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Thermal conductivity of disperse insulation materials and their mixtures

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Abstract. Development of new, more efficient thermal insulation materials is a key to reduction of heat losses and contribution to greenhouse gas emissions. Two innovative materials developed at Thermeko LLC are Izoprok and Izopearl. This research is devoted to experimental study of thermal insulation properties of both materials as well as their mixture. Results show that mixture of 40% Izoprok and 60% of Izopearl has lower thermal conductivity than pure materials. In this work, material thermal conductivity dependence temperature is also measured. Novel modelling approach is used to model spatial distribution of disperse insulation material. Computational fluid dynamics approach is also used to estimate role of different heat transfer phenomena in such porous mixture. Modelling results show that thermal convection plays small role in heat transfer despite large fraction of air within material pores.

1. Introduction

Development of new materials for building is very important nowadays because of global tendency of transfer to energy efficient solutions and environmentally friendly materials (Thapliya un Singh 2014), (Schiavoni, u.c. 2016). However, before coming to market, careful investigation of these materials is necessary. Task of this research is investigation of materials Izopearl and Izoprok produced by Thermeko LLC, determine their heat conductivity, as well as its dependence on temperature. Another important task is investigation material mixture properties and numerical simulations to explain heat transfer within these materials.

Polystyrene is widely used insulation material, with polystyrene products accounting for 14% of polymeric materials used in constructions (Diogo 2014). In (Wigger, Stölken un Schreiber 2011) different wall cavity insulation materials are shown, but all of those made of polystyrene have heat conductivity 0.034 W/mK and above.

Izopearl is granular material made of Polysyrene. Izopearl granules are produced as material for filling voids in constructions, for double walls with air gap between them with thickness about 2-6 cm.

Izoprok is porous thermowool in the form of flakes or slabs. Izoprok in the form of flakes is prepared, to blow under pressure in a specially prepared cavity in the wall, roof, or ceiling of a building or in a sandwich panel. Figure 1 shows different mixtures of Izoprok and Izopearl materials. Figure on the left shows Izopearl material (grey granules) with small addition of Izoprok, which can be easily seen on the right photo (white flakes).

2. Preparation of material mixtures

Materials which are used in this investigation are disperse and should be packed accordingly for thermal conductivity measurements. For this purpose, sample modules were created. Modules consisted of case filled with investigated material. Case was made from diffusion membrane with low vapour resistance. Case side lengths 50 cm x 50 cm; depending on amount of filling material height varied between 5 cm and 10 cm.

For each investigated material, mixture and different moisture content samples modules were filled over again.

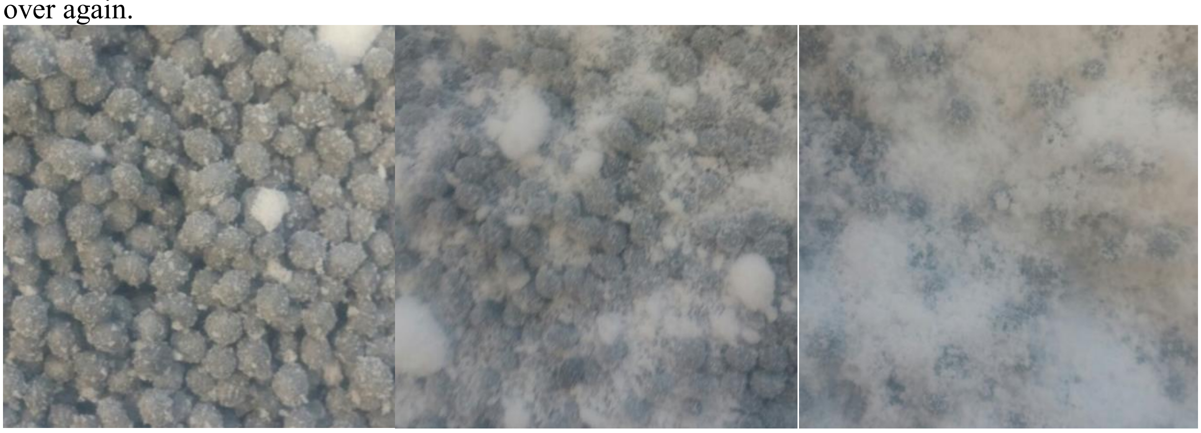

Figure 1. Photographs of Izopearl and Izoprok material mixtures. Left – η=0.12, middle - η=0.46, right - η=0.73.

