EFFECT OF MORPHOLOGICAL AND THERMAL PROPERTIES OF INSULATION CORE TYPE OF SANDWICH PANELS ON THERMAL INSULATION PERFORMANCE IN BUILDING

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Numerical modeling study of the thermal behavior of a sandwich panel with different walls morphology is presented with the use of a 3D mesoscopic scale model. The core in sandwich panel is a porous material represented by polyurethane, and the skins are concrete. The numerical homogenization technique was used to the computation of the effective thermal properties of the wall using a VER cell, the first in which the core is normal, the second is zigzag and the last is shaped corrugated. Effect of the thickness of the core and of the skins as well as the volume fraction of the voids in the core was evaluated with the aim of finding the most efficient panel in thermal insulation. Analytical models were used and linked together in order to find the asymptotic analytical model and compare it with the numerical results. We note that the use of different foam is a power tool to reduce the heat transfer in building and constructions and in addition, with different geometrical composition, the comfort energetic in building and house is improved.

Keywords: Sandwich panel, core and two skins of panel, Algerian Sahara region, numerical homogenization, Analytical models.

1. Introduction

The search for alternative materials to use in thermal insulation, especially in fields of construction and wall systems, has become important in the construction of buildings with low insulation, in order to reduce energy consumption. The choice of insulating materials varies from one region to another like Algerian Sahara region, where the use of natural materials or waste extracted in one region is considered the best in terms of adaptation of these materials to the climate of this region [1].

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Thermal insulation depends on two important points, the first is the use of materials with low thermal conductivity, and the second depends on the geometry or the morphology of structure of the material used [2, 3]. Insulating materials include natural, artificial materials, which are mostly derived from plastics or waste. Plastic materials such as polystyrene [3-7] and polyurethane are used particularly in thermal insulation of buildings, which helps to reduce heat [8, 9].

Composite [12], and porous [13] materials are used for thermal insulation, which will reduce heat leakage and transfer into and out of buildings, where these materials have good advantages in terms of physical properties [14]. In addition, other composite materials appeared in the form of sandwich panels, which contain natural and synthetic materials with good thermal insulation, giving them physical properties such as heat resistance, mechanical properties in terms of resistance to stress [15], and lightweight [3].

Work of Al-Hazmy in [16] investigated the Eco efficiency of a thermal insulation panel that consists of polyurethane (PU) foam core sandwiched between two epoxy composite skins prepared by reinforcing glass fibers (GF) and salinized fly ash (SFA) in epoxy resin. The results showed that the environmental efficiency of these composite panels is positive (47%) and outperforms the current alternatives on the market with polyurethane foam or rock wool cores and steel skins.

An experimental and numerical study carried out by *Al-Hazmy* in [14] with the aim of studying the effect of the heat transfer coefficient of a brick wall, where they noticed that the wall insulation decreases with the increase in the conductivity of mortar material. *Lee* in [15] modeled the heat transfer through a composite sandwich panel made up of two Aleppo pine wood skins glued to a black agglomerated cork core, in one study of the effect of the insulating core type on the thermal conductivity of the sandwich structure. *Haqi ismael* in [16] also studied heat transfer through a common hollow building block, as he studied three different formations of stone bricks, including an aged cavity and an insulating filled cavity, and the results showed that the movement of cellular air within the blocks and gaps contribute significantly to thermal loads. *El moumen* in [17] conducted a study to verify the performance characteristics of precast concrete wall panels with two or three layers separated by air layers, they found that the thermal performance of three layers panels is generally better than two layers panels due to the increased length of the thermal path. *Fedaoui* in [18] evaluated the thermal conductivity and the sound insulation through the walls of the building, adding residues of industrial waste in different proportions to the thermal and sound insulation properties of clay bricks (clay bricks), where it was found that adding palm fibers to the bricks contributed to improving its sound and heat insulation properties.

The homogenization technique has been used in several studies, where it has given their proximity to the analytical results; see [19- 23]. Analytical modeling of thermal conductivity of composite materials with simple physical structures was adopted using basic structural models for two-phase materials, see [24-26]. For materials with complex physical structures, empirical models have been used which are generally obtained by modifying simple models. In addition to these models, strict numerical simulations were performed using the finite element method, the finite element method (FEM), or other numerical techniques. These results are confirmed using analytical models due to their materiality, fast computational cost and reasonable accuracy even when the microstructure is uncertain.

