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Modeling and measuring of the thermal properties of insulating vegetable fibers by the asymmetrical hot plate method and the radial flux method: Kapok, coconut, groundnut shell fiber and rattan

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ABSTRACT

This article presents two methods dedicated to the determination of the thermophysical properties of natural fibers grown in almost all countries of the world. Experimental measurements were carried out on four dry natural plant fibers of low density: kapok fibers; groundnut shell fibers; rattan fiber and coconut fibers. The thermal effusivity has been estimated by a transient method (the asymmetrical hot plate method). With experimental measurement of the specific heat capacity by Differential Scanning Calorimeter (DCS) which made it possible to deduce the thermal conductivity of such fibers. The thermal properties estimated by this method are then compared to the results obtained by radial flux flow method, a steady state method that directly measures the thermal conductivity. The experimental results compared by these two methods are in good agreement (relative error < 5%). The thermal conductivities of kapok fibers ($\lambda = 0.045\,W\,m^{-1}\,K^{-1}$) and coconut fibers ($\lambda = 0.055\,W\,m^{-1}\,K^{-1}$) obtained all showing that they can be used as substitutes for synthetic insulating materials such as polyester fibers ($\lambda = 0.045\,W\,m^{-1}\,K^{-1}$) or glass wool ($\lambda = 0.04\,W\,m^{-1}\,K^{-1}$). Also the thermal conductivities of kapok and coconut fiber measured correspond with the results obtained by other measuring methods in the literature. This can then help us infer that the quadrupole 1D model developed to estimate the thermal properties of bulk fiber is valid and can allow a good estimation of thermo-physical properties. Therefore, the thermal conductivity of groundnut shell fibers and cane fibers is estimated in the order of $\lambda = 0.093\,W\,m^{-1}\,K^{-1}$ and $\lambda = 0.072\,W\,m^{-1}\,K^{-1}$ respectively.

1. Introduction

With the global warming which is increasingly felt on the planet, one of the solutions to slow down the growth of this phenomenon is to reduce the emission of greenhouse gases. In the building sector, greenhouse gases (GHG) emissions is mainly due to the high energy consumption through the use of devices providing a good thermal comfort in the interior of the building, but which strongly emit carbon dioxide (CO_2). This high consumption rate observed is due either to poor insulation of the building or the use of materials with high coefficient value of thermal conductivity. One of the challenges would be to significantly reduce energy consumption by manufacturing insulating building materials or low grey energy insulation materials capable of optimally isolating a building [1].

One of the most used materials nowadays for insulating a building is glass fibers. However, these fibers are not always originally renewable thus, raises the problem of their disposal at end of life cycle. Glass fibers fabrics also pose health and safety problem. For example, they cause skin irritations during manual wrought-handling, transportation or processing. One recommendable ecological alternative to glass fibers would be the use of natural plant fibers.

Some author's studies [1,2] have shown that building materials made from plant fibers are a perfect solution to the problem of environmental impact of materials (gray energy and emissions) and the reduction of energy consumption of the building. In Europe for example, one of the most valued vegetable fibers are hemp fibers. Research [3,4] conducted on this fiber recently has helped determine its mechanical, thermal and water properties. Samri [5] and Evrard [6] have shown that concretes containing hemp has very good hygrothermal performance ($\lambda = 0.046\,W\,m^{-1}\,K^{-1}$) that help provide a good thermal comfort.

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Nomenclature

a	Thermal diffusivity ($m^2\,s^{-1}$)
Bi	Biot number
c_p	Specific heat capacity (J kg−1 K−1)
e	Thickness (m)
E	Thermal effusivity ($J\,m^{-2}\,°C^{-1}\,s^{-1/2}$)
h	Convective heat loss coefficient (W m−2 °C)
p	Laplace parameter
R_c	Thermal contact resistance ($°C\,W^{-1}$)
T	Temperature (°C)
θ	Lapalce transform of temperature (W m−2 °C)
λ	Thermal conductivity (W m−1 K−1)
ρ	Density ($kg\,m^{-3}$)
ϕ	Heat flux density ($W\,m^{-2}$)
Φ	Laplace transform of heat flux
φ	Heat flux dissipated in the heating element (W)
Subscripts	
h	Heating element
i	Insulating blocks

