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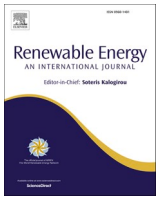

Modeling of heat conduction processes in porous absorber of open type of solar tower stations

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ABSTRACT

An analysis of existing methods for calculating heat and mass transfer processes in porous absorbers of receivers of tower solar power plants is carried out. It is shown that the resulting thermophysical properties of the material are influenced not only by the porosity but also by the location of the pores in the material volume. The criterion of the dislocation vector is proposed as a mathematical indicator of various porous structures. The shortcomings of the existing dependences of the effective thermal conductivity of a material on the type of porosity are shown. The most reliable dependences for determining the thermophysical parameters of a porous medium are also determined and independent factors are proposed on which the mathematical model of heat and mass transfer in open-type solar receivers should be based.

The current state of research on the effective thermal conductivity of the porous structure of solar receivers is described in detail. A new formula for calculating the effective thermal conductivity of a porous structure with regard to the dislocation vector and a method for calculating the processes of heat transfer in open solar receivers based on the proposed formula are proposed. The proposed equation has been tested. It is determined that for simple channel structures it is sufficient to use the existing equations to calculate the thermal conductivity coefficient, while for more complex porous structures, such as the StepRec absorber, it is better to use the proposed equation.

Among the strengths of this study is a new calculation formula that allows us to build an analytical model of heat transfer in a porous medium. The use of the analytical model can significantly reduce the complexity of modern calculations of heat transfer processes in a porous absorber and will help improve the quality of optimization models of solar receivers.

1. Introduction

Given the environmental and political events of 2022, the intensification of solar energy development is a necessity for Europe and the world as a whole. The use of solar energy in concentrated solar power plants can partially solve the energy crisis of mankind and reduce the level of excessive consumption of fossil fuels. The high temperature levels that can be achieved in concentrated solar power plants (CSP) of the tower type allow the use of solar energy for technological production processes: electricity generation, metal smelting and sintering of building materials, hydrogen production, etc. When designing such plants, special requirements are imposed on the model of heat and mass transfer in the tower receiver, as it is crucial for determining the thermal efficiency of the receiver. Therefore, it is necessary to consider the possibility of obtaining an improved, more sophisticated and accurate model of the complex heat and mass transfer processes occurring in the porous absorber of a solar tower, as well as to find a more perfect equation for determining the effective heat transfer coefficient of a porous absorber for solar power plants.

The porous medium homogenization method is a simple and widely used method, but for the engineering problems of optimizing the solar tower receiver, it is better to use the porous continuum method and the local nonequilibrium method. The porous continuum method is relatively simple, considers the different energy flows for the solid frame and the fluid, and allows for preliminary design calculations for the choice of absorber area, which is convenient for design optimization. An improved model with increased accuracy of the porous continuum method, which will depend on a set of independent input factors, will allow optimization to improve the efficiency of solar towers and reduce the cost of energy produced by them. The question of which analytical

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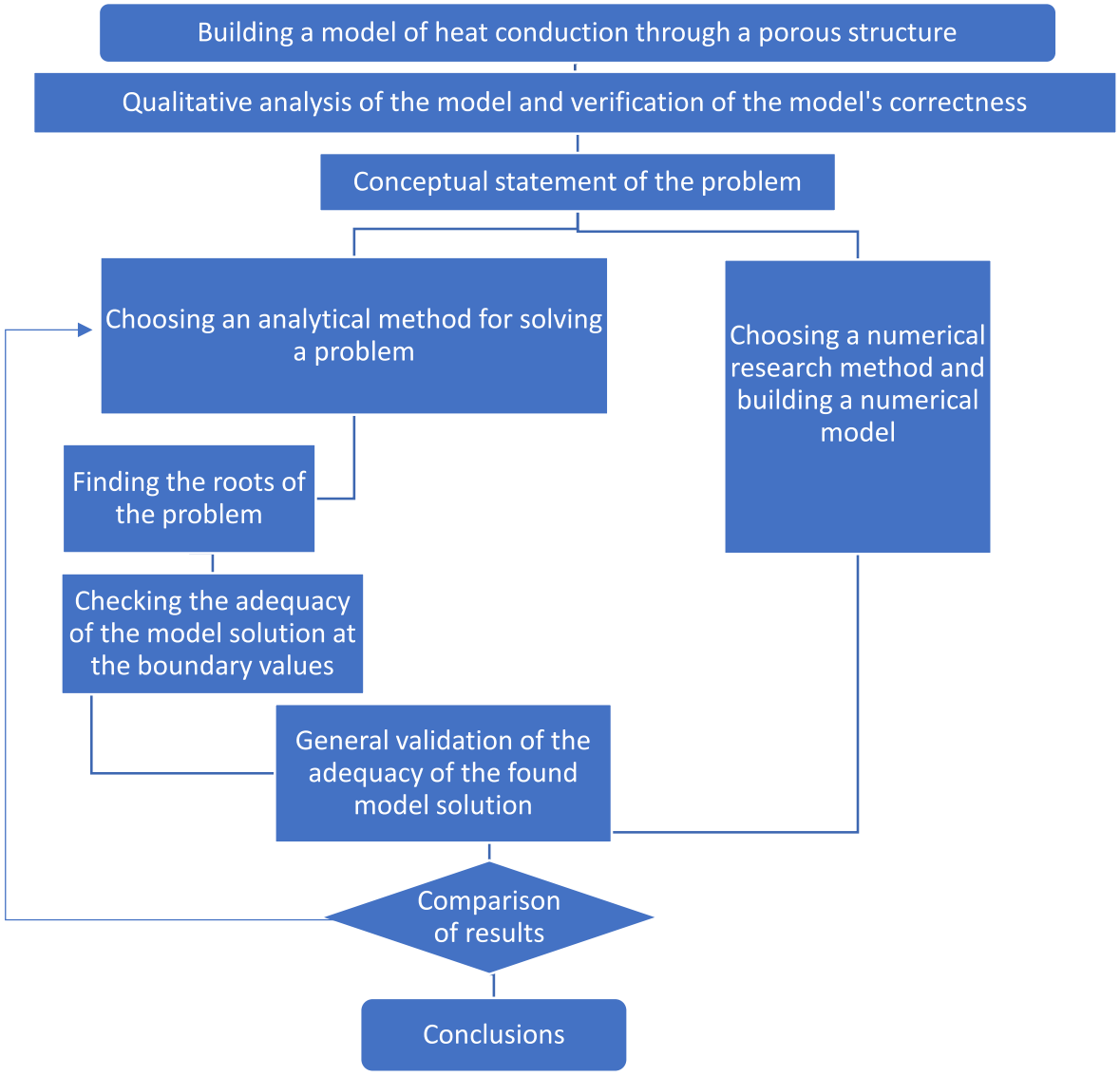

Fig. 1. Methodology for the development of the correlation.

dependence to choose for the thermal conductivity of the porous medium for different types of structures will be evaluated. This work also aims to evaluate which porosity parameters can best describe a geometric porous medium. This understanding is important for modeling heat and mass transfer processes in porous media.

In the energy management system, the energy generation node has the greatest influence on the efficiency of the overall plant [1]. For solar power towers, this is the receiver, as the concentrators or mirrors act as a solar energy transmission and redirection device [2]. The advantages of using air as the heat transfer medium, reliability, high-temperature heating potential and the occurrence of a volumetric effect are important advantages [3]. The volumetric effect in volumetric receivers is defined as obtaining a coolant temperature at the receiver outlet above the temperature of the receiver front surface, by shifting the maximum temperature zone from the surface deep into the receiver. This effect is achieved by using porous media. The main disadvantages of open volumetric receivers are the large volume of air pumped and the difficulty in producing modern absorber models [4]. The calculated thermal efficiency of modern absorber models exceeds 90%, and the air temperature is higher 800 °C [5]. In practice, however, the efficiency in an existing plant reaches of 80% with air temperature at out 650 °C [6].