For preparation of material mixtures, Izopearl component was weighted and corresponding volume $V_{Izopearl}$ was calculated using density ρ = 18 kg/ m^3, and volume of Izoprok component $V_{Izoprok}$ was measure using measuring cylinder. Mixture was obtained by manual mixing of components. Figure 1 shows photographs of different mixures.

Several Izoprok and Izopearl mixtures were prepared with different volume of fraction

$$\eta = \frac{V_{IzoProk}}{V_{IzoProk} + V_{IzoPearl}}$$

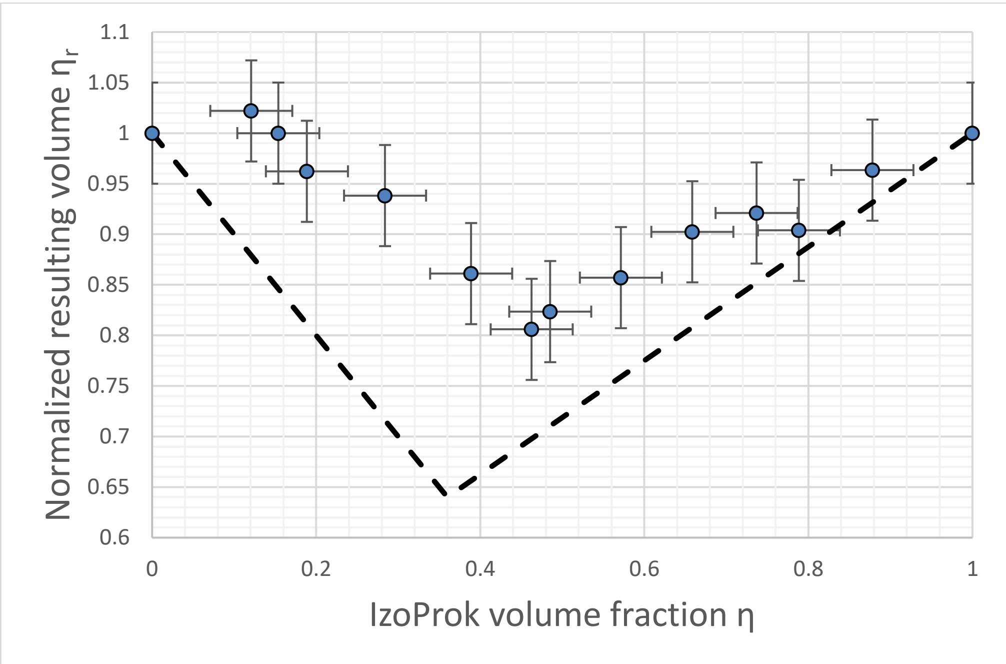

Figure 2. Izoprok and Izopearl mixture volume fraction. Dots are measured points, dashed line is theoretical limit, below which no points can appear.

Here V is initial volume of denoted component. Initial volume represents the space which certain component fills before mixing. Measurement of component volume was done using measuring cylinder, therefore measured volume includes free space between granules/flakes. Component volume has to be distinguished from final volume of mixture. It was observed, that total volume of mixture is less than sum of volumes of components (Izoprok and Izopearl)

$$V_{Mix} \neq V_{IzoPearl} + V_{IzoProk}$$

Therefore measurement series was conducted to measure the reduction of total volume during mixing process. To quantify volume reduction, normalized resulting volume was introduced:

$$\eta_r = \frac{V_{Mix}}{V_{IzoProk} + V_{IzoPearl}}$$

Measurement was started with pure Izopearl material ((0,1) point in Figure 2), and after that certain fraction of Izopearl was added, and resulting mixture volume was measured. Normalized volume fraction η_r is decreasing up to Izoprok volume fraction of 0.46, where η_r=0.81 was obtained.

Theoretically, lowest η_r can be achieved when all empty space between Izopearl granules is filled with Izoprok flakes. Measured empty space fraction is η=0.36. This value was obtained by measuring water volume which can be pushed in space between Izopearl granules.

As seen in Figure 2, minimum of η_r is shifted toward higher Izoprok volume fraction η in comparison with theoretical minimum.

