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MICRO-MACRO MODELLING APPROACH OF VEGETAL WOOLS THERMAL CONDUCTIVITY

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Abstract

Biosourced materials such as vegetal wools offer major thermal insulation advantages in the green buildings field. Experimental characterisations of vegetal wools thermal conductivity as a function of their density show the existence of an optimum conduction-radiation coupled value. This specific point, as well as the properties of vegetal wools are related to the large variability of shapes and sizes of their fibres. In order to take this specificity into account, it seems particularly relevant to use micro-macro modelling methods to predict the thermal conductivities related to both conduction and radiation heat transfer phenomena. In a first time, a self-consistent method based on a cylindrical geometry (SCM_{cyl}) is used as a modelling approach for conduction transfers. Then, a modelling approach developed by Bankvall and based on an equivalent fibre radius value is used for radiation transfers. So, by coupling these two approaches, it is possible to obtain an equivalent thermal conductivity of fibrous materials as a function of density. Finally, this method is validated by comparison with experimental data.

Keywords:

Vegetal wools, thermal conductivity, conduction transfer, radiation transfer, micro-macro modelling approaches

1 INTRODUCTION

A major renovation of the French buildings has already started and will be reinforced in the next years. In order to respond to a significant demand, bio-based insulators made from vegetal fibres such as flax and hemp are now becoming essential materials. They have thermal properties equivalent to more conventional materials (Volf et al., 2015). However, the bio-based materials are always better than the conventional one in terms of global warming impact, whatever the timescale (Zieger et al., 2020). Indeed, they are able to store large quantities of carbon dioxide in a short time (Pittau et al., 2019).

Vegetal fibres in these bio-based fibrous insulating materials are characterized by a large variability of their morphologies, their shapes and their size distributions (Piégay et al. 2018, Piégay et al. 2021). These specificities of the vegetal wools microstructure have a strong influence on their thermal properties and more particularly on their thermal conductivity. Indeed, (Finck 1930, Bankvall 1973 and Stapulionien et al. 2016) underlines that thermal conductivity of fibrous materials is related to the material bulk density and both the microstructural organization of the fibres and their sizes.

The thermal properties are based on the three types of heat transfers: convection, radiation and conduction. However, the convection effects are usually considered as negligible compared to the two other types of heat transfer in the case of fibrous insulators such as vegetal wools (Finck 1930; Lux, 2005; Tilioua et al. 2012). Heat transfer by radiation seems to have an influence in the case of materials with a very high porosity (greater than 95%), and therefore with a low bulk density (Bankvall, 1973; Arnaud and Cerezo, 2001). In the graphs representing the evolution of thermal conductivity as a function of the material density, the impact of radiation is reflected a density optimum for which the thermal conductivity is minimal. In the following of this paper, this optimum is called "the optimum of conduction-radiation coupled transfers". The work carried out in (Finck, 1930) specifies that radiation transfer is also related to fibre size.

Based on these elements and in order to take microstructural specificities of vegetal wools into account, it seems particularly relevant to use micro-macro modelling approaches for their thermal conductivity. Thus, for conduction heat transfer, it is possible to use the self-consistent method with a cylindrical geometry (SCM_{cyl}) developed in (Piégay et al., 2020) for fibrous and anisotropic materials such as vegetal wools. Moreover, in order to take the contribution of heat transfer by radiation into account, it is possible to rely on a modelling approach based on the expression of the radiative flux density developed in (Bankvall, 1973).

2 MODELLING

2.1 Basic hypothesis concerning the fibrous medium

Vegetal wools are considered as a biphasic fibrous medium composed by a solid phase (specific thermal conductivity λ_s) and a fluid phase (specific thermal conductivity λ_f) saturating the medium.

We consider, as a first approximation, that the solid phase of vegetal wools is made of successive horizontal and parallel fibre layers due to their manufacturing process. It gives them an anisotropic behavior (Lei et al., 2018). We also consider that fibres have a constant cross-section over their entire length. Moreover, the fibre length is considered large in comparison with cross-section size. In this configuration, two main working orientations can be considered. The first one is perpendicular to the layers and therefore the fibres. The second one is parallel to these layers. However, based on building field applications, only the first case, in which the heat flow is perpendicular to parallel layers, is taken into account in this paper.