In this paper, study the effective thermal insulation properties of three models of the sandwich panel with three layers, where the first model is a panel with a natural core; the second with a zigzag core and the last with a corrugated core is proposed. This work was divided into two parts, in the first part, the study of the behavior of a typical sandwich with a natural core, where the effect of the thickness of the cell core represented by polyurethane is investigate, this material is a foam material that contains voids in different proportions. The effect of void ratios and the different number of spheres on the thermal insulation of a sandwich model with a natural core will also be studied. As for the second part, it will be a study and comparison of the thermal insulation between the first model and the other two models (a zigzag core and a corrugated core).

2. Structure and material properties

In this section, sandwich panel with different core will be studied; the design of this model and the method of networking the various studied cells will be described. The elementary volumetric representation of the models in this investigation is shown in Figure 1, where the core is constituted with spherical pores (foam structure). Sandwich panels are generally in the form of three layers, they are composed of a central core of a thickness "a" and two facing walls of a thickness "e" on both sides see Fig. 2.

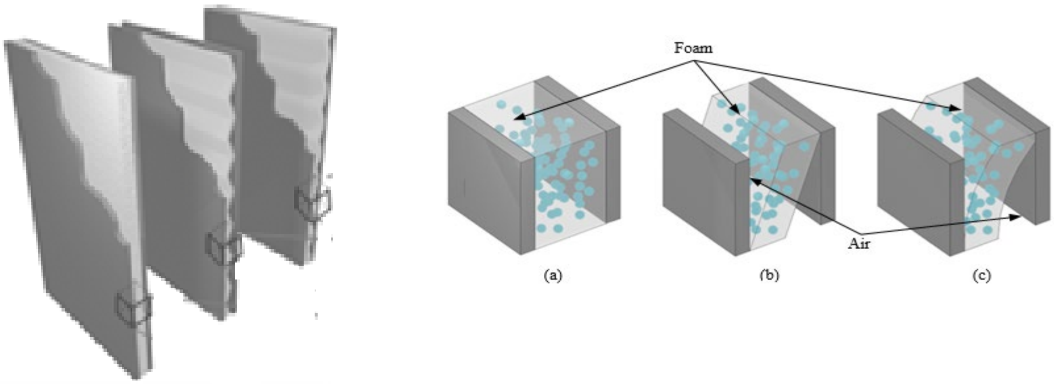


Fig. 1. Three models of sandwich panels, with representative elementary volume (RVE) for the three models, (a) normal core, (b) zigzag core, (c) corrugated core.

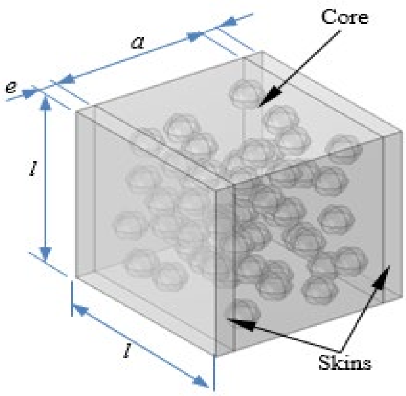


Fig. 2. Dimensions of a sandwich panel cell with core and two skins

The technique for generating spherical voids is the (RSA) technique. This technique has been used in various research works see [19, 20 and 23] so several realizations are generated with models containing different spheres (of 10, 20, 50, 80 and 100 spheres) with three volume fractions (5, 10 and 20%). These models are obtained with the Matlab code, where the generation of the spheres in the core were carried out with the condition of no overlap between them and between the core walls. The dimensions of all three cells are given in Table 1.

Table 1

Dimensions of three cells of model 1 (normal core)

	length $a(mm)$	Width $l(mm)$of the core	Thickness $e(mm)$ of skin
Cell 1	200	190	5
Cell 2		180	10
Cell 3		160	20

Materials for the sandwich panel were the useful generally in practice. Polyurethane material selected for the central core with a porous spherical structure and for outer walls, it is concrete. Table 2 shows the physical properties of these two materials.

