surface is observed, the fractal dimension of which is determined as D_S = 6 - α. The exponent I (s) in this case is defined as α = ΔlgI(s) / Δlg s.

On the SAXS curve of diatomite from the Utesai deposit, three rectilinear sections are distinguished, corresponding to the values of the scattering vector 0.013 – 0.026 Å^{-1}, 0.031 – 0.061 Å^{-1}, and 0.067 – 0.095 Å^{-1}. The parameter α for these sections is 2.59 1.56 and 3.73. Sizes of inhomogeneities are 24 - 48 nm, 10 - 20 nm, and 7 - 9 nm, respectively. The most large-scale scattering objects behave like mass fractals with a fractal dimension D = α = 2.59, which is typical for branched self-organized porous structures. The second rectilinear segment of the indicatrix $\lg I(s) - \lg s$ corresponds to inhomogeneities with fractal dimension D = 1.56, which can be clusters in the form of curved chains of spherical pores of nano- and micrometer scale, possibly pore channels. In addition to mass fractals, the natural diatomite of the Utesayskoye field exhibits inhomogeneities with a fractal interface. The dimensions of such inhomogeneities are 7 - 9 nm, and the fractal dimension is D_S = 6 - α = 2.27. This value of the fractal dimension corresponds to a slightly indented surface, if we take into account that a perfectly smooth surface has D_S = 2.0, and a highly indented porous surface - 3.0. Fractal characteristics of all studied materials are shown in Table 2.

Dispersed microsilica obtained from natural diatomite also contains three types of scattering inhomogeneities, two of which are mass fractals with dimensions 2.32 and 2.13. The scale of such objects is 8 - 40 nm. Small-scale pores 4 - 8 nm have rather heavily indented interfaces (D_S = 2.64). Condensed silica fume, in contrast to other investigated dispersed powders, does not have X-ray scattering inhomogeneities that could be attributed to mass fractals. The interfaces of the SiO$_2$ particles - the pores have a fractal dimension D_S = 2.40. White microsilica contains fractal clusters of pore space with linear dimensions of 4 - 25 nm. The interfaces of larger scattering formations (25 - 40 nm) are strongly indented - their fractal dimension is D_S = 2.83. The scattering curve $\lg I(s) - \lg s$ of the FRONT - VIP filler powder has two crossover points: branched porous aggregates 20 - 40 nm in size have a fractal dimension D = 2.59, and inhomogeneities on a scale of 12 - 20 nm have highly irregular surface with D_S = 2.70. In addition, the data of small-angle X-ray scattering allow us to suggest that on the surface of the smallest elements of the structure of the filler powder (4 - 12 nm), there may be layers of scattering inhomogeneities with a lower electron density than that of silicon dioxide (parameter α = 4,10).

Table 2 - Fractal characteristics of the investigated materials

№	Material	Δs, Å^{-1}	α	D	D_S	d, нм
1	Natural diatomite	0.013 − 0.026	2.59	2.59		24 − 48
		0.031 − 0.061	1.56	1.56		10 − 20
		0.067 − 0.095	3.73		2.27	7 − 9
2	Dispersed microsilica obtained from diatomite	0.016 − 0.025	2.32	2.32		25 − 40
		0.025 − 0.080	2.13	2.13		8 − 25
		0.080 − 0.160	3.36		2.64	4 − 8
3	Condensed microsilica	0.016 − 0.160	3.60		2.40	4 − 40
4	White soot	0.016 − 0.025	3.17		2.83	25 − 40
		0.025 − 0.160	2.66	2.66		4 − 25
5	FRONT - VIP	0.016 − 0.032	2.59	2.59		20 − 40
		0.032 − 0.056	3.30		2.70	12 − 20
		0.056 − 0.160	4.10			4 − 12

Analysis of the data obtained gives grounds to believe that the studied granular systems are suitable: for the creation of new generation heat-insulating materials; as fillers for LTC, VIP. At the same time, condensed microsilica and white soot do not require preliminary heat treatment, since

their low moisture content is determined by the production conditions (subject to the rules of storage and transportation of bulk material). Dispersed microsilica obtained from diatomite and natural diatomite must be calcined at temperatures not lower than 400 - 500 °C for 3 - 5 hours. This modification of dispersed powders leads to their deep dehydration and helps to remove residues of organic material of sedimentary origin present in natural diatomites.