At η values above 0.46, normalized volume fraction η_r is increasing until reaching value of 1 for raw Izoprok.

After mixing all mixtures were packed in sample modules for thermal conductivity measurements.

3. Measurements of material thermal conductivity

3.1. Measurement method and equipment

Measurements are performed using Taurus TCA-500 X equipment which is a measuring system for determining the heat transfer coefficient of specimen samples by the guarded hot plate method (Salmon 2001) in accordance with EN 12667. This equipment also allows measurement of thermal resistance or transfer coefficient for multi-layer samples consisting of different materials, as well as composite materials with inhomogeneous structure.

Investigated sample is placed in measurement unit, where constant temperature difference on both sides of sample is achieved with Peltier elements. On both sides of sample, heat flux sensors are places. Steady state is reached when heat fluxes $\dot{q}$ on both sides are equal. When steady state is reached, thermal resistance of the sample can be calculated using heat flux and temperature difference on sample sides. When steady state is reached, at least 10 measurements are done and results is averaged over obtained data. Since temperatures of both sides of sample are different and total temperature difference is 10 K, it is assumed that thermal conductivity of sample is linear in this temperature range and measured conductivity corresponds to average temperature of the sample.

Table 1. Measured data summary of thermal conductivity of Izoprok and Izopearl material. All data in mW/(m·K).

	T, ºC	λ, mW/(m·K)			
		Izopearl 16	Izopearl 18	Izopearl 20	Izoprok
1	10.4	31.35	31.53	31.49	30.92
2	15.3	31.85	32.07	32.01	31.57
3	20.2	32.41	32.58	32.55	32.24
4	25.1	32.96	33.15	33.11	32.95
λ_{10}	10.0	31.3±0.5	31.5±0.5	31.4±0.5	30.9±0.5
λ(t)		30.19+0.11*T	30.38+0.11*T	30.34+0.11*T	29.47+0.14*T

3.2. Measurement of base materials

Results with different granule density showed very similar results, which are within measurement error margin. Figure 3 shows thermal conductivity of Izoprok material, and Izopearl material with density 16, 18 and 20 kg/m^3. Density of Izopearl material is producers declared value. Obtained data is summarized in Table 1. Results also show that thermal conductivity does not depend on thickness of sample in used range (5 to 10 cm).

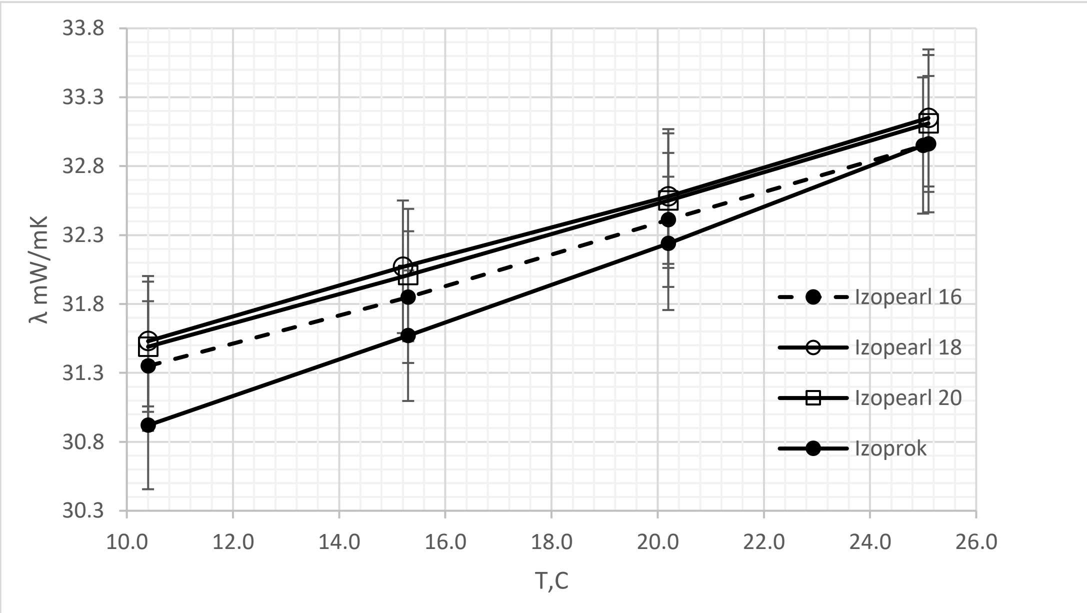

Figure 3. Measured thermal conductivity of Izoprok and Izopearl material with different density.