Regarding the Africa, there is a wide variety of natural plant fiber such as cane; kapok; groundnut shell; rattan; wood; coconut fibers; bamboo; millet pods; palm tree fibers or the sawdust. In Cameroon, these fibers are available in large quantities in the national territory but are not valued. Most of these fibers litter the environment and are sources of pollution or if incinerated, generate large amounts of greenhouse gases responsible for climate change. If recycled, it could be valorized by incorporating them as aggregates with local building materials. Several authors have focused on properties of local materials incorporated with natural fiber insulation. Bal et al. [7] has incorporated into the lateritic soil, millet pods in different proportions. He studied the influence of millet pod content on the thermal conductivity of the composite material lateritic-millet, but his study, lack prior estimate of thermal properties of millet pods that are not known in the literature review. Meukam [8] was incorporated into the lateritic soil, ayous fibers. He showed that this mixture optimizes the insulation capacity of the manufactured composite material. But his study did not equally estimate the thermal conductivity of ayous fiber. Asangwing [9] incorporated into the lateritic soil, oil palm fiber to the proportions ranging from 1% to 12%. He determined the thermal conductivity of the material produced not by an experimental method, but with an electronic device which indicates the thermal conductivity from the application of electrodes of the device on the manufactured material. Also, in his study, the thermal properties of palm fibers are not estimated and are not found in the literature review. Mekhermeche [10] made a composite material by incorporating clay (37%), sand (40%) and 3% of Algeria palm fibers. He arrived in a compressive strength of 3.24 MPa. He showed that bricks made with a maximum of 3% of palm fibers can improve the thermal insulation of a building. But his studies also lack prior knowledge of mixture of thermal conductivity of loose fiber. In all these studies, thermal and mechanical properties of the fibers incorporated as aggregates to local building materials (lateritic mostly) are not determined and are not known in the literature review. However, the addition of these fibers improves the insulation capacity of the composite material used. Therefore, prior knowledge of the thermal and mechanical properties of fibers incorporated is indispensable since its knowledge may predict the insulating character of a composite material when incorporated with different aggregates.

Usually, the main thermo-physical parameter that classifies material as an insulating material is its thermal conductivity. There are several methods for determining the thermal conductivity with the most frequently used being:

- The hot wire method [11,12].
- The guarded hot plate method [13,14].
- The hot-disc method [15,16].
- The three-layer method [17].

Among these methods, the only one that *a priori* may identify the thermal conductivity of the bulk fibers is the hot wire method. The other methods are used for samples, having a specific geometric shape. The samples studied here is that of bulk and light fiber, a hot wire with a very small diameter (less than 1 mm) would not be very suitable for measuring the temperature increase along the wire through the fiber samples. If the contact between the fibers and the thread is not perfect, it could lead to an erroneous value of the estimated thermal conductivity.

The purpose of this study is the experimental determination of the thermal conductivity of plant fibers: kapok fibers, coconut fibers, groundnut shell fiber and rattan fibers. The choice of these fibers is due to the fact that they are the most available fibers and some are even cultivated in households. Knowing their thermal conductivity will justify the reason of their future usage to manufacture insulating composite material or for the building of cold rooms to be used for food stuffs conservations for example.

Two methods are then proposed for measuring the thermal conductivity of these plant fibers. The first methods: the asymmetrical hot plane method (new experimental device) which is a transient method, which allows the estimate of the thermal effusivity E from the experimental temperatures. The experimental measuring of the mass specific heat using Differential Scanning Calorimeter helps to deduce the thermal conductivity of these fibers. The second method: the radial flux method is a steady state method that provides a direct measurement of the thermal conductivity. Calculating the relative differences between the two measurement methods allow us to validate the experimental results of the conductivity of the fibers and compare to those of the literature review.

2. Fibers preparation and experimental testing

2.1. Fibers preparation

2.1.1. Kapok fibers

Kapok fiber is a natural cellulosic fiber which grows on the kapok plan. It consists of unicellular fibers such as cotton but they are seven times less dense [18] than the latter and have a buoyancy which may have twenty times its weight. Kapok (Fig. 1a) studied in this paper was taken from the region in the Far North of Cameroon.

Several authors were interested in the kapok fibers. Voumbo et al. [19] measured the thermal conductivity of kapok fibers using the box methods [20,21]. It conductivity values obtained varied between 0.03 $W\,m^{-1}\,K^{-1}$ and 0.04 $W\,m^{-1}\,K^{-1}$. Pend and Fumei et al. [22] studied a heat transfer for different temperatures through kapok fibers. The value of the thermal conductivity of kapok fibers used for his experiments was 0.0486 $W\,m^{-1}\,K^{-1}$. Fumei [23] after his study proposed kapok fibers could be used jackets instead of duck fibers from ducks.

The process for obtaining kapok fibers for the measurement of thermal properties is as follows:

- The fibers englobing the grain matures (Fig. 1a) at this stage, they are separated from the kapok fruit cob and treated by removing solid grains and the result is a light-weighted fiber as shown in (Fig. 1b).