Conclusions

1. It was found that dispersed microsilica obtained from natural diatomite also contains three types of scattering inhomogeneities, two of which are mass fractals with dimensions 2.32 and 2.13. The scale of such objects is 8 - 40 nm. Small-scale pores 4 - 8 nm have rather heavily indented interfaces (D_S = 2.64). Condensed silica fume, in contrast to other investigated dispersed powders, does not have X-ray scattering inhomogeneities that could be attributed to mass fractals. The interfaces of the SiO_2 particles - the pores have a fractal dimension D_S = 2.40. White microsilica scoot contains fractal clusters of pore space with linear dimensions of 4 - 25 nm. The surface of the larger scattering formations (25 - 40 nm) are strongly indented - their fractal dimension is D_S = 2.83. The scattering curve $\lg I(s) - \lg s$ of the FRONT - VIP filler powder has two crossover points: branched porous aggregates 20 - 40 nm in size have a fractal dimension D = 2.59, and inhomogeneities on a scale of 12 - 20 nm have highly irregular surface with D_S = 2.70. In addition, the data of small-angle X-ray scattering allow us to suggest that on the surface of the smallest elements of the structure of the filler powder (4 - 12 nm), there may be layers of scattering inhomogeneities with a lower electron density than that of silicon dioxide (parameter α = 4.10).

The results obtained confirm the presence of a developed pore space of particles and agglomerates of dispersed silicon dioxide of nanometer sizes, can be used to calculate the effective thermal conductivity of heterogeneous systems, for example, mineral silica powders of various origins. The investigated dispersed materials have similar parameters of the pore system at the nanometer level.

2. As a result of the analysis of the influence of the structural parameters of a granular system formed from synthesized silicon dioxide particles, it was found that during the production of LTC, their heat-shielding properties can be adjusted by changing: pressure, viscosity of the molecular weight of the gas; porosity of the macrostructure and clusters; thermal conductivity of the solid and gas phase of the system; accommodation coefficient; coordination number; size of primary particles; fractal dimension that characterizes the topological features of the structure of particles, aggregates, globules, clusters and their tendency to dissipate the energy of gas molecules.

Conflict of interests

On behalf of all authors, the correspondent author declares that there is no conflict of interests.

Түйіршіктелген микрокремний жүйелерінің құрылымдық сипаттамаларының жылу оқшаулағыш материалдардың қасиеттеріне әсерін бағалау

[1] Сангулова И.Б., [2]Селяев В.П., [3]Кулдеев Е.И., [4]Нурлыбаев Р.Е., [4]Орынбеков Е.С.

[1]"Халықаралық білім беру корпорациясы" Жауапкершілігі шектеулі серіктестік, Алматы, Қазақстан

[2] Н.П. Огарев ат. Мордовия мемлекеттік университеті, Мордовия, Ресей

[3]Сәтбаев Университеті, Металлургия және кен байыту институты, Алматы, Қазақстан

[4] "SAVENERGY" Жауапкершілігі шектеулі серіктестік, Алматы, Қазақстан

ТҮЙІНДЕМЕ

Мақалада азбұрышты рентгендік шашырау әдісімен құрылымдалған микрокремнезем бөлшектерінің мөлшері мен формасын эксперименттік зерттеу және жылу оқшаулағыш материалдардың қасиеттері үшін түйіршіктелген жүйелердің құрылымдық сипаттамаларын бағалау мақсатында күрделі гетерогенді құрылымдардағы фотофононды жылу беру процесінің теориялық сипаттамасы қарастырылған. Түйіршікті, кеуекті жүйелердегі жылу беру механизмі өте күрделі, өйткені жылу алмасу екі фазадан (қатты және газ) тұратын материалда және фазалық шекарада жүреді. Сұйық жылу оқшаулағыш жабындарда жылу беру бір қатты бөлшектен екіншісіне берілуі мүмкін. Бұл жағдайда жылу өткізгіштік: материалдың химиялық және элементтік құрамына; бөлшектердің гранулометриясына; бет топологиясына – беттің әртектілігіне, бетте ақаулардың болуына; бөлшектердің жанасу саны мен жанасу аймағына байланысты болады. Кеуектерде газдың жылу беруі газ молекулаларының соқтығысуы арқылы жүзеге асырылады. Жылу өткізгіштік - молекулалардың бос жүрісі мен кеуектердің сызықтық өлшемдерінің қатынасы, газ фазасының температурасы мен динамикалық тұтқырлығы, газ молекулаларының қатты фазамен өзара әрекеттесу сипаты арқылы анықталады. Сәулемен жылу беру бөлшектердің табиғатына, диэлектрлік, магниттік өткізгіштікке және бөлшектердің бетінің қаралық деңгейіне байланысты. Түйіршікті жүйелердегі жылу берудің мүмкін болатын механизмдерін талдауға сүйене отырып, жүйенің тиімді жылу өткізгіштігі түйіршікті материалдардың кеуек кеңістігінің құрылымына, топологияға және бөлшектердің жанасу санына байланысты болады деп айтуға болады. Мінсіз тегіс шарлардың реттелген қатпарлары түріндегі түйіршікті материалдар құрылымының идеалдандырылған модельдерін қарастыра отырып, біз құрылымның бірнеше нұсқасын аламыз, олар: төрт қырлы, алтыбұрышты, кубтық қаптамасы бар шар тәрізді.