Receiver of solar tower stations consists of many modules with porous absorbent material, which are inserted in a simple matrix, for example in a staggered arrangement. The best-known open volume receiver is HiTRec. This type of receiver has been used successfully for many years in the Julich solar tower [7] and many modern researchers compare newly developed designs with it as a benchmark. It is also worth noting that scientists at DLR have developed a new type of receiver, VoCoRec, which features an innovative two-stage heating of the air. Structurally, each module is an open cavity with a conical internal shape and a hexagonal cross-section [8].

The core element of the receiver is an open-porous absorber. The absorber absorbs solar energy by converting it into its internal energy and releases the thermal energy to the air stream that flows through it. Depending on the different porous structures, there are many effective porous absorbers, for example: channel structure - HiTRec II, EmiRec [9], MetRec [10]; wire meshes structure - Phoebus-TSA and SOLAIR [11, 12]; chaotic structure - ceramic foam [13]; Needle structure – StepRec [14]. Also ordered morphological cell units: Diamond, Tetrakaidecahedron, Rotated Cube, Cube Shifted, Voronoi the following article Avila Marin [15]. The porous structure in such absorbers can be constant or can vary. If the porosity varies along the length of the absorber, the more efficient structure for absorption and minimization of frontal radiation losses to the external environment is to reduce the porosity along the

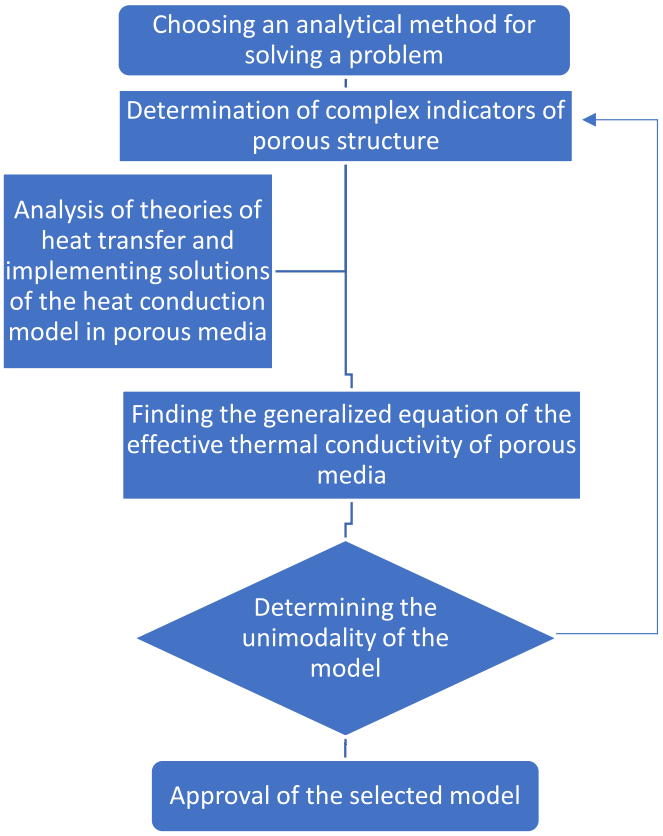

Fig. 2. Methodology for finding the equation of effective thermal conductivity.

coolant current [16].

The materials that are used for porous structures are also different. That and SiSiC or SiC for HiTRec II and ceramic foam, Inconel 600 [8], alloying on the basis of NiCr [17], Ti6Al4V in the experimental prototype StepRec, heat-resistant alloy in Emitec. Alloy Ti-Al is quite studied and is common in metallic porous materials [14,18–20].

The objective of the work is to choose a method for compiling an analytical model of heat conduction transfer processes in the porous absorber of open-type receivers of a solar tower. The practical goal is algorithms for finding the effective heat conduction coefficients in a porous medium, considering the variety of porous structures.

2. Methodology

There are many approaches for modelling of porous media as solar absorbers. The most common are one-dimensional continuum models that do not model the exact geometry of the structure but use effective parameters that describe the relevant characteristics of the structure [21]. In contrast to detailed 3D CFD simulations, these models require rather modest computational capacities and are therefore particularly suitable for use in numerical optimization methods. The quality of these models is obviously largely determined by the effective parameters used. The three ways to determine practically useable effective parameters are analytical derivation, elaborate measurements or detailed 3D simulations. The analytical approach has the advantages of covering a large range of structures and allowing to assess their potential with modest effort.

The variety of designs and porous structures that have been investigated until now shows not only the scientific interest in the field of open-air receivers, but also the lack of a single mathematical model for the calculation of porous absorbers with specific unambiguity conditions. Almost all articles use porosity and specific surface area, absorption coefficient or radiation dissipation coefficient as defining geometric characteristics of the porous structure. But according to Cheilytko [22–24] these indicators are not sufficient to study the heat and mass transfer processes in porous structures, and heat transfer processes in porous structures are not proportional to material porosity, but more dependent on pore shape. In addition, the input parameters used are dependent on each other, which makes it difficult to analyze the regression dependencies obtained in experimental studies of porous structures. A similar situation is with the outgoing model parameters. Sometimes the ultimate goal of improving a particular parameter is not clear. Of course, all these parameters are important in operation, but for a possible optimization, tighter boundary conditions are required. The desired effect is to maximize the efficiency of the entire solar tower, so the absorber efficiency must include inherent losses, such as for pumping air through the porous structure. The above does not refer to a specific absorber model, but to publications on the subject in the last five years. It is therefore necessary to improve the existing scientific and engineering foundations for creating porous absorbers for open-air receivers, considering the discovery of fundamentally new structures and modelling methods to create a methodology for optimizing the porous structure. The following methodologies are proposed for determining the equations describing heat transfer through a porous structure and included in the thermal conductivity model: methodology for finding the equation of effective thermal conductivity (Fig. 1) and methodology for the development of the correlation (Fig. 2).

This paper proposes to improve the Porous Continuum method of calculating porous absorbers of open-type receivers by introducing an additional independent parameter describing the location of pores in space.

3. Proposed of mathematical model

3.1. An additional parameter to the description of a porous structure

The description of the porous structure of an absorber is usually based on general porosity indicators: pore size, porosity, specific surface area, shape of pore. These parameters used for standard determination of complex indicators of porous structure according to Fig. 2. Porosity is a parameter that depends on the size and number of pores in the material. Most existing studies of porous absorber consider porosity as the main material characteristic and very rarely also consider pore size or type. But even joint consideration of the porosity coefficient, pore size and pore type does not unambiguously characterize the porous structure. There is no mathematical description of the structure of porosity and the way of formation of this structure. Therefore, it is proposed to describe the pore packing density in the material in a new way so that this parameter does not depend on the pore size [25].

One of the possible descriptions of the pore arrangement in space is the description by the Bravais translation system (Bravais lattice), in which the pore is the center. An alternative way is to construct a structure by the Voronoi method. Also, often for the description of porosity of a material the statistical distribution of pores on volume of a material is specified [26].

Any structured system can be described if it has at least a few constants that repeat at regular intervals. Thus, if in a porous system it is possible to find at least a few constants that repeat at regular intervals, then the system ceases to be chaotic and can be described.

When choosing a method to describe the porous system, it was decided to draw an analogy between the nodes of the crystal lattice and the pores. The Bravais lattice was used to describe the arrangement of pores. Varieties of the Bravais lattice allow describing a large number of ways to arrange the pores.