Table 2

Thermal properties of each phase used for numerical computations

Thermal conductivity	Polyurethane	Concrete	Air
Thermal conductivity λ (W/(m.K))	0.29	0.8	0.026
Density kg/m3	30	2300	1.25
Heat capacity J/(kg.K)	1400	880	1000

3. Material and method

In this section, after a small presentation of heat transfer law of Fourier, boundary conditions were presented. The FE homogenization technique based on RVE is used to estimate the effective thermal conductivity of sandwich panel structures with three shapes, a normal core, a zigzag core and a corrugated core. The finite element homogenization method based on the representative volume element (RVE) has been used in several studies to simulate the mechanical and thermal responses of compounds at the microscopic scale, see [21-23]. The core is porous in structure. Several models with different dimensions have been designed in order to find the efficient model for thermal insulation. In the case of heat transfer through superimposed walls (Fig. 3), these walls are assumed layers of different thicknesses and thermal properties. The heat transfer through these walls is assumed to be one-dimensional.

Heat transfer law

The thermal conductivity of a wall can be obtained from the heat flow and the temperature gradient inside the material using Fourier's thermal conduction law as shown in (Eq. 1),

$$\boldsymbol{q} = -\lambda \frac{\partial \boldsymbol{T}}{\partial \boldsymbol{x}} (\boldsymbol{W}/\boldsymbol{m}^{2}) \tag{1}$$

Where λ is the conductivity thermal, q is the heat flow through a distance, x, and T is the temperature.

In the case of thermal insulation, heat is transferred in a direction along the x-axis. The thermal conductivity laws remain the same for the case of a representative elementary cell or the RVE, except we apply what are called periodic boundary conditions; the conductivity becomes an average thermal conductivity of the form**:**

$$< \underline{\mathbf{q}} > = -\boldsymbol{\lambda}\, \nabla \mathbf{T} \tag{2}$$

With, ∇T is the gradient vector of temperature.

The conditions of the uniform temperature gradient ∇T type UGT (Uniform gradient of temperature at the boundary) were applied to the outer surfaces of cell V, with:

$$< \boldsymbol{T} > = \underline{\boldsymbol{G}}.\underline{\boldsymbol{x}} \quad , \forall \underline{\boldsymbol{x}} \in \partial \boldsymbol{V} \tag{3}$$

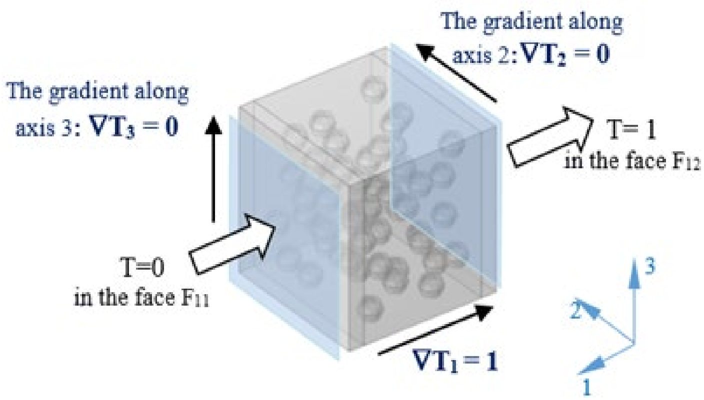


Fig .3. Boundary conditions in x direction

With $\underline{\boldsymbol{G}}$ is a constant vector independent of the position x, $\underline{\boldsymbol{G}}$ is the volume integral of a gradient:

$$\underline{\boldsymbol{G}} = \frac{\mathbf{1}}{\boldsymbol{V}} \int \underline{\boldsymbol{\nabla}} \boldsymbol{T} \boldsymbol{dV} \tag{4}$$

Macroscopically, the macroscopic heat flux is obtained by the average of the microscopic fluxes along V:

$$\underline{\boldsymbol{Q}} = < \underline{\boldsymbol{q}} > = \frac{\mathbf{1}}{\boldsymbol{V}} \int \underline{\boldsymbol{q}} \boldsymbol{dV} \tag{5}$$

(Fig. 3) shows all of the parameters necessary to apply these boundary conditions.