Түйін сөздер: рентгендік дифрактометр, микрокремний, жылу өткізгіштік, диатомит, құрылым, толтырғыш.

Авторлар туралы ақпарат:

Сангулова Индира Беркинбаевна — Зертхана меңгерушісі, құрылыс технологиялары, инфрақұрылым және менеджмент факультеті, "Халықаралық білім беру корпорациясы" жауапкершілігі шектеулі серіктестігі, Алматы, Қазақстан. Email: indiraberkinbaykyzy@gmail.com, https://orcid.org/0000-0002-4066-8238

Селяев Владимир Павлович — Техника ғылымдарының докторы, профессор, Мордовия мемлекеттік университетінің Құрылыс құрылымдары кафедрасының меңгерушісі, Мордовия, Ресей. Email: ntorm80@mail.ru, https://orcid.org/ 0000-0003-3343-094X

Кульдеев Ержан Итеменович — Геология-минералогия ғылымдарының кандидаты, Корпоративтік даму және стратегиялық жоспарлау жөніндегі проректор, Сәтбаев университеті, Металлургия және кен байыту институты, Алматы, Қазақстан. Email: kuldeev_erzhan@mail.ru, https://orcid.org/0000-0001-8216-679X

Нурлыбаев Руслан Ергалиевич — PhD доктор, «SAVENERGY» жауапкершілігі шектеулі серіктестігінің директоры, Алматы, Қазақстан. Email: rusya_nre@mail.ru, https://orcid.org/0000-0003-0161-6256

Орынбеков Елжан Серикович — Техника ғылымдарының кандидаты, «SAVENERGY» жауапкершілігі шектеулі серіктестігінің ғылыми кеңесшісі, Алматы, Қазақстан. Email: eljan_79@mail.ru, https://orcid.org/0000-0003-2131-6293

Оценка влияния структурных характеристик зернистых систем микрокремнезема на свойства теплоизоляционных материалов

¹ Сангулова И.Б., ²Селяев В.П., ³Кулдеев Е.Е., ⁴Нурлыбаев Р.Е., ⁴Орынбеков Е.С.

¹Товарищество с ограниченной ответственностью "Международная образовательная корпорация", Алматы, Казахстан
² Мордовский государственный университет им. Н.П. Огарева, Мордовия, Россия
³ Satbayev University, Институт металлургии и обогащения, Алматы, Казахстан
⁴Товарищество с ограниченной ответственностью "SAVENERGY", Алматы, Казахстан

АННОТАЦИЯ

В статье рассматриваются экспериментальные исследования размера и формы структурированных частиц микрокремнезема методом малоуглового рентгеновского рассеяния и теоретическое описание фотофононного процесса теплопередачи в сложных гетерогенных структурах с целью оценки структурных характеристик гранулированных систем для свойств теплоизоляционных материалов. Механизм теплопередачи в гранулированных, пористых системах довольно сложен, поскольку теплообмен происходит в материале, состоящем из двух фаз (твердой и газовой) и на

границе раздела фаз. Передача тепла в жидких теплоизоляционных покрытиях может осуществляться от одной твердой частицы к другой. В этом случае теплопроводность будет зависеть от: химического и элементного состава материала; гранулометрии частиц; топологии поверхности - наличия неоднородностей, дефектов на поверхности; количества касаний и площади контакта между частицами. Теплопередача газа в порах осуществляется при столкновении молекул газа. Теплопроводность будет определяться соотношением свободного пробега молекул и линейных размеров пор, температурой и динамической вязкостью газовой фазы, характером взаимодействия молекул газа с твердой фазой. Передача тепла излучением зависит от природы частиц, диэлектрической, магнитной проницаемости и степени черноты поверхности частиц. Основываясь на анализе возможных механизмов теплопередачи в гранулированных системах, можно утверждать, что эффективная теплопроводность системы зависит, при прочих равных условиях, от структуры порового пространства гранулированных материалов, топологии и количества соприкосновений частиц. Рассматривая идеализированные модели структуры зернистых материалов в виде упорядоченных складок идеально гладких шариков, мы можем получить несколько вариантов структур: с четырехгранной; шестиугольной; кубической упаковкой шариков.

