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CFD Analysis of Conductive Heat Transfer in Different Porous Foams

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ABSTRACT

A very large number of computational models have already been proposed to evaluate thermal conductivity for high-porosity foams. Each and every approach considered different cellular morphologies and used different solution methods and all they have significant differences. Porous foams are generally used as insulators. So, the effective thermal conductivity of high porous materials, like polyvinyl chloride, expanded polystyrene, asbestos and fiberglass for various meshes are measured to determine the best porous foam that gives the best insulation. Then the results are compared between them and with the results of the previous investigations. It had been found out that effective thermal conductivity is inextricably related to porosity. Effective thermal conductivity decreases with the increasing of porosity such as for polyvinyl chloride, the value decreases from 0.56 to 0.43 for increasing the porosity from 0.75 to 0.95. Similar results are observed for other materials too.

Keywords: Thermal conductivity, porosity, solid fraction.

1. Introduction:

Heat transfer process can be seen surrounding us. It is a condition wherein the energy transfer occurs between frameworks that communicate with each other due to differences in temperature. It is also a phenomenon that occurs at the boundary of the system. It tends to be portrayed as a rearrangement of internal energy in the system. Conduction occurs when two objects at different temperatures are in contact with each other. Heat flows from the hotter to the cooler item until they both attain a similar temperature. Conduction is the movement of heat through a substance by the collision of molecules. Constant and fast mechanical advances in modern manufacturing necessitate that plan and activity issues be settled as fast as conceivable so as to keep organizations competitive, particularly in terms of energy efficiency and low costs. For a long time, tests and observational examinations have been the favored arrangement devices for mechanical investigation. Despite the robust and reliable nature of experimental methodology, certain variables limit its relevance scope. For example, computation of effective thermal conductivity in different materials for various porosity is usually very complicated thing. But use of the CFD code can bring both simple significance and acceptable solution.

At first, a non-thorough survey of the scientific and mathematical models created to anticipate the effective conductivity of cell materials, and it was conducted by Coquard and Baillis [1]. The first attempt of estimation was made by Russel with this effective conductivity from theoretical considerations, and a correlation was proposed by him for plastic foams with high-porosity. Also, he examined conduction through a solid lattice, with cubic cells surrounding inline accepting a uniform cell-wall thickness [2]. Other authors, for example, Maxwell or Eucken, Doherty and Misnar proposed connections like this relation, wherein the porosity is the main auxiliary parameter. They have been audited by Solo'rzano et al. [3] what's more, prompted fundamentally the same as varieties of the effective conductivity. Later it is discovered that the state of the cell structure impacts the conductive heat transfer. Consequently, an increasingly broad investigation was directed by Schuetz and Glicksmann [4]. They were enthusiastic about the conductivity of high-porosity polymeric foams formed of closed or open-cells. They simplified some of the methodology (homogeneous cells, windows with steady thicknesses, swaggers with square cross segments, dodecahedral cells and so forth). They described the foam as a system of thermal resistances and made a few assumptions about how the method would be solved to obtain an explanatory expression for the effective conductivity in which the solid fraction and the porosity in the struts f_s are the only structural parameters:

$$k_{eff} = \varepsilon k_{fluid} + ((1-\varepsilon)\ (2-f_s)/3)\ k_{solid}$$

However, the assumptions permitting analytical treatment of the issue, which can arise question. Later

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Ahern et al. [5] indicated that the assumptions made by Glicksmann prompted in the prediction of the effective conductivity. in the same way, they proposed another connection dependent on the Maxwell connection for combinations of materials of different electrical conductivities, that they must be continuously applicable:

$k_{eff} \approx k_{fluid} + (k_{solid} - k_{gas})\, \beta\, (1- \varepsilon) + (1-f_s)\, \beta_{wind}$