Since the key role is played by the comparison and correlation of the obtained characteristics of the porous structure and the Bravais lattice, it is possible to use different dimensions of the vector lengths. Since the pores in the absorber are a finite lattice with nodes H formed by a set of points, they satisfy the following requirements: $N = N_x N_y$; $0 \leq n_x < N_x$ i

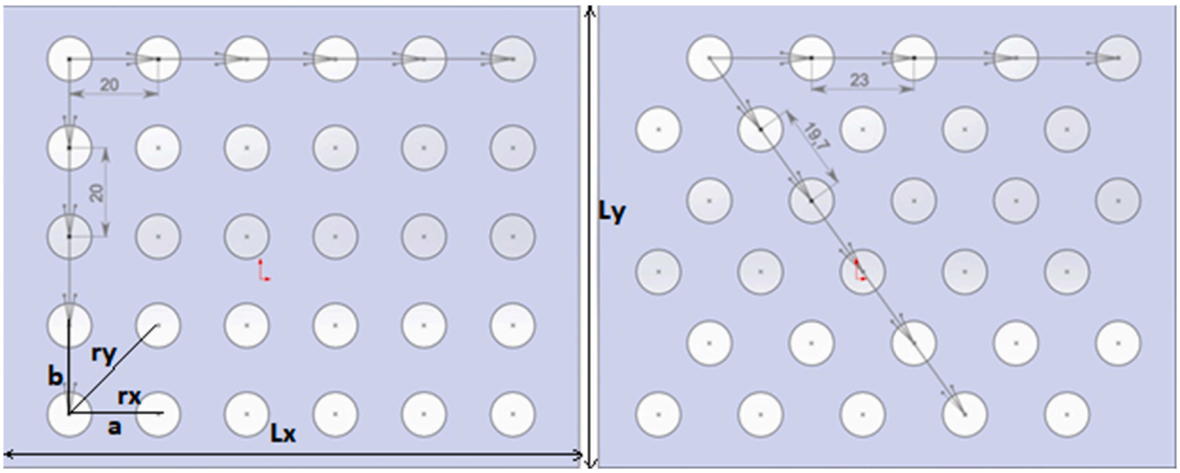

Fig. 3. Examples of locations with vectors on them $k_y = 1.182$ (left), $k_y = 1$ (right).

$0 \le n_y < N_y$ (where n-number of vectors in a certain direction).

For the three-dimensional problem the basic cubic lattice is defined by vectors: $r\hat{x}$; $r\hat{y}$; $r\hat{z}$ where $\hat{x}$, $\hat{y}$, $\hat{z}$ – three orthogonal unit vectors. The average values of the vectors over the entire porous material will be

$$k_x = \int_0^{Nx} r\hat{x}dn$$

$$k_y = \int_0^{Ny} r\hat{y}dn$$

$$k_z = \int_0^{Nz} r\hat{z}dn$$

r – unit vector,

nx, ny, nz – the number of unit vectors.

To set the 3D geometry of the porous structure using the considered method, it is necessary to know three radius-vectors and two angles.

The volume of a unit cell can be calculated from the constant lengths and angles of the lattice. If the sides of the cell are represented as vectors, the volume is equal to the scalar triple product of these vectors

$$V_{cell} = \mathrm{asb}\sqrt{1 + 2\cos\alpha\cos\beta\cos\gamma - \cos^2\alpha - \cos^2\beta - \cos^2\gamma}$$

Considering the chaotic arrangement of pores, it is easy to conclude that an ordered structure is a special case of chaotic distribution. Let us describe a system of closed porous structures.

As an example, we calculated the radius vectors R that produce a double lattice with different hole arrangements. The points located in the center of holes were taken as nodes.

Total radius vectors for the corridor and staggered arrangement of pores with different sizes: $r_x = a$; $r_y = b/\cos\gamma$, $k_x = n_x\langle r_x\rangle/L_x$, $k_y = n_y\langle r_y\rangle/L_y$, $L_y k_y = n_y\langle b\rangle$. γ – angle between b and r_y. L_y, L_x is the length of the curve connecting the pore centers in this direction. For an elementary cell with one channel $k_y = \langle b\rangle n_y/L_y \sin\beta$ (Fig. 3).

In this case, the values of porosity and specific surface area will be the same. This testifies to the independence of such a parameter as the radius-vector from porosity and specific surface area. The unit vector is a completely independent factor, while the dislocation-vector is proposed to be calculated through the number of pores, hence it will refer to secondary parameters of the porous medium.

For channel porosity

$$\left(\bar{k}_y\right)_y = n_y\langle r_y\rangle \Big/ L_y$$

$$\left(\bar{k}_y\right)_x = n_x\langle r_x\rangle \Big/ L_x$$

For a single cell $(\bar{k}_{disloc})_y = \frac{b}{\cos\gamma L_y}$, $(\bar{k}_{disloc})_x = a/\sin\gamma L_x$, $(\bar{k}_{disloc})_x = 1/\sin\gamma$.

$$k_y = \sqrt{\left(\bar{k}_y\right)_x^{\,2} + \left(\bar{k}_y\right)_y^{\,2}}$$

The chaotic arrangement of micropores is described as a rule by their average value along the cut of the material. For absorbers of porous receivers, the quantitative characteristic of pores (cell centers) is set in the direction of radius vectors.

Having basic parameters of porous medium description (3 basic parameters): distribution of pores in space, pore dimensions in the direction of basic forces, and number of pores per unit length of porous material in the direction of vector radii, it is possible to find the following parameters of the porous structure: porosity [27,28], specific surface area [29,30].

3.2. The effective thermal conductivity coefficient of porous structure

To build a model of a porous absorber, structures of two scales were used [31]. The second scale structure will be the material itself with internal microporosity. With this method, the total porosity will be equal to

$$\varnothing = \varnothing' + \varnothing''$$

The optical parameters of the material will affect the radiative heat transfer through the porous material, as well as affect the absorption efficiency of the absorber of solar radiation. They are reasonably described Avila-Marin [32].

Optimization of bulk type solar receivers requires the availability of computational models of heat transfer and hydrodynamics of sufficient accuracy. The effective coefficient of thermal conductivity and effective heat transfer coefficient of porous material for these equations is a convenient value that generalizes the complex heat and mass transfer processes in the porous structure.

The energy equation for the porous material frame which is considered as a macrostructure in the porous continuum method can be written as follows

$$0 = \frac{\partial}{\partial x}\left(\lambda_{eff,s}\frac{\partial T_s}{\partial x}\right) - \alpha A_v\left(T_s - T_f\right) + q_{source}$$

The energy equation for the fluid phase is defined as

$$\rho_f\left(c_p\right)_f\left(\frac{\partial T_f}{\partial \tau} + \vec{u}T_f\right) = \alpha A_v\left(T_s - T_f\right) + \frac{\partial}{\partial x}\left(\lambda_{eff,f}\frac{\partial T_f}{\partial x}\right)$$

with s – an index that refers to solid;

f – an index that refers to fluids;
τ- time;
$\vec{u}$ – fluid flow rate.
α - volumetric heat transfer coefficient
q_{source} – thermal energy of heat sources. It may consist of radiation energy, heat of chemical reactions, heat consumption for melting and evaporation, etc.

For further consideration of the convective heat transfer coefficient, first of all, it is necessary to determine that in the structures under consideration the Knudsen criterion is much less than unity, since it determines the conditions of heat and mass transfer in porous material.

To find the effective coefficient of thermal conductivity of a solid material, it is necessary to consider the molecular thermal conductivity of the material itself (second-scale structure), as well as the thermal conductivity of contact surfaces and sharp constrictions that may be present in a chaotic structure. For the radiation component, it is necessary to consider that photon heat transfer is carried out simultaneously with convective energy transfer in the fluid, and also occurs in the second-order structure.

The proposed universal method for calculating the effective thermal conductivity coefficient of an open-type porous absorber with any geometric structure of the porous medium is given in the conclusions.

Let us introduce the assumption that the effective heat transfer coefficient for the second-scale structures and for the steady-state mode is equal to the sum of its constituent heat transfer coefficients of conductive, the convective coefficient and radiative heat transfer coefficients

$$k_{ef} = k_{\lambda} + k_{\alpha} + k_{rad}.$$

This assumption is used for the limiting cases of optically thin and optically thick porosity layers [33,34]. In this case, the thermal conductivity of the gas is calculated by two different dependences:

- for an optically thin layer

$$\lambda_{eff.f} = \lambda_{f\_\lambda} + \lambda_{f\_rad} = \frac{\lambda_{f\_\lambda}}{1 + \left(\frac{4\gamma}{\gamma+1}\right)\left(\frac{2-a}{a}\right)\left(\frac{Kn}{Pr}\right)} + 4\varepsilon_{pr}\sigma_{SB}T^3\overline{\delta},$$

- for the optically thick layer

$$\lambda_{eff.f} = \lambda_{f\lambda} + \lambda_{frad} = \frac{\lambda_{f\lambda}}{1 + \left(\frac{4\gamma}{\gamma+1}\right)\left(\frac{2-a}{a}\right)\left(\frac{Kn}{Pr}\right)} + \frac{16}{3}\frac{n_{pr}}{\alpha}\sigma_{SB}T^3 \bullet Y(\varepsilon_s, \tau),$$

$Y(\varepsilon_s, \tau)$ – function of the influence of optical pore thickness τ and the degree of blackness ε_s,
n_{pr} – refractive index,
α – volumetric spectral absorption coefficient,
σ_{SB} – became Stefan Boltzmann's,
$\gamma = Cp/Cv$ – adiabatic index
a – accommodation coefficient, characterizing the degree of completeness of energy exchange of a gas molecule with a solid material (in Ref. [35] is 0.85 for air).
Kn – Knudens criterion,
Pr – Prandl's criterion
$\overline{\delta}$ – average layer thickness.