Ключевые слова: рентгеновский дифрактометр, микрокремний, теплопроводность, диатомит, структура, наполнитель.

Сангулова Индира Беркинбаевна	*Информация об авторах:* *Заведующий лабораторией, факультет строительных технологий, инфраструктуры и менеджмента, Товарищество с ограниченной ответственностью "Международная образовательная корпорация", Алматы, Казахстан. Email: indiraberkinbaykyzy@gmail.com, https://orcid.org/0000-0002-4066-8238*
Селяев Владимир Павлович	*Доктор технических наук, профессор, заведующий кафедрой строительных конструкций Мордовского государственного университета, Мордовия, Россия. Email: ntorm80@mail.ru, https://orcid.org/ 0000-0003-3343-094X*
Кульдеев Ержан Итеменович	*Кандидат геолого-минералогических наук, проректор по корпоративному развитию и стратегическому планированию, Satbayev University, Институт металлургии и обогащения, Алматы, Казахстан. Email: kuldeev_erzhan@mail.ru, https://orcid.org/ 0000-0001-8216-679X*
Нурлыбаев Руслан Ергалиевич	*PhD доктор, директор товарищества с ограниченной ответственностью «SAVENERGY», Алматы, Казахстан. Email: rusya_nre@mail.ru, https://orcid.org/0000-0003-0161-6256*
Орынбеков Елжан Серикович	*Кандидат технических наук, научный консультант товарищества с ограниченной ответственностью «SAVENERGY», Алматы, Казахстан. Email: eljan_79@mail.ru, https://orcid.org/0000-0003-2131-6293*

Reference

[1] Petoukhov MV, Franke D, Shkumatov AV, Tria G, Kikhney AG, Gajda M, Gorba C, Mertens HTD, Konarev PV, Svergun DI. New developments in the ATSAS program package for small-angle scattering data analysis. J. Appl. Cryst., 2012, 45, 342-350.

[2] Savelyeva IYu. Matematicheskoye modelirovaniye protsessov teploprovodnosti metodom konechnykh elementov [Mathematical modeling of thermal conductivity processes by the finite element method]: textbook. IYu Savelyeva, IV Stankevich. Moscow: Bauman Moscow State Technical University, 2018. p. 178. (in Russ.)

[3] Selivanova ZM. Teoreticheskiye osnovy postroyeniya intellektual'nykh informatsionno-izmeritel'nykh sistem dopuskovogo kontrolya teploprovodnosti teploizolyatsionnykh materialov [Theoretical foundations of the construction of intelligent information and measurement systems for the tolerance control of thermal conductivity of thermal insulation materials]: monograph. ZM Selivanova, KS Stasenko. - Tambov: Tambov State Technical University, EBS DIA, 2015. p. 200. (in Russ.)

[4] Patent of the Russian Federation 2144595. Kokoev M.N., Fedorov V.T. Vakuumnoye teploizolyatsionnoye izdeliye [Vacuum thermal insulation product]. Byul. N 220.01.2000. (in Russ.)

[5] Kudinov IV. Teoreticheskiye osnovy teplotekhniki. Chast' II. Matematicheskoye modelirovaniye protsessov teploprovodnosti v mnogosloynykh ograzhdayushchikh konstruktsiyakh [Theoretical foundations of heat engineering. Part II. Mathematical modeling of thermal conductivity processes in multilayer enclosing structures]: textbook IV Kudinov, EV Stefanyuk. - Samara: Samara State University of Architecture and Civil Engineering, EBS DIA, 2013. p. 422. (in Russ.)

[6] Sevostyanov AV. Eksperimental'noye opredeleniye koeffitsiyenta teploprovodnosti tverdogo tela: metodicheskiye ukazaniya k laboratornoy rabote po distsipline "Teplomassoobmen" [Experimental determination of the coefficient of thermal conductivity of a solid: guidelines for laboratory work on the discipline "Heat and mass transfer"] AV Sevostyanov, TG Manukovskaya. Lipetsk: Lipetsk State Technical University, EBS DIA, 2017. 16 p. (in Russ.)

[7] Andreev LA. Fizikokhimiya poverkhnostnykh yavleniy: propitka poristykh materialov [Physical chemistry of surface phenomena: impregnation of porous materials]. Textbook. LA Andreev. - Moscow: MISIS Publishing House, 2011. 118 p. (in Russ.)

[8] Krainov AYu. Osnovy teploperedachi. Teploperedacha cherez sloy veshchestva [Fundamentals of heat transfer. Heat transfer through a layer of matter]: textbook. Tomsk: STT, 2016. 48 p. (in Russ.)