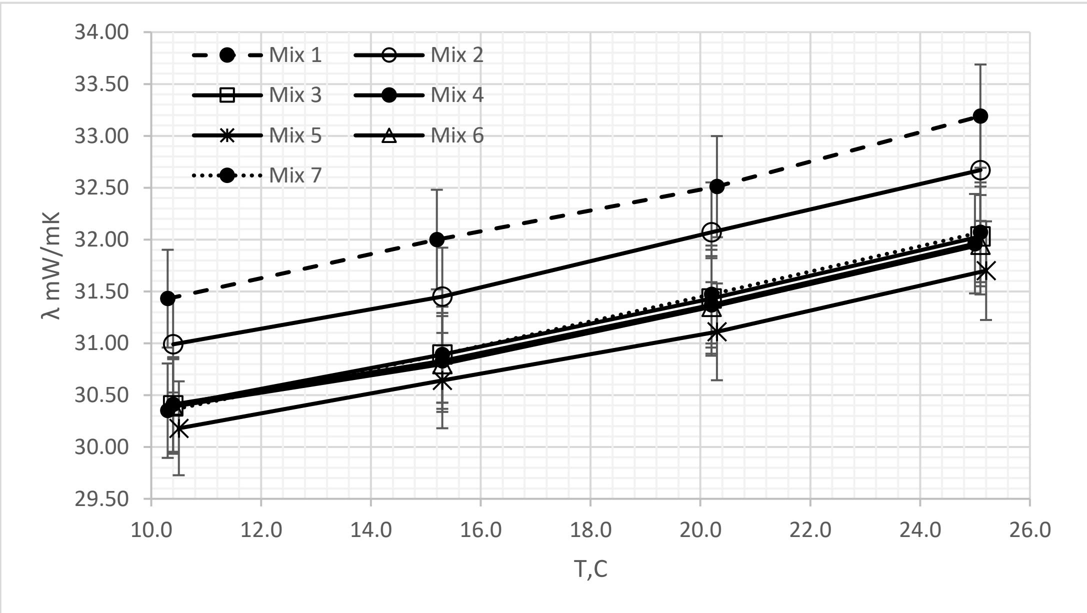

Figure 4. Measured thermal conductivity of different material mixtures.

3.3. Mixture measurements

To determine best mixture of Izoprok and Izopearl in terms of thermal conductivity, modules with different mixtures were prepared, where volume of fraction η varied between 0 (Izopearl only) to 1

(Izoprok only). Table 2 summarizes measured data for mixtures. It also shows thermal dependency of heat conductivity (λ(T)).

Figure 4 shows that there is almost no distinguishable difference between mixtures Mix 3, Mix4, Mix 6 and Mix 7. Due to low Izoprok content, mixtures Mix 1 and Mix 2 have λ values well above those of other mixtures. Lowest thermal conductivity value is found for mixture Mix 5, where volume fraction of Izoprok is 0.42.

Table 2. Measured data summary of thermal conductivity for different mixtures of Izoprok and Izopearl. Thermal conductivity data in mW/(m·K), volume fraction data dimensionless.

	T, ºC	λ, mW/(m·K)						
		Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
1	10.4	31.43	30.99	30.40	30.41	30.18	30.39	30.35
2	15.3	32.00	31.45	30.89	30.83	30.64	30.80	30.89
3	20.2	32.51	32.07	31.43	31.37	31.11	31.35	31.47
4	25.1	33.19	32.67	32.03	31.96	31.70	31.95	32.07
λ_{10}	10.0	31.4±0.5	30.9±0.5	30.3±0.5	30.3±0.5	30.1±0.5	30.3±0.5	30.3±0.5
λ(t)		30.20+ 0.12·T	29.74+ 0.12·T	29.22+ 0.11·T	29.26+ 0.11·T	29.08+ 0.10·T	29.23+ 0.11·T	29.13+ 0.12·T
η	-	0.12	0.22	0.29	0.36	0.42	0.52	0.50