Another approach to determine the effective thermal conductivity can be based on the diffusion of the particles in an optically dense medium, and the transport equation should be replaced by the diffusion equation.

The main drawback of the above dependences is the averaging of parameters. In the real structure there are inhomogeneities of porous medium, which lead to irregularity of average characteristics. Also, these dependences do not consider the existence of free radicals, which are active participants in the creation of an additional electric potential of interaction of gas molecules in a porous medium.

For each particular porous structure there is a different dependence of thermal conductivity coefficient. For multicomponent structures, the method of reducing the structure to a two-component one is used by means of successive approximation. To do this, in the first step of the calculation, one of the porosity components is omitted and other concentration values are used, but in the same proportion. The effective heat transfer coefficient for the simplified structure is found. In the next step, the removed component is considered and the mixture is again treated as simplified. In this approach, the first component is always assumed to be the bonding framework.

In the article [31] also, the analysis of 17 different models for calculating the effective thermal conductivity coefficient is presented and it is concluded that the models without shape-forming parameters have a total standard deviation > 10%, which confirms the correctness of the choice of independent basic parameters.

The formula derived by Aiken [36,37] also applies to the calculation of the thermal conductivity of fill

$$\lambda_{ef} = \frac{\lambda_s + 1 + \frac{2\varnothing\left(1-\frac{\lambda_s}{\lambda_f}\right)}{\frac{2\lambda_s}{\lambda_f}-1}}{1 - \varnothing\frac{1-\frac{\lambda_s}{\lambda_f}}{\frac{2\lambda_s}{\lambda_f}+1}};$$

and Torcar's formula [36,37].

$$\lambda_{ef} = \frac{\lambda_s}{1-\varnothing}.$$

According to the authors, the most universal equation that has high accuracy for various porous structures will be the coefficient of effective thermal conductivity is the Dulnev's equation for a unit cell [34]:

$$\lambda_x = \lambda_s\left[1 - \frac{d_y d_z}{l_y l_z} + \frac{\frac{d_y d_z}{l_y l_z} \bullet \frac{\lambda_f}{\lambda_s}}{\frac{d_x}{l_x} + \frac{\lambda_f}{\lambda_s}\left(1 - \frac{d_x}{l_x}\right)}\right]$$

For channel porosity $d_x = l_x$.

$$\lambda_x = \lambda_s\left[1 - \varnothing_y\varnothing_z + \varnothing_y\varnothing_z \bullet \frac{\lambda_f}{\lambda_s}\right]$$

For the two-dimensional problem

$$\lambda_x = \lambda_s\left[1 - \varnothing + \varnothing \bullet \frac{\lambda_f}{\lambda_s}\right]$$

The Dulnev's equation is derived by partitioning the structure into adiabatic planes and is applicable if the heat flux direction does not deviate from the conventional adiabatic planes. To understand the place of the structure in this equation, it was assumed assume that the cell has the geometric parameters of a Bernard cell and the corresponding sides of this cell should be multiplied by unit vectors. Therefore

$$\lambda_x = \lambda_s\left[1 - \frac{k_y l_y k_z l_z}{L_y L_z} + \frac{\frac{k_y l_y k_z l_z}{L_y L_z} \bullet \frac{\lambda_f}{\lambda_s}}{\frac{l_x}{L_x} + \frac{\lambda_f}{\lambda_s}\left(1 - \frac{l_x}{L_x}\right)}\right],$$

At the same time, porosity is a generalized indicator $\varnothing_y = k_y\frac{\langle d\rangle_y}{l_y}$, $\varnothing_z = k_z\frac{\langle d\rangle_z}{l_z}$,

The main drawback of this model is the physical explanation of the additional resistance. The additional path for the heat flow is explained through imaginary quantities, as well as the dependence of the structure coefficient on the ratio of the thermal conductivity coefficients of the solid structure and the fluid in the region of zero porosity. Positive features are the minimum number of required parameters to determine.

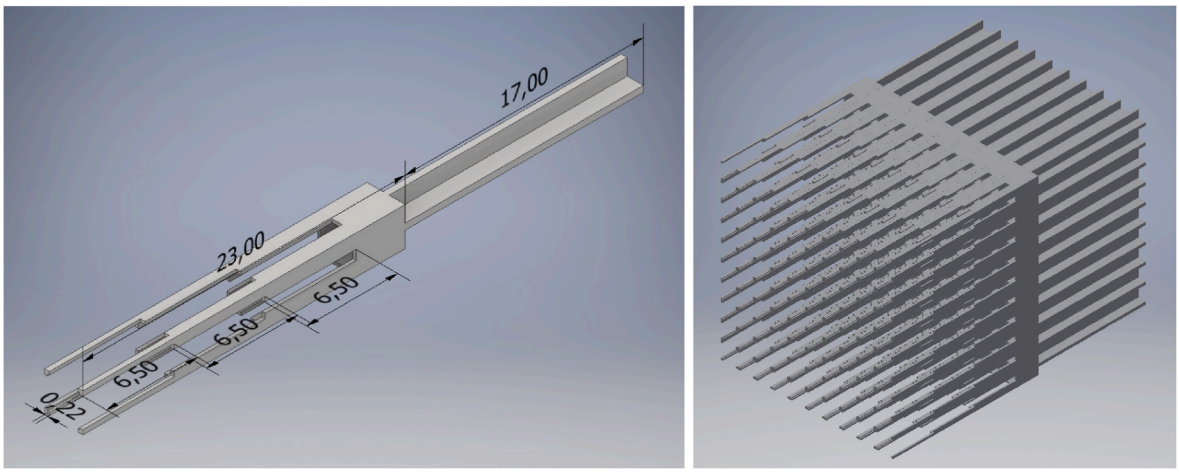

Fig. 4. The model absorber a one adiabatic channel StepRec (left) [38] and the model of a part of a module StepRec (right). Average porosity = 78,18%.

The above calculations contain an imaginary rectangular cell with rectangular pores. The principle of using elementary cells used in the method of electro-thermal analogy has many averaged parameters in a real porous structure that leads to arithmetic averaging of thermal conductivity. Therefore, it makes no sense to use complex calculations using the Bessel function for cylindrical pore channels.

Another approach to finding the effective thermal conductivity coefficient was proposed by Lichtenacker, who proposed the logarithmic dependence of the combination in binary systems. In the simplest case, this dependence can be represented by the following expression

$$\lambda_{ef} = {\lambda_s}^{1-\varnothing} \bullet {\lambda_f}^{\varnothing}$$

It is worth noting that although the proposed solution of the effective thermal conductivity coefficient does not consider the peculiarities of the location of the pores and their geometric size, the principle of logarithmic dependence seems to be more promising for porous systems than the method of electro-thermal analogy with the division of the material by adiabatic or isothermal planes. Although the logarithmic law can also be obtained by dividing the pore structure into isothermal planes with cylindrical channels, but then it will be necessary to use the Bessel function and introduce mathematical averages.