In the case of an isotropic property, as in the case of this study, the temperature gradient following x is given as follows:

$$\underline{\boldsymbol{G}} = \begin{pmatrix} \mathbf{1} \\ \mathbf{0} \\ \mathbf{0} \end{pmatrix} \tag{6}$$

We note here that the periodic boundary conditions PBC converge faster in terms of (RVE) size, to the mean overall effective thermal conductivity by [19, 22]. The homogenized thermal conductivity taking into account Eq. 5 and Eq. 6 is given by:

$$\lambda = \frac{\mathbf{1}}{\mathbf{3}} \left(\langle \underline{\boldsymbol{q}} \rangle \right) \tag{7}$$

Analytical model

For this work and in the case of sandwich panel with different configuration of structures arrangement, we have developed a new equation for the computation of thermal conductivity from the knowledge of the elementary thermal conductivity of the components. Regarding the analytical models, we know that for a series and parallel model, the effective thermal conductivity is given respectively as:

$$\lambda^{eff} = p\lambda_i + (1-p)\lambda_m \quad (8)$$

$$\lambda^{eff} = \frac{1}{\frac{p}{\lambda_i}+\frac{1-p}{\lambda_m}} \quad (9)$$

Where λ_i , λ_m are respectively the thermal conductivity of inclusions and matrix of the porous core and p is the volume fraction of one of the materials of the structure.

Krischer proposed in [27, 28] a weighted harmonic mean of the Series and Parallel models, where the weighting parameter f (where distribution factor) has a value between 0 and 1:

$$\lambda^{eff} = \frac{1}{\left(\frac{1-f}{(1-p)\lambda_1+p\lambda_2}+f\left(\frac{1-p}{\lambda_1}+\frac{p}{\lambda_2}\right)\right)} \quad (10)$$

Where f is equal to zero, the Krischer model is reduced to the Parallel model, and when f is equal to unity, the Krischer model is reduced to the Series model.

For n-layer with porous model, see figure, global equation was developed from the others analytical model:

$$\lambda^{eff} = \sum_{i=1}^{n} p_i\lambda_i + \left(1-\sum_{i=1}^{n} p_i\right).\frac{\lambda_i+2\lambda_m+2p_i(\lambda_f-\lambda_m)}{\lambda_i+2\lambda_m-p_i(\lambda_f-\lambda_m)} \quad (11)$$

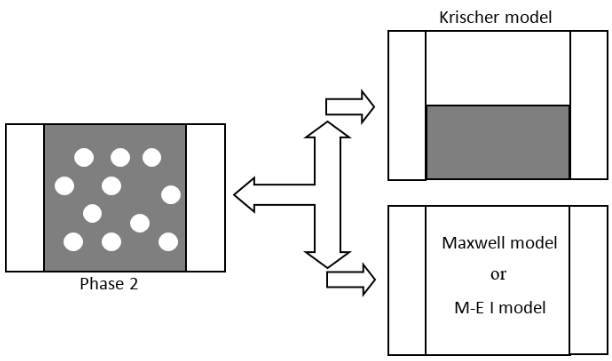


Fig. 4 Modeling technique of equivalent models

Effective Medium Theory (*EMT*), see figure 4, this model is suitable for obtaining the *ETC* of random mixtures whose conductivities are widely different from each other. The *EMT* model give the effective thermal conductivity by the expression, see [29].

$$p\,\frac{\lambda_1-\lambda^{eff}}{\lambda_1+2\lambda^{eff}}+(1-p)\,\frac{\lambda_2-\lambda^{eff}}{\lambda_2+2\lambda^{eff}}=0 \qquad (12)$$

Model mesh proposed

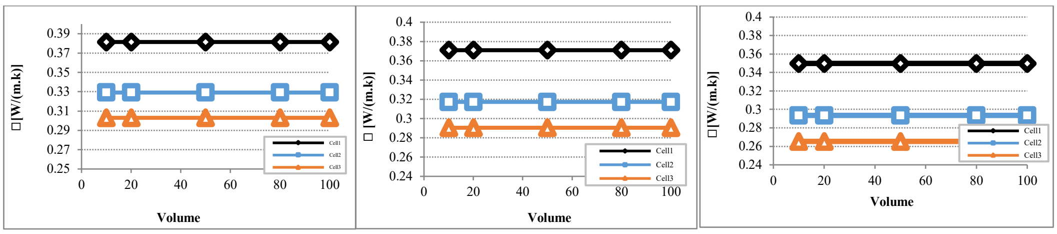
The mesh used for the different sandwich panel cells is a free mesh, where for the cell containing 50 spheres with the fraction 5%, the number of elements was equal to 79,076 elements, and for the cell containing 50 spheres with a volume fraction by 20%, the number of elements was equal to 64,680 elements. In the case of cells containing 10 spheres in the core, the number of elements was 23,485 elements for the 5% fraction and 26,338 elements for the 20% fraction.