$\beta_{strut} = 1/3\ (1+ (4\ k_{fluid}) / (k_{fluid} + k_{solid}))$

$\beta_{wind} = 2/3\ (1+ k_{fluid}/k_{solid})$

By then, Boomsma and Poulikakos [6] proposed an analytical effective thermal conductivity model of immersed open-cell metal foams, light of the admired three-dimensional (3-D) basic cell geometry, the tetrakaidekahedron. The foam is shown as a framework made out of cubical nodes, set on the vertices of the tetrakaidekahedron, and barrel formed ligaments that are joining these nodes. Fu et al. [7] also explained hypothetically the effective conductivity of open cellular materials by creating two-unit of cell-based models: the cubic-shaped box and the other one is solid cube voided at the center by a sphere. After that numerical computation methodology was introduced to complicated microstructures. For instance, Druma et al. [8] built up a mathematical finite part investigation for open and closed-cell carbon foams with very different levels of porosity beginning from 0 to 1. They thought about a homogenous scatter of spherical voids within a solid matrix. Saadatfar et al. [9] developed a numerical model supported tomographic representations of a spread of closed-cell polymeric materials so as to calculate their effective thermal conductivities. The work of Wang and Pan [10] who settled the energy transport equations through irregular open-cell porous foams employing a highly-efficient lattice Ludwig Boltzmann methodology can even be referred to. They built up an irregular generation-growth formula to repeat the structures of open-cell foam materials by using computer modeling. This study shows the appreciable quantity of various work in the effective conductivity of high-porosity foams. Every unique model is based on assumptions to previous one and prompted different variations of k_{eff} with the structural parameters. It'd be helpful to determine the porous foam that gives the best insulation.

2. Computational Setup:

Geometry:

The model simulates 3-D steady-state thermal conductivity measurement apparatus. The piece considered is a slab of material with perfectly insulated sides which is sandwiched between two slabs of non-porous solid maintained at temperatures T_{cold} and T_{hot}. The other two sides are at adiabatic conditions. Assuming the temperature of hot junction is 300K and cold junction is 273K. The length and width are both considered as 30mm. Then it is extruded about 30mm. So, the model looks like exactly a cubic shape. Figure with necessary assumptions and boundary conditions is given below-

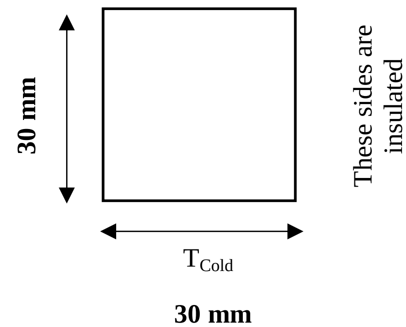

Fig. 1: Geometry of experimental setup

Boundary Conditions Setup:

The procedure is dependent on the investigation of the thermal field in the foam microstructure as it considers the governing differential equation of steady-state heat conduction. There is no internal heat generation in the structure. The steady-state heat conduction equation describes heat balance at each nodes of the two-phase material. Then the governing equation is fathomed mathematically in each and every elementary volume via an iterative method based on an energy balance. It can be written like that in Cartesian coordinates:

$$\frac{\partial}{\partial x}\left(k_{x,y,z}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{x,y,z}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{x,y,z}\frac{\partial T}{\partial z}\right) = 0$$

$$T\big|_{z=0} = T_{cold};\ \ T\big|_{z=Z} = T_{hot}\ \frac{\partial T}{\partial x}\Big|_{x=0}\ \frac{\partial T}{\partial x}\Big|_{x=X} = 0$$

$$\frac{\partial T}{\partial y}\Big|_{y=0}\ \frac{\partial T}{\partial y}\Big|_{y=Y} = 0$$

In order to apply and use these equations in each point of the foam, the model necessitates a spatial discretization of the foam section into nx× ny × nz parallelepiped rudimentary volumes denoted by (i, j, k) or V. Each volume is made of solid or gas phases with various conductivity ($k_{i,j,k} = k_{solid}$ for solid nodes and $k_{i,j,k} = k_{fluid}$ for fluid ones) [11-12].