We have proposed a new formula for calculating the channel porosity in absorbers. The mathematical model of the proposed equation was based on a conditional isothermal channel with additional resistance to fluctuations in the direction of the dislocation vector. Equation DLR of the effective coefficient of thermal conductivity

$$\lambda_{eff,s} = \frac{\frac{\lambda_f \lambda_s}{\lambda_s \varnothing + \lambda_f (1-\varnothing)}}{\frac{\lambda_s}{\lambda_f}\varnothing + 2\Psi + \frac{\lambda_f}{\lambda_s}(1-\varnothing) + 1} \left[\frac{\lambda_s}{\lambda_f}\varnothing + (1-\varnothing) + \Psi\right] \left[\varnothing + \frac{\lambda_f}{\lambda_s}(1-\varnothing) + \Psi\right]$$

Ψ - indicator of porous structure; For different models of heat transfer, the solution of this model has different roots Ψ.

For open channel structure

$$\Psi = \frac{1}{k_y}(\varnothing - 1)\frac{(\lambda_s - \lambda_f)}{\lambda_s \lambda_f}\left[\lambda_f(\varnothing - 1) - \lambda_s(\varnothing)\right]$$

For porous mesh or catalyst, the following solution is recommended (this equation considers the uncertainty of k_y)

$$\Psi = (\varnothing - 1)\frac{1 - \frac{\lambda_f}{\lambda_s} + \sqrt{\left(1 - \frac{\lambda_f}{\lambda_s}\right)^2 + 4}}{2} + \varnothing\frac{1 - \frac{\lambda_s}{\lambda_f} + \sqrt{\left(1 - \frac{\lambda_s}{\lambda_f}\right)^2 + 4}}{2}$$

For fluid in the LTNE model

$$\Psi_f = \left(k_y\frac{1 - \frac{\lambda_f}{\lambda_s} + \sqrt{\left(1 - \frac{\lambda_f}{\lambda_s}\right)^2 + 4}}{2}\right)^{1-\varnothing} \times \left(k_y\frac{1 - \frac{\lambda_s}{\lambda_f} + \sqrt{\left(1 - \frac{\lambda_s}{\lambda_f}\right)^2 + 4}}{2}\right)^{\varnothing}$$

For porous open absorbers in the LTNE model

$$\Psi_s = \frac{1}{k_z}(\varnothing - 1)\frac{(\lambda_s - \lambda_f)}{\lambda_s \lambda_f}\left[\lambda_f(\varnothing - 1) - \lambda_s(\varnothing)\right]$$

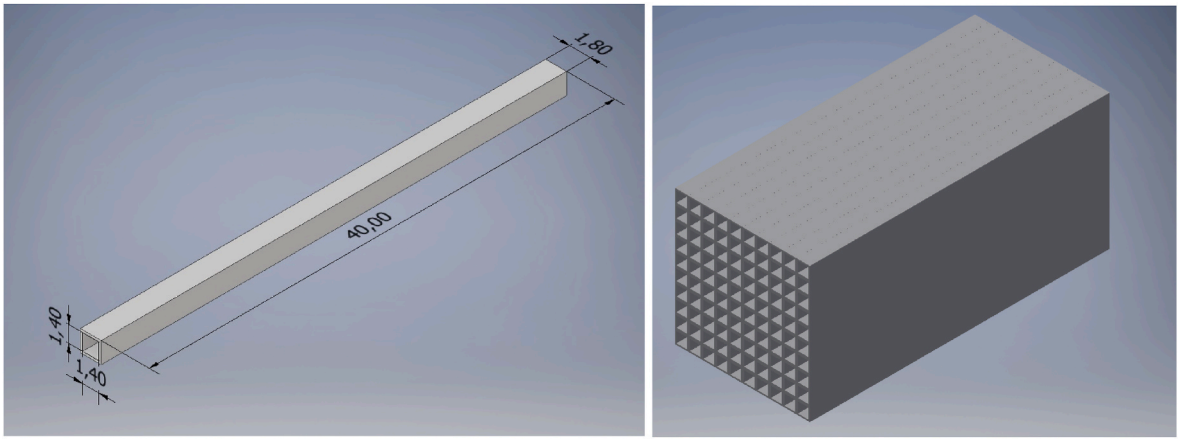

Fig. 5. The model absorber a one adiabatic channel HiTRec 2 (left) and the model of a part of a module HiTRec 2 (right). Porosity = 60,5%.

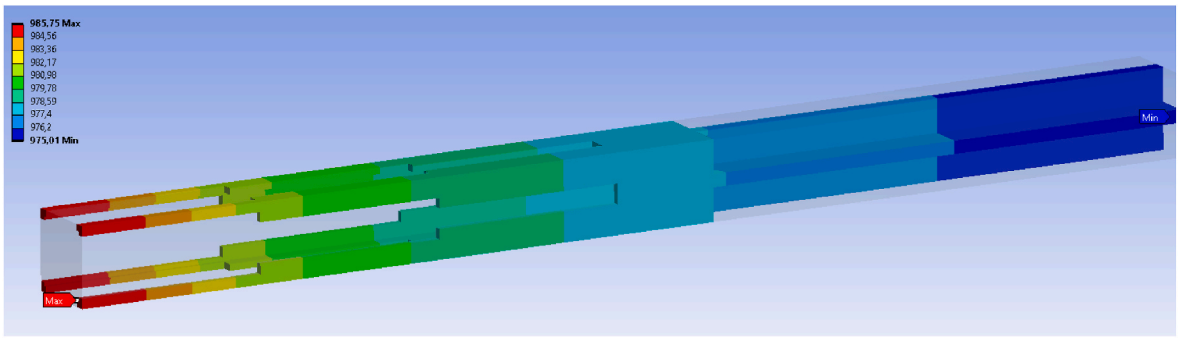

Fig. 6. Distribution of temperature by one adiabatic channel StepRec: all solar radiation is perceived by the front surface.

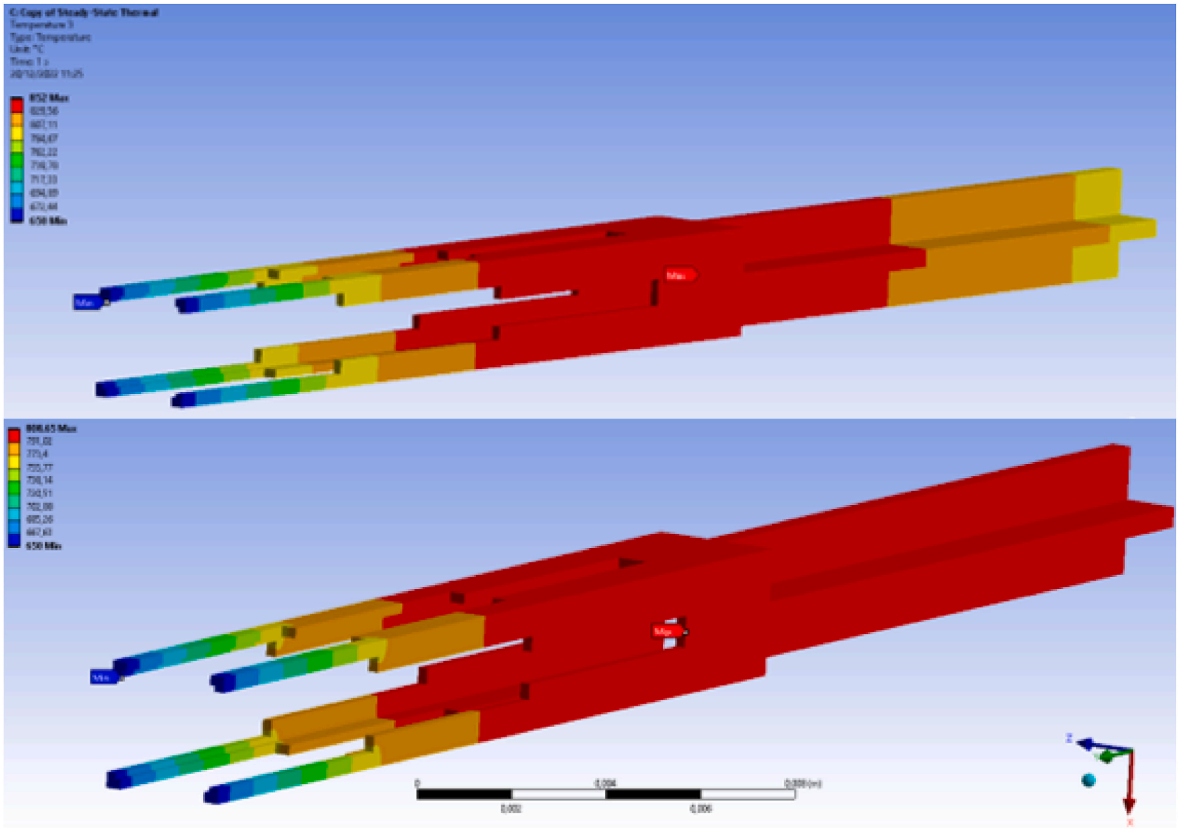

Fig. 7. Distribution of temperature by one adiabatic channel StepRec: solar radiation is perceived along the length of the channel (different absorption area).