[9] Maxim VA, Vitaly SR. Eksperimental'noye opredeleniye koeffitsiyenta teploprovodnosti sverkhtonkikh zhidkikh kompozitsionnykh teploizoliruyushchikh pokrytiy. Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring

georesursov [Experimental determination of the thermal conductivity coefficient of ultrathin liquid composite thermal insulation coatings. Proceedings of Tomsk Polytechnic University. Georesource engineering]. 2015;326(9):15-22. (in Russ.)

[10] Kolmychkov VV, Mazhorova OS. Issledovaniye ustoychivosti kvadratnykh yacheyek v zhidkosti s koeffitsiyentom teploprovodnosti, zavisyashchim ot vertikal'noy koordinaty, Preprinty IPM im. MV Keldysha [Study of the stability of square cells in a liquid with a thermal conductivity coefficient depending on the vertical coordinate, Preprints of M.V. Keldysh IPM]. 2020. 112. https://doi.org/10.20948/prepr-2020-112 (in Russ.)

[11] Gladkov SO. Gazokineticheskaya model' teploprovodnosti geterogennykh veshchestv [Gas-kinetic model of thermal conductivity of heterogeneous substances]. Zhurnal tekhnicheskoy fiziki = Journal of Technical Physics. 2008; 7:12-15. (in Russ.)

[12] Kudinov IV, Stefanyuk EV, Eremin AV, Kotova EV. Analiticheskiye resheniya zadach teploprovodnosti i termouprugosti s peremennymi fizicheskimi svoystvami sredy [Analytical solutions to problems of thermal conductivity and thermoelasticity with variable physical properties of the medium]: textbook. IV Kudinov et al. Samara: Samara State Technical University, EBS DIA, 2016. (in Russ.)

[13] Glazkov VN. Metody izucheniya struktury i kolebaniy kristallov [Methods of studying the structure and vibrations of crystals]. M.: MIPT, 2015. 42 p. (in Russ.)

[14] Anisimov MV, Rekunov VS. Eksperimental'noye opredeleniye koeffitsiyenta teploprovodnosti sverkhtonkikh zhidkikh kompozitsionnykh teploizoliruyushchikh pokrytiy. Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov [Experimental determination of the thermal conductivity coefficient of ultrathin liquid composite thermal insulation coatings. Proceedings of Tomsk Polytechnic University. Georesource engineering]. 2015; 9:15-22. (in Russ.)

[15] Maneshev IO, Pravnik YuI, Sadykov RA, Safin IA. Eksperimental'noye opredeleniye koeffitsiyenta teploprovodnosti i effektivnosti sverkhtonkikh teploizolyatsionnykh pokrytiy [Experimental determination of thermal conductivity coefficient and efficiency of ultrathin thermal insulation coatings]. Izvestiya KGASU = News of KGASU. 2013; 1:135- 142. (in Russ.)

[16] Khabibullin YuKh, Barysheva OB. Razrabotka teploizoliruyushchikh pokrytiy i metodiki opredeleniya ikh teplofizicheskikh svoystv [Development of heat-insulating coatings and methods for determining their thermophysical properties]. Izvestiya KGASU = News of KGASU. 2015; 3:245-249. (in Russ.)

[17] Pavlov MV, Karpov DF, Sinitsyn AA, Mnushkin NV. Opredeleniye koeffitsiyenta teploprovodnosti zhidkoy teplovoy izolyatsii v laboratornykh usloviyakh [Determination of the thermal conductivity coefficient of liquid thermal insulation in laboratory conditions]. Vestnik Volgogradskogo gosudarstvennogo arkhitekturnostroitel'nogo universiteta = Bulletin of the Volgograd State University of Architecture. 2014; 37:79-86. (in Russ.)

[18] Selyaev VP, Osipov AK, Kupriyashkina LI, Sedova AA, Kichutkina EL, Suponina LA. Vozmozhnost' sozdaniya teploizolyatsionnykh materialov na osnove nanostrukturirovannogomikrokremnezema iz diatomite [The possibility of creating thermal insulation materials based on nanostructured silica from diatomite]. Nauka: 21 vek = Nauka: 21st century. 2011; 15(3):76-86. (in Russ.)

[19] Selyaev VP, Osipov AK, Neverov VA, Neverov VA, Mashtaev OG, Sidorov VV. Polistrukturnaya model' teploizolyatsionnogo materiala na osnove dispersnogo mikrokremnezema [Polystructural model of thermal insulation material based on dispersed silica]. Regional'naya arkhitektura i stroitel'stvo = Regional architecture and construction. 2012; 13(2):5-11. (in Russ.)