As mentioned in a number of works in the literature (Bankvall, 1973; Bomberg and Klarsfeld, 1983; Finck, 1930; Karamanos et al., 2004; Ye et al., 2006), the contribution of each heat transfer type can be represented by a specific thermal conductivity: λ_{cond} for the conduction transfer and λ_{rad} for the radiation transfer.

So the equivalent thermal conductivity, λ_{eq} , can be expressed by the following relationship:

$$\lambda_{eq} = \lambda_{cond} + \lambda_{rad} \quad (1)$$

2.2 Modelling of conduction thermal conductivity

To obtain the thermal conductivity of the conduction transfer, the self-consistent method (SCM) initially developed in (Hashin, 1968) is used. In this approach the material at the macroscopic scale and the microstructural parameters follow the same behaviour law. Thus, it is possible to establish analytical relationships between the parameters of each phase and the macroscopic properties.

The SCM is based on the fundamental assumptions of homogenisation methods (Auriault, 1991), the existence of a representative elementary volume and the separation between the microscopic scale and the macroscopic scale. In the case of fibrous media, we consider a generic inclusion with a cylindrical geometry in an equivalent homogeneous medium. Then, the relationship established by the SCM is based on the energy conservation between the generic inclusion and the equivalent homogeneous medium. The work carried out in (Piégay et al., 2020) led to the following expression for the conduction thermal conductivity of a fibrous media:

$$\lambda_{cond} = \lambda_s \frac{(\lambda_s + \lambda_f) - \phi(\lambda_s - \lambda_f)}{(\lambda_s + \lambda_f) + \phi(\lambda_s - \lambda_f)} \quad (2)$$

For $\lambda_s \neq \lambda_f$.

ϕ is the material porosity.

2.3 Modelling of radiation thermal conductivity

Bankvall's modelling introduces a separation distance, L_0 , between each parallel layer of fibrous material. As a first approximation, it is assumed that the both heat and radiative transfer equations are decoupled. Thus, it is possible to obtain an expression of the radiation thermal conductivity, λ_{rad} , related to the radiative flux density. It is expressed by the following relationship:

$$\lambda_{rad} = 4\sigma_{sb} \langle T_{mean} \rangle^3 \beta' L_0 \quad (3)$$

$$L_0 = \frac{\pi R f_{eq}}{4(1-\phi)} \quad (4)$$

σ_{sb} is the Stefan-Boltzmann constant, $\sigma_{sb} = 5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$. $\langle T_{mean} \rangle$ corresponds to the mean temperature between both sides of the material. β' is a radiation coefficient. $R f_{eq}$ is an equivalent value of the fibre radius.

2.4 Coupled conduction-radiation modelling

The expression of the equivalent thermal conductivity, λ_{eq} , for a fibrous material based on both conduction and radiation transfers can be expressed by the following relationship:

$$\lambda_{eq} = \lambda_s \frac{(\lambda_s + \lambda_f) - \phi(\lambda_s - \lambda_f)}{(\lambda_s + \lambda_f) + \phi(\lambda_s - \lambda_f)} + 4\sigma_{sb} \langle T_{moy} \rangle^3 \beta' \left(\frac{\pi R f_{moy}}{4(1-\phi)} \right) \quad (5)$$

3 VALIDATION AND DISCUSSION

In this section, the coupled conduction-radiation modelling, represented by Eq. 5, is validated by comparison with experimental measurements. The modelling input parameters and the macroscopic thermal properties are obtained by the characterization of two vegetal wools. Finally, the modelling method used in this paper is discussed.

3.1 Materials and Methods

Characterised materials are a flax wool (referred as "Flax") and a hemp wool (referred as "Hemp"). They are thermobonded vegetal wools manufactured as a single panel with one kind of vegetal fibres. They are shown in Fig. 1. As shown in Tab. 1, the both materials have relatively different thickness and bulk density values to lead to different thermal conductivity behaviours.