This dependence has the following disadvantages: uncertainty in the area of zero porosity, as well as too cumbersome form. The disadvantages also include that the solution of the length ratio $\frac{l_x}{l_y}$ equation has several roots. Its main advantage is considering the vector of dislocations k_y as an additional parameter of porous structure description.

Checking the adequacy of the model solution at the boundary values (according to Fig. 1) for open channel structure gives the following results: if $\varnothing = 0, k_y = 1$ than $\Psi = 1 - \frac{\lambda_f}{\lambda_s}$, $\lambda_{eff.s} = \lambda_s \frac{2-\frac{\lambda_f}{\lambda_s}}{2-\frac{\lambda_f}{\lambda_s}+1}$; if $\varnothing = 1, k_y = 1$ than $\Psi = 0$, $\lambda_{eff.s} = \frac{\lambda_f \lambda_s}{\lambda_s + \lambda_f}$.

And although the solution of the equations at the boundary values of the proposed model does not give a satisfactory result, according to the adopted methodology (Fig. 1), proceed to the next step, namely general validation of the adequacy of the found model solution.

4. Results and discussions

To verify the proposed formula, 3D models of modern absorbers were built in Autodesk Inventor Professional 2018 and analyzed in Ansys 2022 R Steady-State Thermal. As a result of the analysis, the distribution of temperatures on the surfaces of the model was obtained and the effective coefficient of thermal conductivity was calculated assuming that the air in the absorber is stationary. According to the methodology for the development of the correlation (Fig. 1), for General validation of the adequacy of the found model solution needed Choosing a numerical research method and building a numerical model. As modern models of the absorber for verification of the invented formula were chosen: StepRec (Fig. 4) and HiTRec (Fig. 5). The Ansys model was validated by comparing the results obtained with the results calculated using the special DLR model in OpenFOAM [38].

All geometric characteristics of the simulated absorbers are taken from open literature sources. To compare the results of heat flow

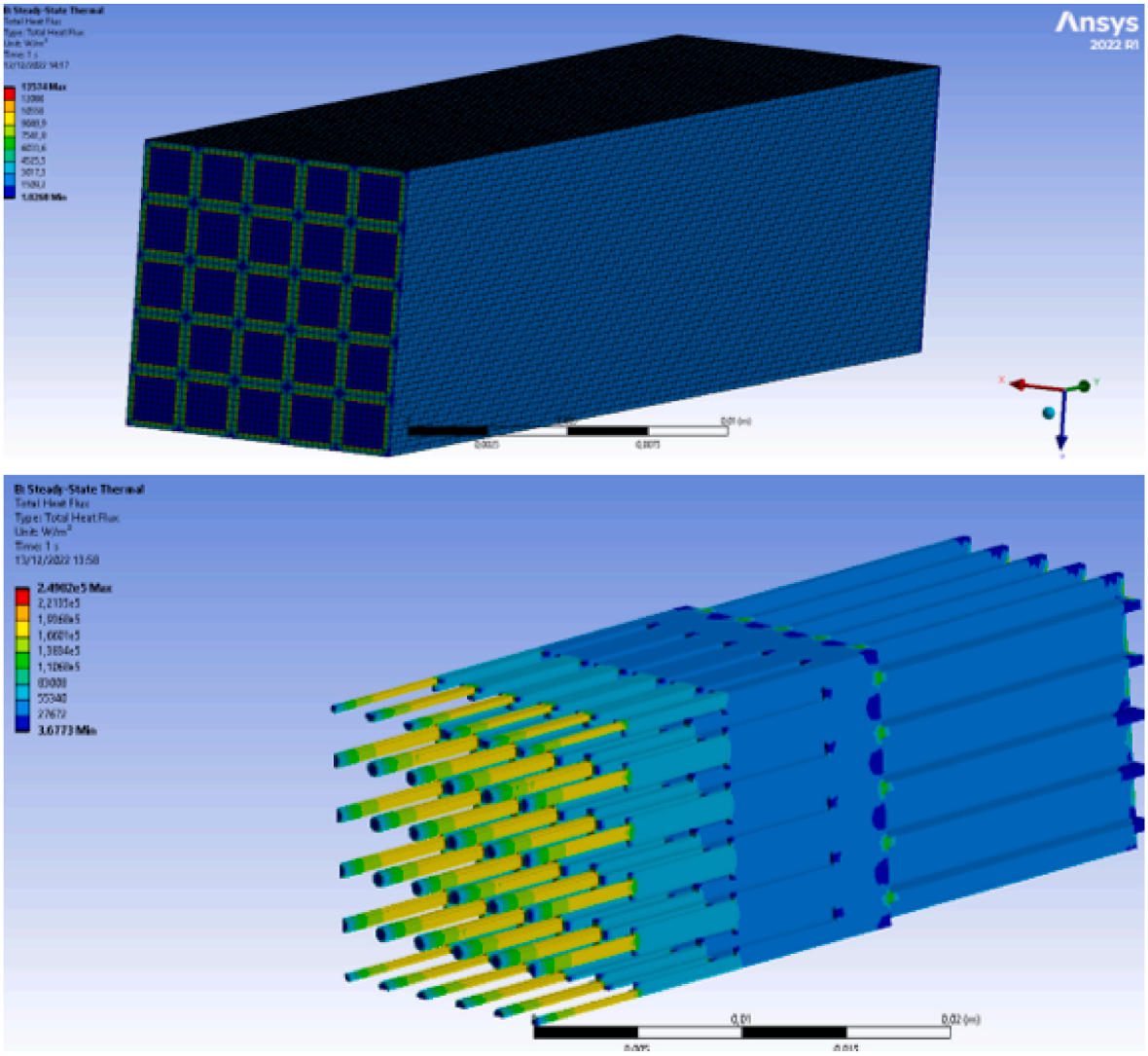

Fig. 8. Distribution of total heat flux by part of a module HiTRec 2 (on top) and StepRec (down): all solar radiation is perceived by the front surface.

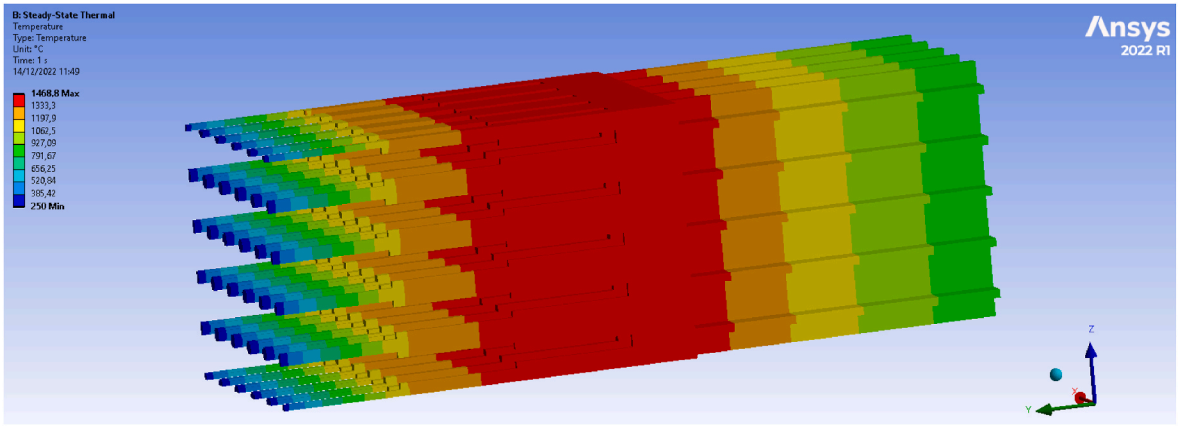

Fig. 9. Distribution of temperature by part of a module StepRec for the solid part.

simulation, the material for all absorbers was chosen – Inconel 718. All thermophysical parameters of a solid are a function of temperature. The coefficient of thermal conductivity of air is 0.02582 W/mK. Element CFD mesh size for HiTRec2 = 0,2 mm, for HiTRec channel 0,01 mm, for StepRec canal 1,209125 mm and for StepRec 0,00024182 mm. The definition of a solar radiation model for porous absorbers is not the purpose of this study, so solar radiation is considered only indirectly as thermal energy transferred per square meter (without considering ray tracing).