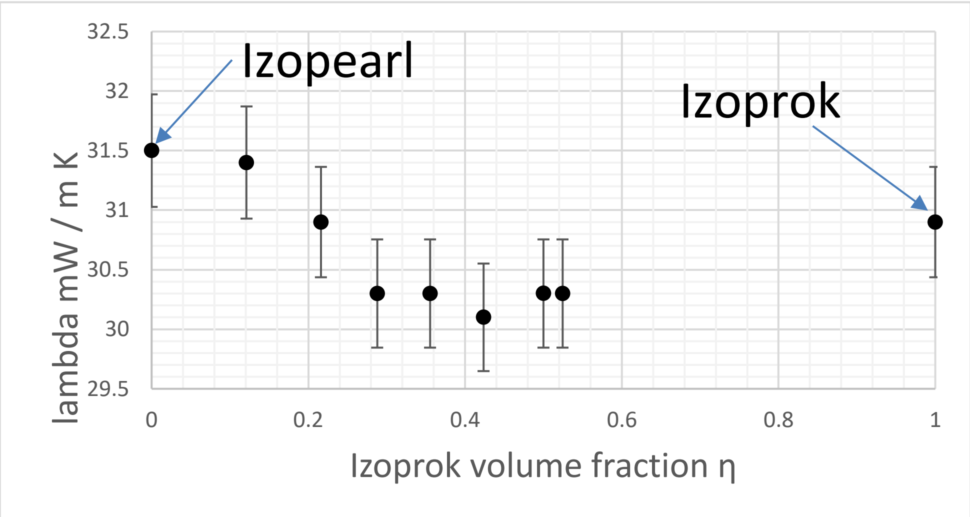

Figure 5. Thermal conductivity of different mixtures at 10ºC.

Figure 5 shows thermal conductivity for mixtures Mix 1 – Mix 7, and raw materials at 10ºC. It is even better visible how thermal conductivity decreases with increase of Izoprok volume fraction until η value of 0.42. At this point, thermal conductivity of 30.2 mW/ m K is obtained. Further increase of η lead to increase of thermal conductivity.

4. Mathematical modelling

4.1. Model for granule filling and simulation results

For proper simulation of heat transfer effects in granular structure, proper distribution of granules is necessary. Theoretical ellipsoid packing with fill factor 0.753 (Bezdek un Kuperberg 1991) is improbable in nature, therefore it would underestimate void fraction and consequently also underrate role of convection.

Simulation of granule dynamics was performed using LAMMPS software with Hookean force between granules which become in contact (Plimpton 1995):

$$F = k_n \delta \vec{n}_{ij} - m\gamma_n \vec{v}_n - k_t \Delta \vec{s}_t - m\gamma_t \vec{v}_t$$

Here δ is overlap distance between two particles, k_n – elastic constant of normal contact, k_t - elastic constant of tangential contact, γ_n – viscoelastic damping constant for normal contact, γ_t – viscoelastic damping constant for tangential contact, v – relative velocity of the 2 granules, n – unit vector along the line connecting 2 granules, Δs – tangential displacement vector between two particles. Simulation is done by tracking every single particle and its interaction with neighbor particles.

To obtain proper distribution of ellipsoids in wall gap, a model was created, where granules were filled in rectangular prism with size 2 cm x 7 cm x 25 cm. Granules were inserted in domain from top and three insertion velocities were used 0 m/s, 0.5 m/s, 1.0 m/s. At the end of simulation, volume was filled with 18000 granules. Figure 6 shows granule filling dynamics for case with 0 m/s insertion velocity.

Results of filling calculation showed insignificant dependence of fill factor on granule insertion velocity. These results are summarized in Table 3. These values are in good agreement with measurements of granule fill factor which was obtained experimentally using water displacement method – 0.63.