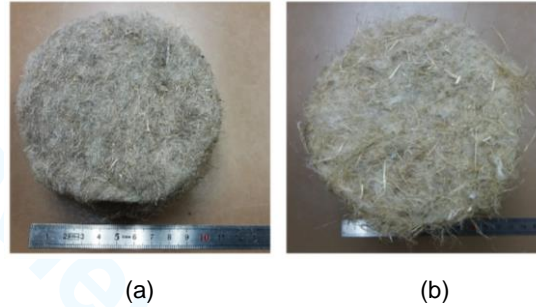


Fig. 1: The materials: (a) "Flax", (b) "Hemp"

Equivalent values of fibre radii are obtained by wool microstructure images analysis. These pictures have been realised using a DEI Quanta 400 Scanning Electron Microscope (SEM) in secondary electron imaging mode in low vacuum. Thus, a mean fibre radius value is determined for each material by at least 300 measurements from a minimum of 20 pictures in order to comply with work recommendations set out in (Kerdudou et al., 2015; Piégay et al., 2018 and Singha et al., 2012). Values are presented in Tab. 1.

The porosity was experimentally characterised using the air values comparison method described in (Leclaire et al., 2003). This method leads to the determination of the open porosity of materials by determining directly the volume of their solid phase. The results presented in Tab. 1 were obtained from five measurements on both materials.

The thermal conductivity of the materials was obtained by transient measurement method. A Hot Disk TPS 3500, based on the transient plane source method related to the standard ISO 22007-2, has been used. The determination of the thermal conductivity of this experimental device is based on the work developed in (Gustafsson, 1991 and Gustavsson et al., 1994). The experimental measurements have been performed with a power of 0.1W and a measurement time of 120 s. For each test, the temperature increase is in the range [15- 20]°C. In order to obtain more experimental thermal conductivity values for higher bulk densities, materials have been compressed. A one-dimensional compression along the axis perpendicular to the fibre layers and without impact on the fibres radii has been performed. In these conditions, the material thickness decreases without any significant modifications of other dimensions of the samples. The experimental tests were carried out under the following laboratory hygrothermal conditions: a temperature of $T = 25 \pm 0.8^\circ\text{C}$ and a relative humidity of $HR = 40 \pm 2\%$.

Tab. 1 : Experimental characteristics of the vegetal wools obtained under a thermal condition of $T = 25 \pm 0.8^\circ\text{C}$ and a relative humidity of $HR = 40 \pm 2\%$. Data are presented with mean value \pm standard deviation.

Material	Initial Thickness (mm)	Initial Bulk Density ($\text{kg}\cdot\text{m}^{-3}$)	Initial Porosity (%)	Mean Fibre Radius (μm)
Flax	48 ± 1	26.6 ± 1.1	98.4 ± 0.2	11.8 ± 1.6
Hemp	107 ± 2	40.8 ± 2.7	97.4 ± 0.2	16.7 ± 1.7

3.2 Modelling validation

In order to determine the equivalent thermal conductivity of each material, it is necessary to use both solid and fluid phases thermal conductivity values.

For the fluid phase, the work carried out in (Bankvall, 1973) shows that inside a fibrous material, the thermal conductivity of the fluid phase is not equal to the air thermal conductivity. Thus, he uses a reference thermal conductivity for the fluid phase which depends on the temperature and pressure conditions at the pore microstructure. It evaluates this conductivity by $\lambda_f = 0.0275 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for the air at $T = 25^\circ\text{C}$.

For the conductivity of the solid phase in the case of a flow perpendicular to the fibres, for each type of vegetal fibre the values listed in (Piégay, 2019) are used. In the lack of experimental data in the literature, the values were determined by inversion modelling as is done in a number of works (Boutin, 1996; Collet and Pretot, 2014; Gourlay, 2014; Hashin, 1968). These values are specified in Tab. 2.

Bankvall's modelling also requires a radiation coefficient value, β' . As for the thermal conductivity of the solid phase, there are no values available in the literature. The coefficients used in this paper and shown in Tab. 2 are also taken from (Piégay, 2019), which gives indicative values.

The conduction-radiation coupled modelling (SCM_{cyl} coupled with Bankvall modelling) leads for both wools to results very close to the experimental values as shown in Fig. 2.

Tab. 2: Indicative values for the thermal conductivity of the solid phase in the perpendicular case and for the radiation coefficient specific to bankvall modelling for flax and hemp wools.