To obtain correct data it is necessary to understand how and for what

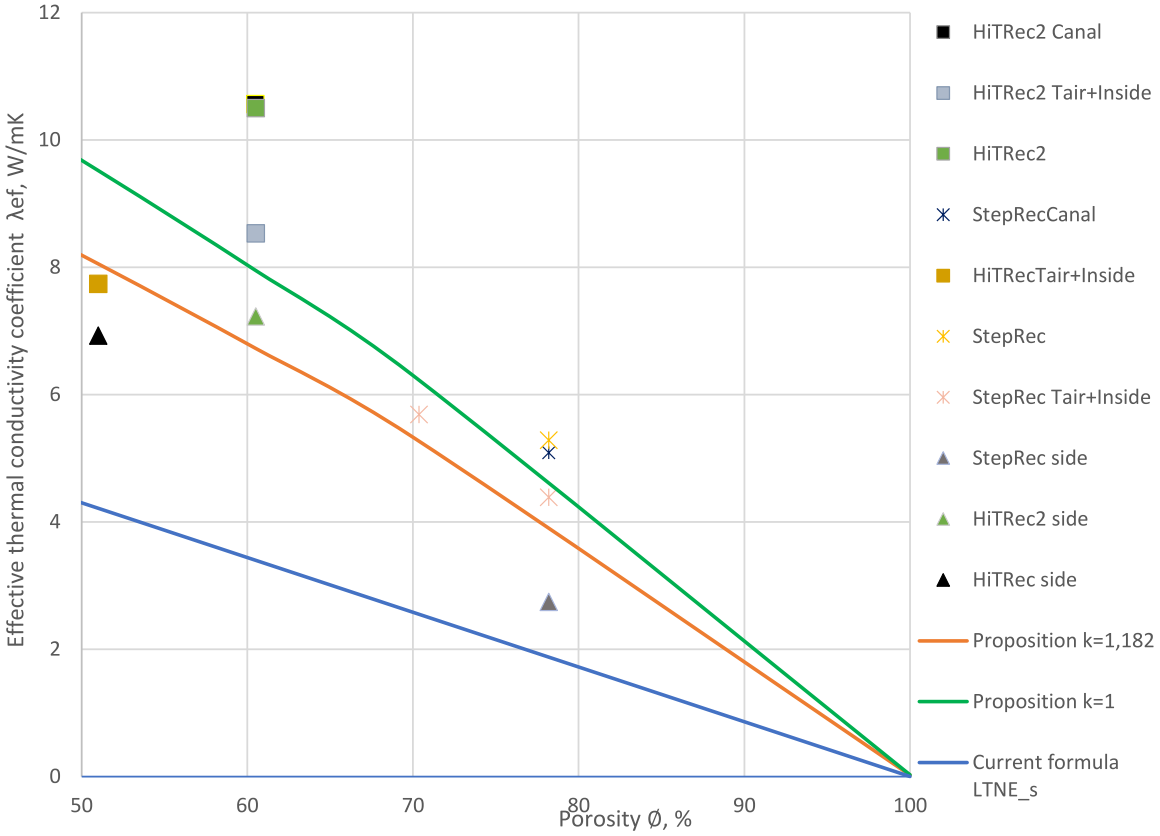

Fig. 10. Validation of the proposed formula.

the model will be used. As an example of different temperature distributions under different initial conditions, the temperature distribution for one StepRec channel is shown. When solar radiation falls only on the front surface of the absorber (Fig. 6) and when simulating its fall on all possible internal surfaces (Fig. 7), different temperature distributions were obtained.

To calculate the effective coefficient of thermal conductivity of the absorber in Ansys, the heat flux to the front surface of the absorber was set and the temperature for the rear surface was set. In Steady-State Thermal, the temperature distribution over the absorber and the total heat flux through the absorber were calculated (Fig. 8). Knowing the average integral temperatures on the opposite surfaces and the average heat flux through the absorber, the effective of thermal conductivity coefficient was calculated. To eliminate statistical errors, the calculation was performed for five different heat fluxes and temperatures, and then its average value was taken (see Fig. 9).

In order to calculate the effective heat transfer coefficient for the homogeneous absorber model of a solar tower, it is also important to understand the temperature that are set at the front and back surfaces of the absorber. For the case considered in the continuum model theory, two independent temperature fields for fluid and solid are considered. This model uses the effective heat transfer coefficient for the solid and the average integral temperature of the front surface of the solid on which the solar radiation is incident. A simpler homogeneous porous medium model, described by a single differential heat conduction equation, uses the average integral temperature across the absorber plane between the temperature of the incoming fluid and the temperature of the front surface of the solid. But the simple model does not allow to consider the volumetric effect arising in the porous medium of the open-type receiver. The solution of such a linear model for the value of the effective coefficient of thermal conductivity is obtained and indicated in Fig. 10 by the symbol Tair after the name.

To calculate the effective coefficient of thermal conductivity of porous absorbers, the simulation was carried out without air movement inside. An example of temperature distribution over a part of the StepRec module without air movement through the receiver is shown on Fig. 8.

All the data obtained for the calculation of the effective thermal conductivity of one channel of the absorber or part of the absorber module were summarized in Fig. 10. To validate the obtained formula, the results of numerical simulation of two types of absorbers with different conditions of use and different porosity were compared.

Fig. 10 shows the adequacy of the proposed formula for the considered absorbers, considering the complex heat transfer processes occurring in two different heat flows: solid and liquid. The proposed formula is given for two values of the dislocation vector k = 1 and k = 1.182. Increasing the scalar magnitude of the dislocation vector is expected to reduce the effective thermal conductivity of the material. Value HiTRec2 Chanel and HiTRec2 differ by less than 1% and are consistent with the analytical method of «Flat Chanal » calculation (Fig. 11), which confirms the correctness of the used computer model. The calculations of the StepRec and StepRec Chanel models have a discrepancy of 3.9% due to the needle porous structure. StepRec Tair + Inside shows an effective thermal conductivity value 13.7% lower than the simulated StepRec (yellow cross) and a difference of up to 4.62% from the proposed formula (green line). The values of HiTRec Tair + Inside does not fit well (discrepancy 22.9%) and HiTRec2 Tair + Inside differs by 7.4% from the proposed formula. Therefore, the formula does not consider ray tracing and energy transfer by radiation must be calculated separately. In general, the proposed formula shows a low convergence with the HiTRec