4. Results and discussion

To study the heat transfer of heterogeneous materials, a numerical technique with RVE concept is used [19, 29, 47-48]. This approach consists in considering different realizations of generated random microstructures. COMSOL Multiphysics (5) software from **National Polytechnic School of Constantine ENPC, Algeria** was used to simulate the results [30].

Effect of the skins and core thickness

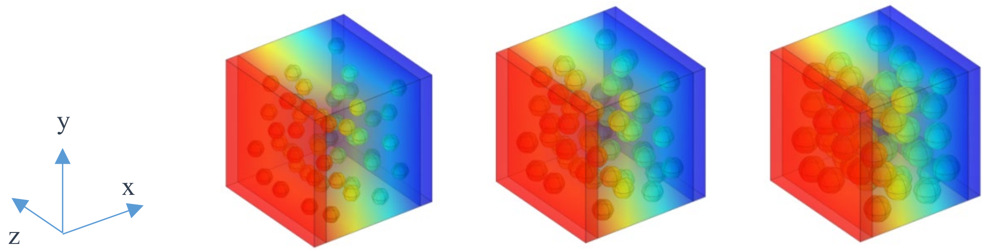
Effect of skins thickness and core morphology as well as the volume fraction of voids in the central core have a significant effect on thermal conductivity. So for cell 3 the value of thermal conductivity is lower compared to the other two cells 1 and 2, and this is for the three cases considered of volume fraction. In addition, the central core, the conductivity has an almost constant trend depending on the number of pores contained in each cell, see Figures 5.



(a) (b) (c)

Fig.5. Change in apparent thermal conductivity as a function of volume size in a microstructure containing non-interconnected pores: (a) cell 1, (b) cell 2 and (c) cell 3.

Figures 5 illustrates the local distribution of temperature transfer in a volume in the x direction with respect to the initial state of the geometry, where the curves of figures 6 show, respectively, the temperature variations compared to the volume fractions (5, 10 and 20%).



(a) (b) (c)

Fig.6 Local distribution of temperature for cell 1 containing 50 pores with the fractions: (a) 05%, (b) 10% and (c) 20%.

Volume fraction Effect

For normal central core, the results showed that for the three cells in the case of higher pore rate, lower thermal conductivity coefficient was observed in all volume fractions cases. For 5% of pores, the thermal conductivity is becomes higher in the three cases of the sandwich type cell models. Figure 7 shows the different variations of the effect of the volume fraction as well as the effect of the morphology in different sandwich models.

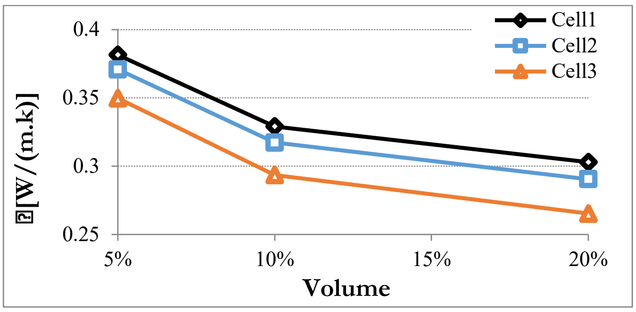
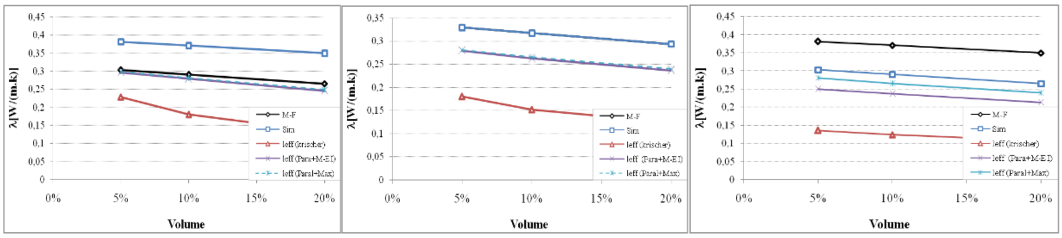


Fig.7 **T**hermal conductivity as a function of pore volume fraction in the core for all cell type.