Meshing:

Meshing is parting the segment in a reasonable number of pieces, and then measuring the stresses for each of the elements and finally putting them together at a constant interval to sum up that component. The more density of meshing ensures greater accuracy of evaluation, and difficulty in solving the problems will also be greater. Even though complex geometry is quite difficult to mesh with hex, tetrahedron or rectangular elements, they are the most suitable type for the simulation. So tetrahedron or rectangular mesh will be done to measure conductivity in high-porosity foams [13].

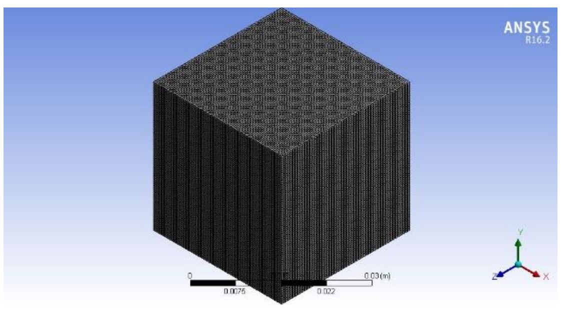

Fig. 2: Generated Rectangular Mesh

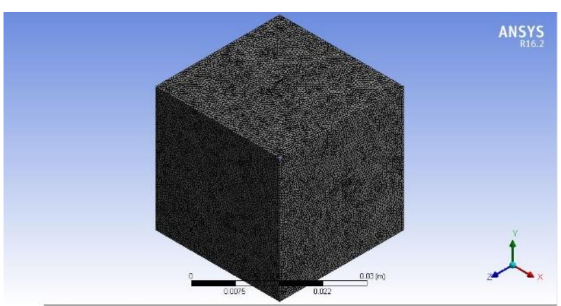

Fig. 3: Generated Tetra Mesh

Material Selection:

Those material which have high porosity foams, in other word, high thermal insulation, such as, wool, fiberglass, polyvinyl chloride, extruded polystyrene, expanded polystyrene, urethane foam, asbestos, vermiculite, NiCrAl foam etc. [14] would give proper result for this research work. Here four materials, polyvinyl chloride (PVC), expanded polystyrene (EPS), fiberglass and asbestos had been used as they have so much importance in this field. Their thermal properties are given below:

Material	Specific Heat	Thermal Conductivity
PVC	1005 J/kg-K	0.16 W/m-K
EPS	1300 J/kg-K	0.033 W/m-K
Fiberglass	700 J/kg-K	0.04 W/m-K
Asbestos	840 J/kg-K	0.08 W/m-K

Solution Method:

The CFD software Fluent 16.2 was used to obtain the numerical results, which is based on the Finite Volume Method (FVM) to solve the governing equations of the fluid motion and heat transfer. It is exceptionally adaptable for altogether different structures and can be modified effectively, as all the various strides of calculation are manually controlled. The algorithm Semi Implicit Method for Pressure Linked Equations (SIMPLE) was considered to couple the momentum and continuity equations. Using an iterative method based on an energy balance, the governing equation (2a) is solved computationally in each and every elementary volume. Once the analysis is completed the resulting data can be easily evaluated by the Fluent postprocessor.

Mesh Dependency:

At first for rectangular meshing elements size were taken as 0.0005mm, and for this the number of nodes were found 195112 and corresponding elements were 185193. After that fine meshing had been performed taking high smoothing as elements size were 0.0004mm. Then 438976 elements were found in this case and the number of nodes were found to be as 421875. Finally, the results for all these cases are presented in the graph to check the variation.

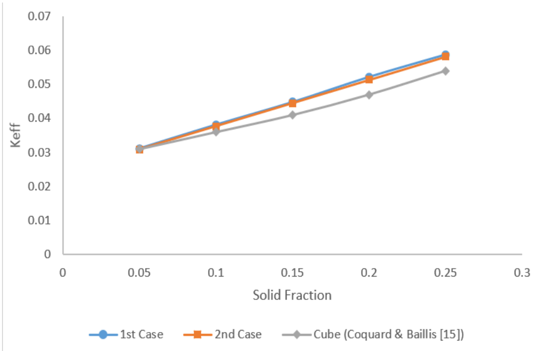

Fig. 4: Variation of k_{eff} along Solid Fraction for Various Meshes.