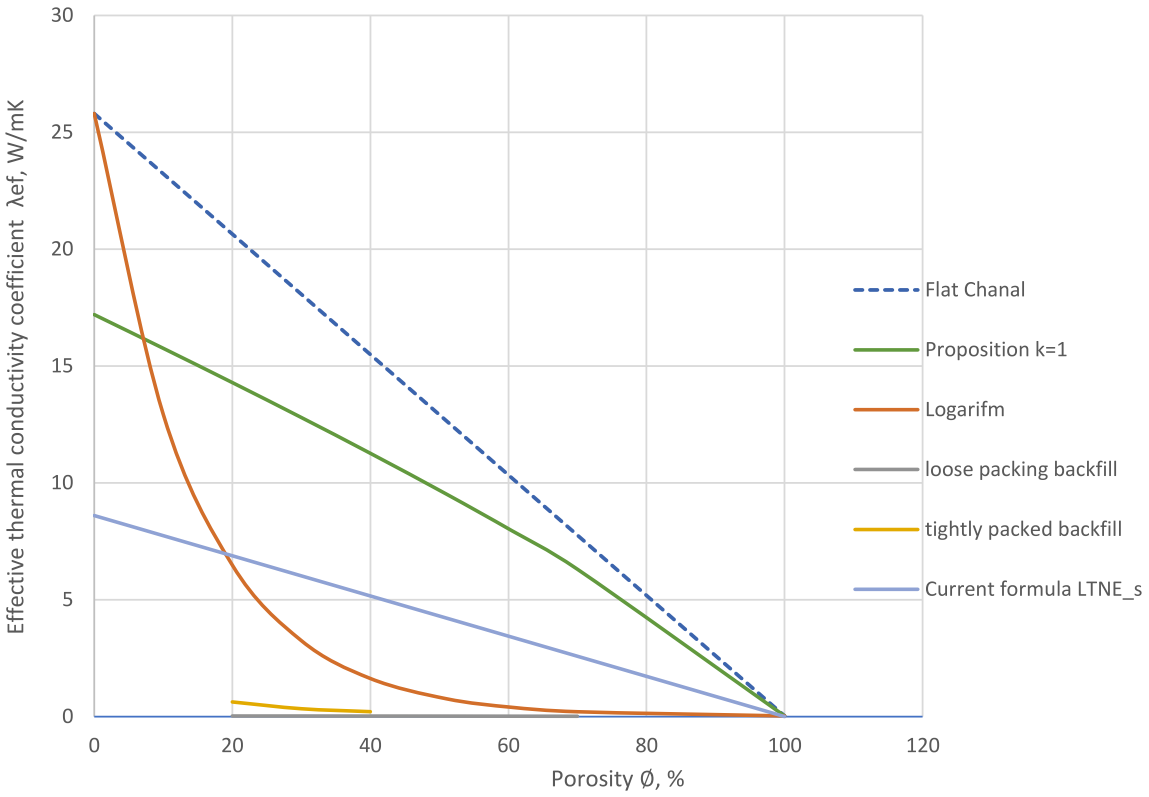

Fig. 11. Comparison of different models of calculation of the effective coefficient of thermal conductivity.

structure (max discrepancy 24.3%), but have max discrepancy of less than 5% for StepRec. According to the authors, the proposed formula is suitable for complex absorber shapes, while simple channel absorber shapes are better calculated by the classical Dunev's equation. In all cases, the current model used for the effective thermal conductivity currently gives significantly underestimated results.

To calculate the reliability and range of application of the proposed formula, it is necessary to consider the results of modeling for a larger number of absorbers. Also, the possibility of applying this formula for use in the LTNE model requires a more detailed analytical analysis of the proposed formula in combination with the model of convective and radiative heat transfer, since the existing numerical models partially average and mutually compensate the processes of heat and mass transfer between convection and conduction.

Fig. 11 shows a comparison of the different dependencies of the effective thermal conductivity on the porous structure. «Flat Canal» is a porous medium with ordered channel porosity with the arrangement of channels along the heat flow (like HiTRec) with the effective heat transfer coefficient calculated according to the classical heat and mass transfer relationship, that the Dulnev equation is calculated [34]. «Cross porosity » porous medium with ordered lamellar closed porosity with the arrangement of hollow plates perpendicular to the heat flow. This is the limiting case when channel porosity becomes closed and through movement through this porous medium in the direction of heat flow is not possible. «Loose packing backfill» is a ordered porous dispersed medium with the lowest possible compaction coefficient, provided that there is a contact of solid phases [36,37]. «Tightly packing backfill» is a porous dispersed medium with the highest possible packing coefficient [36,37].

«Current formula » for a LTNE method is

$$\lambda_{eff,s} = \frac{(1-\varnothing)}{3}\lambda_s$$

As can be seen from Fig. 11, the value of the effective thermal conductivity coefficient calculated by the above equation at porosity more than 20% approaches the values of channel porosity, but is always below it. So, the equation can be used to calculate open absorbers with porosity of the first scale.

The proposed dependence has the following disadvantages: uncertainty in the area of zero porosity, as well as too cumbersome form. The disadvantages also include that the solution of the length ratio equation has several roots, in this problem only one is given.

Recent studies combining the continuum and discrete models [39] use a calculation algorithm that includes the calculation of the Stark number and other effective porous structure parameters described in the previous section. According to the authors, it is possible to improve the proposed model by calculating the effective thermal conductivity using the proposed formulas.

5. Conclusions

Independent indicators of porous structure are proposed for further calculations of heat and mass transfer processes in CSP receivers. It is proved that it is necessary to use the parameter as a dislocation vector for structures with similar porosity and different spatial distribution of pores.

It is obvious that porosity is not a unimodal criterion for choosing one or another type of dependence for the calculation of thermal processes of heat transfer in a porous medium. At the same time, porosity is a very simple and understandable criterion, so a new analytical calculation formula for the effective thermal conductivity coefficient for porous media with open pores has been proposed, which can be applied to the absorbers of open receivers of the solar tower. The proposed formula includes dislocation vector that allows to calculate different porous structures with the same porosity value.

The formula for calculation of the effective thermal conductivity

coefficient in porous structures is derived

$$\lambda_{eff,s}=\frac{\frac{\lambda_f\lambda_s}{\lambda_s\varnothing+\lambda_f(1-\varnothing)}}{\frac{\lambda_s}{\lambda_f}\varnothing+2\Psi+\frac{\lambda_f}{\lambda_s}(1-\varnothing)+1}\left[\frac{\lambda_s}{\lambda_f}\varnothing+(1-\varnothing)+\Psi\right]\left[\varnothing+\frac{\lambda_f}{\lambda_s}(1-\varnothing)+\Psi\right],$$

$$\Psi=\frac{1}{k_y}(\varnothing-1)\frac{(\lambda_s-\lambda_f)}{\lambda_s\lambda_f}\left[\lambda_f(\varnothing-1)-\lambda_s(\varnothing)\right].$$

This formula has been validated on a computer model of porous gravel of the HiTRec, HiTRec2 and StepRec types. The proposed formula shows a low convergence with the HiTRec structure (max discrepancy 24.3%), but are well suited for StepRec (max discrepancy is less than 5%).

Other important results include the theoretical possibility (based on an analysis of the engineering literature) of using the proposed formula in a wide range of engineering calculations, such as porous catalysts, porous walls of the combustion chamber of gas turbines, and other structures with an open microporosity channel.

The proposed formula is suitable for complex absorber shapes, while simple channel absorber shapes are better calculated by the classical Dulnev's equation [34]. In all cases, the current model used for the effective thermal conductivity currently gives significantly underestimated results.

Based on the analysis of literature sources and the development of a new LTNE model of the thermal process in a porous medium, a methodology for calculating the effective coefficient of thermal conductivity in an open-type porous absorber is proposed, which includes the following calculation steps for porous structures.

I. Calculation of the effective thermal conductivity coefficient of fluid considering the radiation component for the second scale structure
II. Calculation of the effective thermal conductivity coefficient of the second scale structure by the logarithmic equation
III. Calculation of the effective coefficient of thermal conductivity of the fluid considering the radiation component for the structure of the first scale
IV. Calculation of the effective thermal conductivity coefficient of the first scale structure according to the proposed inventive equation for complex shapes of absorbers, for simple shapes of absorbers it is better to calculate by the classical Dulnev's equation [34].

Future research directions include determining the convective heat transfer coefficient in a porous medium. Having a stable universal solution for the thermal conductivity coefficient, it is possible to find a universal solution for the analytical dependence of the Nusselt criterion in a porous medium for different types of porous structure.

CRediT authorship contribution statement

Andrii Cheilytko: Methodology, Creation of models, Validation, Verification, Formal analysis, Investigation, Writing – original draft, Visualization. **Peter Schwarzbözl:** Conceptualization. **Kai Wieghardt:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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