Material	λ_s^\perp ($W \cdot m^{-1} \cdot K^{-1}$)	β'
Flax	1.03	6
Hemp	1.00	9

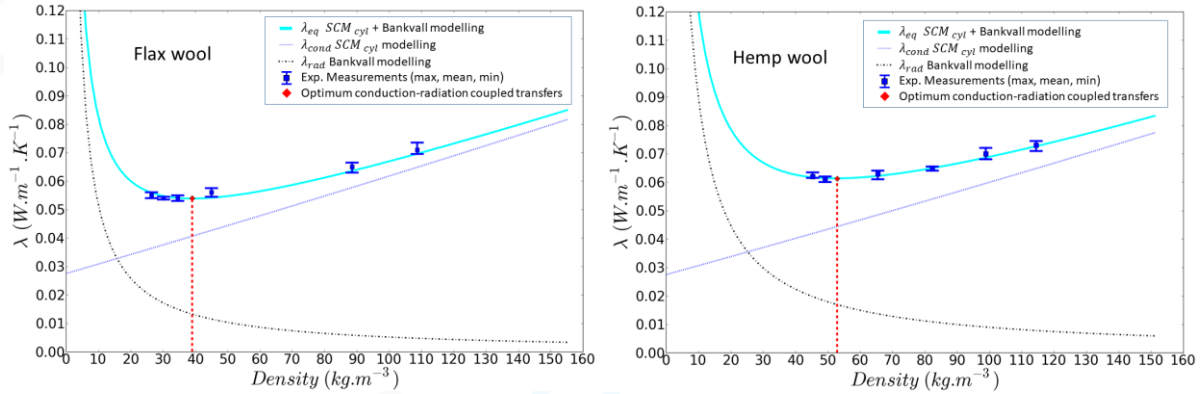


Fig. 2: Comparison of the SCM_{cyl} and Bankvall coupled modelling with the results of experimental thermal conductivity characterisations

3.3 Discussion

As previously mentioned, Fig. 2 shows that radiant heat transfer is predominant at lower densities. Thus, the balance of conduction and radiation heat transfer contributions are established at about $\rho_a \approx 15 \text{ kg} \cdot \text{m}^{-3}$ for the flax wool and at about $\rho_a \approx 25 \text{ kg} \cdot \text{m}^{-3}$ for the hemp wool. Beyond these values, the transfer by conduction becomes quickly preponderant. Nevertheless, these results underline, that for this type of material, radiation transfer cannot be neglected.

The graphs shown in Fig. 2 also show that the coupled conduction-radiation modelling leads to an accurate identification of the optimum of conduction-radiation coupled transfers. For flax wool, it is at $\rho_a \approx 39 \text{ kg} \cdot \text{m}^{-3}$ and for the hemp wool, it is at $\rho_a \approx 53 \text{ kg} \cdot \text{m}^{-3}$. Thus, the coupled conduction-radiation modelling provides valuable elements for optimising the thermal conductivity performance of fibrous insulators.

4 CONCLUSION

The use of bio-sourced materials such as vegetal wools has become a key element in the green buildings field. Thus, it is necessary to rely on a micro-macro modelling approach in order to predict the thermal conductivity of vegetal wools. Indeed, taking the specificities of vegetal fibres into account, it seems particularly relevant to connect microstructural parameters to macroscopic properties. For conduction transfers, it is possible to use a self-consistent method based on a cylindrical geometry. For radiation transfers, the Bankvall model based on a mean fibre radius value has been selected. By coupling these two models, it is possible to determine an equivalent thermal conductivity for fibrous materials. In this paper, this conduction-radiation coupled modelling method has been validated by comparison with experimental characterisations performed on a flax wool and on a hemp wool. The results showed that even if above a density of $25 \text{ kg} \cdot \text{m}^{-3}$ the conduction transfer becomes preponderant, the radiation transfer should not be neglected. In addition, this modelling leads to the determination of the optimum conduction-radiation coupled transfers. Finally, in order to optimise the thermal performance of fibrous insulators such as vegetal wools, it could be relevant to analyse the influence of parameters such as porosity or fibre radii values on their thermal conductivity.

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