From the graph, it is observed that the results deviated further in case of coarse mesh but when considering fine mesh for 2nd case by considering 438976 elements, the deviation is comparatively low to the result of the paper. So, the result of mesh with 421875 elements has been presented throughout this paper. For tetrahedron mesh, 0.0005mm elements size is considered. And now for this mesh, nodes were found to be as 322016 and corresponding elements were 1859205.

3. Results:

Variation of Effective Thermal Conductivity:

Along with Solid Fraction: In this research work, solid fraction plays a vital role. The effective thermal conductivity is calculated for different values of solid fraction starting from 0.05 to 0.25 by taking an interval of 0.05. From the results, it is seen that for the increasing of solid fraction, the values of effective thermal conductivity also increase at almost proportionally. But in some situation the change is not happened at proportional rate.

Along with Porosity: Porosity is one of the most important parameters, as conductive heat transfer is directly related to porosity. For different values of porosity starting from 0.75 to 0.95 by taking an interval of 0.05 the effective thermal conductivity is calculated. From the results, it can be seen that porosity and effective thermal conductivity related with each other at inversely proportional rate, though the deviation also can be seen.

For Various Meshes: The little variation for different meshes can be noticed if the plots are presented at a correct manner. It is seen that the values of effective thermal conductivity in terms of solid fraction for rectangular mesh is slightly larger than the obtained result from the tetrahedron mesh. Again, in terms of porosity, the values of k_{eff} is little lower for tetrahedron mesh than the rectangular mesh.

Polyvinyl Chloride (PVC):

Validation for Variation of Effective Thermal Conductivity along with Porosity:

R. Coquard & D. Baillis, the author of the research paper which is followed had done the work mainly with PVC. So, at first the values of effective thermal conductivity are computed for PVC material in order to check the validity of the present work.

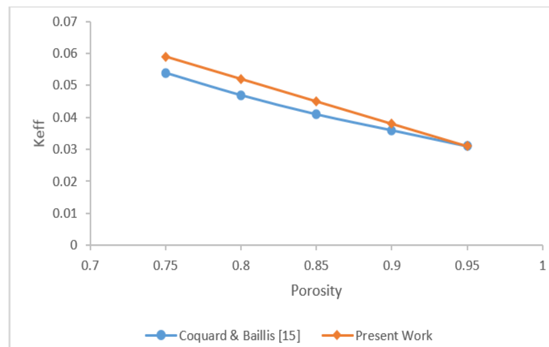

Fig. 5: Validation of k_{eff} along Porosity for Rectangular Mesh for PVC.

From the figure 5 & figure 6, it is seen that for rectangular and tetrahedron meshes for the increasing of solid fraction, the values of effective thermal conductivity also increase at almost proportional rate, though the little deviation also can be seen. So, it can be said that the results are validated.

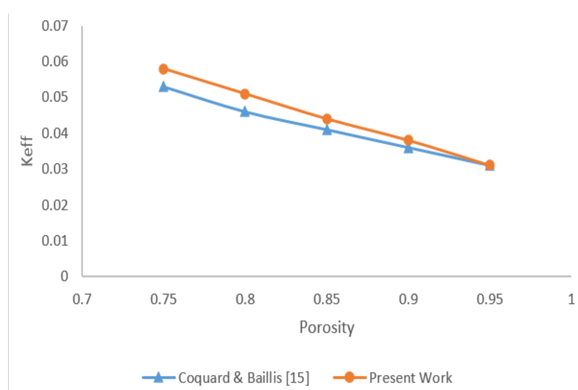

Fig. 6: Validation of k_{eff} along Porosity for Tetra Mesh for PVC.