The numerical results are compared with those obtained by Krisher model, the analytical combination (parallel model + Maxwell model) and the combination (parallel model + Maxwell-Eucken I model). These results are represented in Figures 8. In the case of cell 1 with (dimensions e = 5mm; $\boldsymbol{l}$ = 190mm), the numerical results are not in good agreement with analytical models. In the second case of cell 2 with (dimensions e = 10mm; l = 180mm), the numerical results coincide with the mean-field M-F model, also the combination models (parallel +

M and parallel + M-EI) are close to the numerical results. For the third case of cell 3 with (dimensions e = 20mm; l = 160mm), for the two fraction 10% and 20%, the Krischer model is close to the numerical results, and the other models are far.

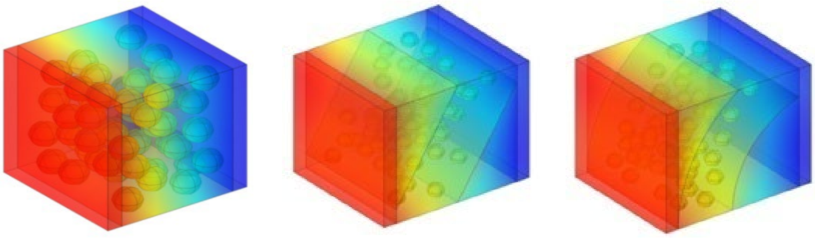


(a) (b) (c)

Fig.8 Comparison of the thermal conductivity effective with the models analytical. a) model 1, b) model 2, c) model 3.

Comparison between three models of sandwich

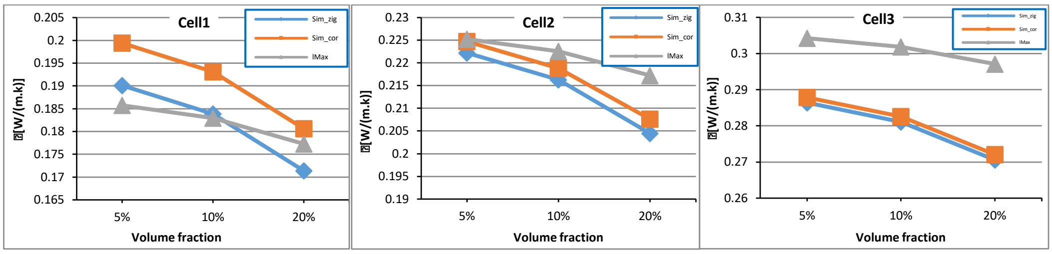
After studying the effective thermal behavior of model 1 (sandwich panels with a normal central core) for the three cells. We choose the best cell represented by "cell 3" with better thermal insulation to compare it with the two other models mentioned at the beginning (see Figure 1), these two models are in perspective view, sandwich with central zigzag core and sandwich with corrugated central core. These two cells contain two additional voids parts compared to the first cell, see figure 9.



(a) (b) (c)

Fig.9 Local distribution of temperature for three core cells containing 50 pores with fractions, (a) normal core, (b) zigzag core, (c) corrugated core.

These results show that the thermal conductivity for the zigzag type central core model is less than the other two models, also for the three models, the thermal conductivity decreases with increasing volume fraction. Regarding the distribution of temperatures in Fig. 9, we observe an improve of exchange in heat transfer for the case of 20% of voids in the core.



(a) (b) (c)

Fig.10 Comparison of the effective thermal conductivity between the three panel models (normal core, zigzag core and corrugated core) and equivalent analytical model

The curves in (Fig. 10) show the effect of the effective thermal conductivity as a function of the volume fractions for the two zigzag and wavy models. These results show that for the refractor model, the thermal conductivity is lower than the curved model for the ratios studied volumes. The results were also verified using the equivalent analytical model, error introduced indicated which model best matched the numerically observed thermal conductivities.

$$\text{Error (\%)} = \left|\frac{k_{analytic} - k_{numeric}}{k_{analytic}}\right| \tag{13}$$