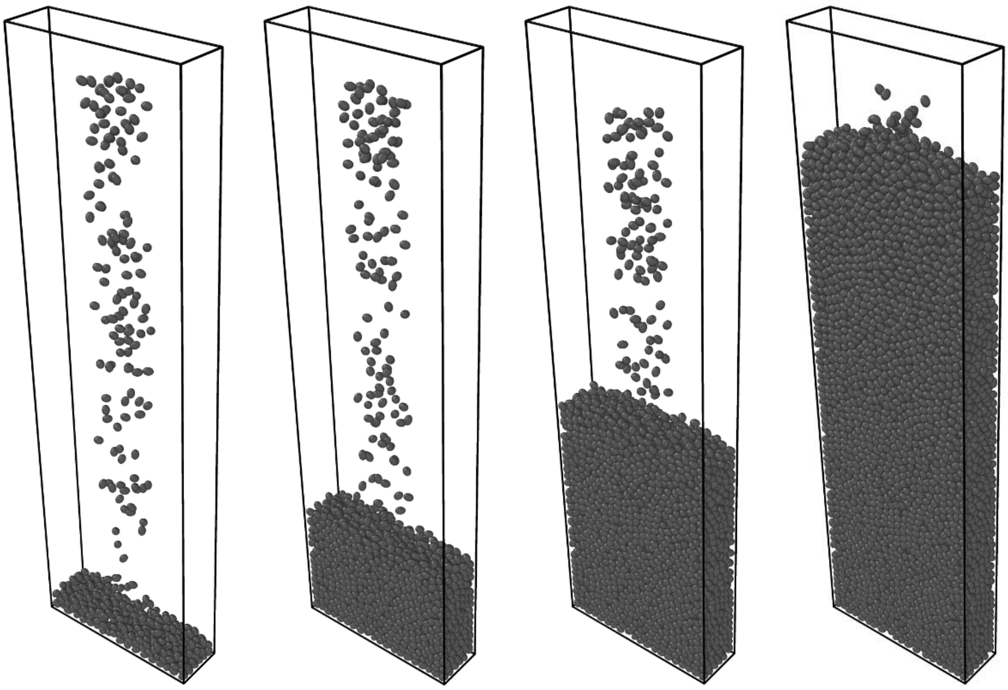

Figure 6. Granule filling dynamics at different time from beginning of filling. From left to right - 0.6s, 3s, 6s, 12s.

Table 3. Fill factor in filling simulations with different insertion velocity.

Insertion velocity, m/s	0	0.5	1.0
Fill factor	0.629	0.641	0.643

4.2. Heat transfer model and simulation results in local model with resolved granules

Distribution of granules was taken from filling model and transferred to finite element simulation platform ANSYS. Distribution of heat in finite element model is calculated for heat transfer equation

$$\rho c_p \left[\frac{\partial T}{\partial t} + \nabla(T\vec{u})\right] = \lambda \Delta T$$

In liquid and gaseous domains this equation is strongly coupled with fluid flow which is described by Navier Stokes equation

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} + \frac{1}{\rho}\nabla p - \nu \nabla^2 \vec{u} = \vec{g}$$

Model also took into account Monte Carlo radiation heat transfer model from ANSYS CFX software. Model consisted of 10M finite elements, which were required to resolve all contact zones between individual granules.

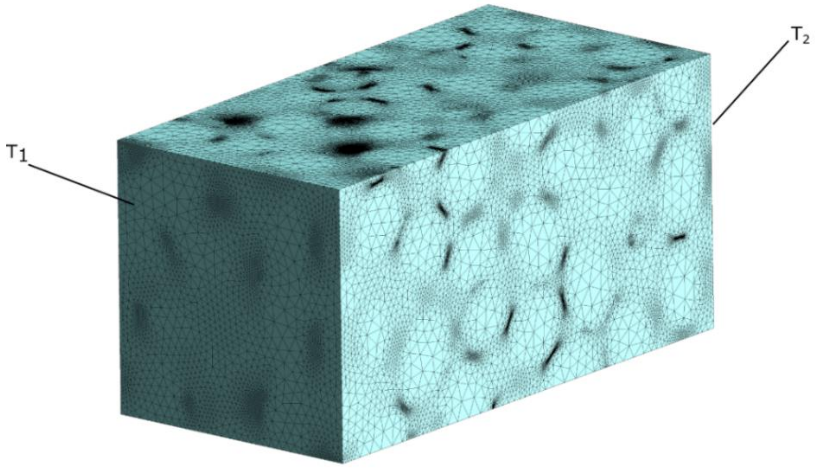

Figure 7. Computational mesh with resolved granules. Sides where constant temperature was applied are shown.