Expanded Polystyrene (EPS):

Variation of Effective Thermal Conductivity along with Solid Fraction:

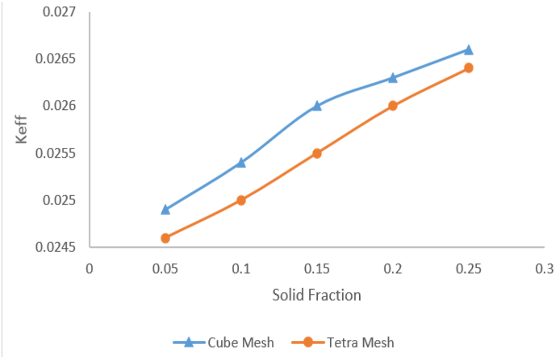

Fig. 7: Variation of k_{eff} along Solid Fraction for Various Meshes for EPS.

From the figure 7, it is seen that for tetrahedron mesh for the increasing of solid fraction, the values of effective thermal conductivity increase at almost proportional rate. But for rectangular mesh little deviation can be seen. When the value of solid fraction crosses 0.15, then effective thermal conductivity has not increased as it used to be.

Variation of Effective Thermal Conductivity along with Porosity:

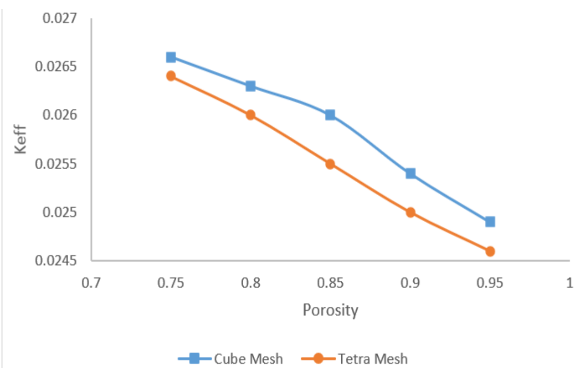

Fig. 8: Variation of k_{eff} along Porosity for Various Meshes for EPS.

From the results, it is found out that for tetrahedron mesh porosity and effective thermal conductivity related with each other at inversely proportional rate. But for rectangular mesh a little fluctuation is noticed.

Fiberglass:

Variation of Effective Thermal Conductivity along with Solid Fraction:

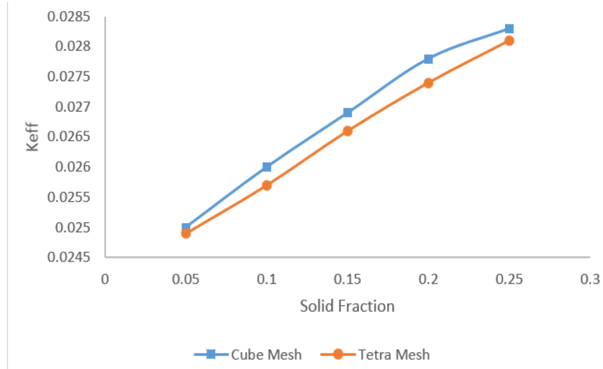

Fig. 9: Variation of k_{eff} along Solid Fraction for Various Meshes for Fiberglass.

From the graph, it is seen that for tetrahedron mesh for the increasing of solid fraction, the values of effective thermal conductivity increase at almost proportional rate. But for rectangular mesh little deviation can be seen when the value of solid fraction crosses 0.2.

Variation of Effective Thermal Conductivity along with Porosity:

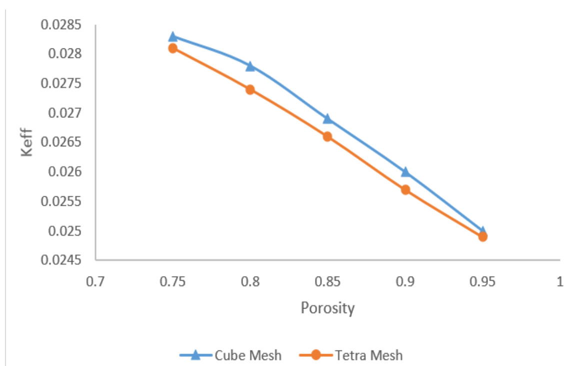

Fig. 10: Variation of k_{eff} along Porosity for Various Meshes for Fiberglass.