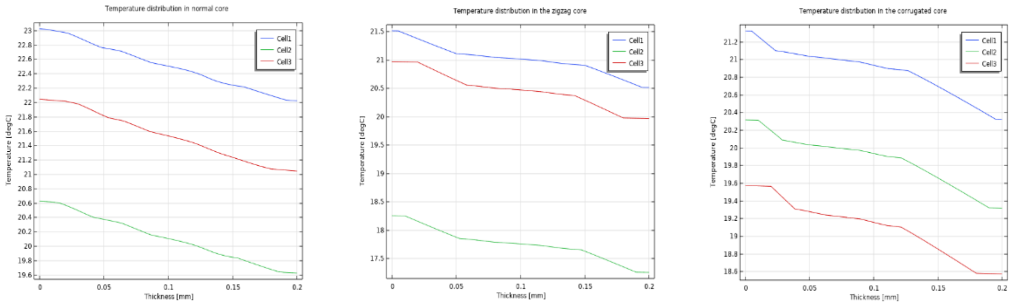
In Table 4, the error was determined for the zigzag and corrugated models with their convergence to the proposed equivalent analytical model. Where we found that the error rates were lower in each of the following cases: For example, for the zigzag core model, the error rate was 2.4% at 5% of the pores, while for the corrugated core model; it was 7.4% at the same ratio. For the two models of the second cell with the 10% fraction, it was between 1.7% and 2.8%. For the third cell, the error was close to 20%.

Table 4

Errors found between different core models and the equivalents model

Model	**Numerical results**			**Equivalent model**			**Error**		
Zigzag model	5%	10%	20%	5%	10%	20%	5%	10%	20%
Cell1	0,190	0,184	0,171	0,186	0,225	0,304	**0,024**	0,184	0,437
Cell2	0,222	0,216	0,204	0,183	0,223	0,302	0,215	**0,028**	0,323
Cell3	0,286	0,281	0,271	0,177	0,217	0,297	0,615	0,294	**0,089**
Corrugated model									
Cell1	0,199	0,193	0,181	0,186	0,225	0,304	**0,074**	0,143	0,406
Cell2	0,225	0,219	0,208	0,183	0,223	0,302	0,229	**0,017**	0,312
Cell3	0,288	0,283	0,272	0,177	0,217	0,297	0,624	0,301	**0,084**

Fig. 11 show of temperature distribution in the three models for 20% of core pores, as these results show that for the sandwich with a broken core, the temperature decreased better for the other two models. From above graph, we can conclude that the use of different foam is a power tool to reduce the heat transfer in building and constructions. With the use of different geometrical composition, we can optimize the comfort energetic in buildings and houses.



(a) (b) (c)

Fig.11 Temperature distribution in the three models with a 20% volume fraction of core pores. (a) Normal core, (b) zigzag core, (c) corrugated core.

The optimal dimensions of the sandwich panels used here have a great effect in the insulation performance of such structures, see figures 11a and 11b. The use of zigzag core foam have a better low temperature than the others form of core. From figure 11a for (20 °C), it is noted that the lower temperature is located in this configuration. Further, it can see that the temperature is below than possible environment temperature in case of building insulations. If such insulations are applied in, building applications it can tolerate the temperature low to the ambient temperature with (1 to 2 °C).

5. Conclusion

In this paper, the thermal insulation of sandwich models consisting of a foam core and two skins was studied, where the numerical homogenization method was used to calculate the thermal conductivity of these models. Three types of sandwich panel with core (normal, zigzag and corrugated) were studied. These models are represented in the form of a representative elementary volume (*RVE*), where the thermal conductivity of the three models was determined based on the volume fractions of the voids of the foam as well as the dimensions of the sandwich. The work was to determine the ideal model for thermal insulation.

For the normal (flat) core sandwich panel, several models have been produced depending on the thickness of the end walls, the thickness of the core and the volume fraction of the foam. The microstructural models of the cells were generated by “RSA” method, which stipulates a random distribution of the voids in spherical form in the core without overlapping between them nor against the walls. The results show that for the normal central core panel model, the cell with large end thickness has the minimum conductivity compared to other cells of the same type.

The comparison between the normal model with the best insulation (thickness and pores numbers) and the other two models (zigzag, corrugated core) shows that the thermal conductivity of the zigzag core model is lower than the other two models. This allows that the zigzag core model to be the best model in terms of thermal insulation; this can be explained by the presence of more vacuum in the cavities between the core and the walls of the two skins.

From results of this study, the use of different foam is a power tool to reduce the heat transfer in building and constructions and in addition, with different geometrical composition, the comfort energetic in building and house is improved.

The equivalent model for several walls with a porous core in the middle was defined by Eq. 12 that gave close values for the zigzag and corrugated core models.

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