First task is determination of thermal conductivity of Izopearl granules $\lambda_{granule}$. One has to distinguish between thermal conductivity of Izopearl material $\lambda_{Izopearl}$ and $\lambda_{granule}$. First is thermal conductivity of material as it is filled in building construction, with air gaps between granules. Second is local value of granule material. To determine $\lambda_{granule}$, a model was created, where constant temperature difference 10 ºC was applied between two sides of calculation box (Figure 7), and $\lambda_{granule}$ was varied between 0.02 and 0.1 W/m·K. Heat flux was calculated on side, and corresponding effective thermal conductivity was estimated. This model also includes radiation heat transfer with emissivity of granules 0.6 (measured in our laboratory).

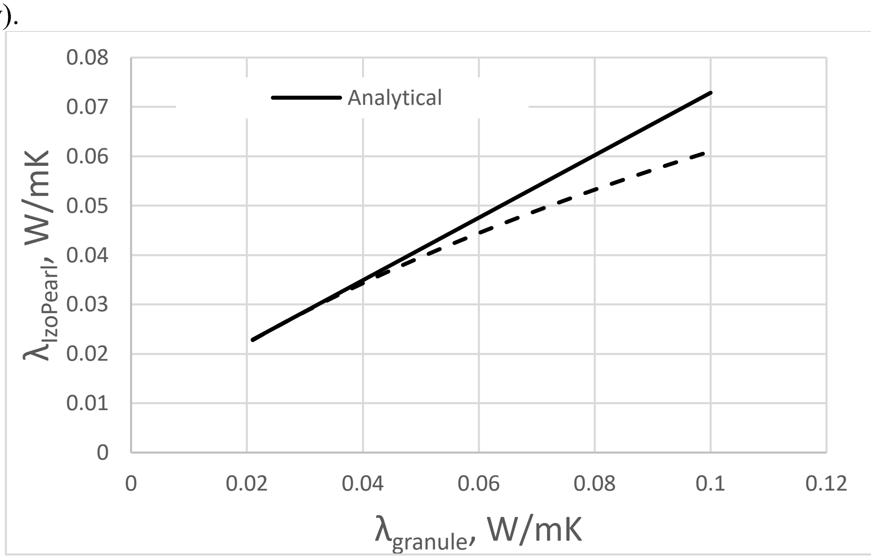

Figure 8. Calculated thermal conductivity of Izopearl.

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Another approach was analytical, where thermal conductivity of Izopearl was calculated by formula

$$\lambda_{IzoProk} = \eta_{granule}\lambda_{granule} + \eta_{air}\lambda_{air}$$

Results (Figure 8) show that difference between calculated and analytical is below 0.001 W/mK for all $\lambda_{granule}$ values below 0.026. For higher values discrepancies are large and therefore analytical model cannot be used. Such difference is explained with influence of radiation heat transfer. For $\lambda_{granule}$=0.033 W/mK expected value of Izopearl thermal conductivity is found (0.0315 W/mK). This value for granules will be used in further calculations.

Radiation heat transfer plays important role in overall thermal conductivity of Izoprok material. Simulations show that most part of heat transfer is conduction heat transfer in air and granules, and it makes 96.4 %. Radiation transfers 3.4%, and convection transfers less than 0.2%. It is important to note, that convection transfer influence could be even less, because equation systems for transfer in solid material and material with gaseous phase differ significantly and this value is close to precision limit of model.

5. Conclusions

This investigation can be separated in two parts – experimental and computational.

- Results show that $\lambda_{10,dry}$ for both investigated materials is 0.031 W/m·K.
- Mixtures of Izopearl and Izoprok have lower thermal conductivity value than raw materials, and numerical simulations show that it can be connected with reduction of radiation heat transfer when Izoprok flakes are filling voids between granules. Another possible reason is increased contact resistance between granules and flakes.
- Simulations of granule filling show slight dependence of fill factor on granule injection speed. However, fill factor is still in range of 0.63, while theoretical maximum is 0.75
- Simulations also show that in Izopearl material heat conduction is main heat transfer phenomena with 96.6% influence. Radiation heat transfer is responsible for 3.4% of effective thermal conductivity, and influence of convection is below 0.2%.
- All results show that this material has potential for use in building insulations. Furthermore, part of mixture is granules which are made of polystyrene. Polystyrene has proved its stability over decades, therefore investigated material will have good durability.

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