From the figure 10, it is found out that for tetrahedron mesh porosity and effective thermal conductivity related with each other at almost inversely proportional rate. But for rectangular mesh a little fluctuation is occurred.

Asbestos:

Variation of Effective Thermal Conductivity along with Porosity:

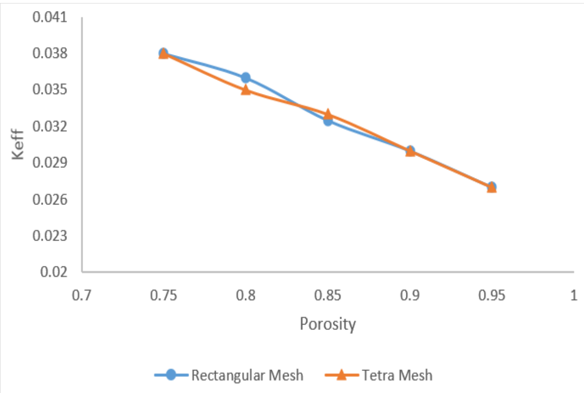

Fig. 12: Variation of k_{eff} along Porosity for Various Meshes for Asbestos.

4. Conclusion

The values of effective thermal conductivity for each material are computed using two meshing method, rectangular mesh and tetrahedron mesh. For PVC, the values of k_{eff} is highest and increasing more rapidly in terms of solid fraction because of its own thermal conductivity. Similarly, as EPS has lowest thermal conductivity among these materials, so the values of k_{eff} is also low, increase so slow along solid fraction that it seems like a straight line.

From the results, it is found out that porosity and effective thermal conductivity related with each other at almost inversely proportional rate, though different material has different values of k_{eff} in terms of porosity. Most changes of k_{eff} can be seen in PVC, whereas least changes are found in EPS.

5. References:

1. Coquard R, Baillis D. In: O¨ chsner A, Murch GE, de Lemos M, editors. Thermal properties of cellular and porous materials. Weinheim: Wiley-VCH; 2008. p. 343–84.
2. Russell HW. J Am Ceram Soc, 1935; 18:1.
3. Solo´rzano E, Reglero JA, Rodrı´guez-Pe´rez MA, Lehmhus D, Wichmann M, de Saja JA. Int J Heat Mass Transfer, 2008; 51:6259–67.
4. Glicksmann LR, Schuetz MA. In: Hilyard NC, Cunningham A, editors. Low density cellular plastics. London: Chapman & Hall; 1994. p. 104–52.
5. Ahern A, Verbist G, Weaire D, Phelan R, Fleurent H. Colloids Surf, A: Physicochem Eng Aspects, 2005; 263:275–9.
6. Boomsma K, Poulikakos D. Int J Heat Mass Transfer, 2001; 44:827–36.
7. Fu X, Viskanta R, Gore JP. Int Commun Heat Mass Transfer, 1998;25:151–60.
8. Druma AM, Alam MK, Druma C. Int J Therm Sci, 2004; 43:689–95.
9. Saadatfar M, Arns CH, Knackstedt MA, Senden T. Colloids Surf A: Physicochem Eng Aspects, 2004; 263:284–9.
10. Wang M, Pan N. Int J Heat Mass Transfer 2008;51:1325–31.
11. Druma AM, Alam MK, Druma C. Int J Therm Sci 2004;43:689–95.
12. Coquard R, Loretz M, Baillis D. Adv Eng Mater 2008;10:323–37.
13. Edelsbrunner, Herbert (2001), "Geometry and Topology for Mesh Generation", Applied Mechanics Reviews, Cambridge University Press, ISBN 978-0-521-79309-4.
14. Radiative and Conductive Thermal Properties of Foams (2006), Dominique Baillis and Re´mi Coquard.
15. Numerical investigation of conductive heat transfer in high-porosity foams, R. Coquard, D. Baillis, Acta Materialia, 2009 – Elsevier.

NOMENCLATURE

T:	Temperature
k:	Thermal conductivity
k_{eff}:	Effective thermal conductivity
β:	Coefficient of volumetric expansion
f_s:	Solid fraction
ε:	Porosity