EXPERIMENTAL INVESTIGATION ON THE THERMAL BEHAVIOR OF THREE DIFFERENT INSULATION MATERIALS: WOOD, POLYSTYRENE AND HEMP WOOL

M.DLIMI[#1], O.IKEN[#], R.AGOUNOUN[#], R.SAADANI[#], K.SBAI[#], A.ZOUBIR[#], M.RAHMOUNE[#]
[#]Laboratoire d'Etude des Matériaux Avancés et Applications (LEM2A),
Université Moulay Ismail, Faculté des Sciences, Ecole Supérieure de Technologie Meknès, Morocco.
[1]dlimi.maryam@gmail.com

***Abstract*— The aim of this work is to study experimentally the thermal behavior and the energetic efficiency of a homogeneous wall.**

The materials chosen are polystyrene such as organic insulation material, then wood and hemp wool such as ecological insulation materials.

The work carried out consists of characterizing the thermal properties of these three materials and then, evaluating one by one the thermal performance of each material by applying three different fluxes with the variation of the material thicknesses from 2cm to 4cm, which allow us to evaluate their impact on the thermal ability of the wall.

Keywords: Building envelope, Experimental study, Thermal insulation, Thermal resistance

I. INTRODUCTION

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Despite of the Strengthening of the thermal regulation, emissions of the greenhouse gases from the building sector are in grow since 20 years.

The buildings sector accounts for about one-third of global energy use. In morocco, this sector accounts for 36% of the global energy consumption and the industrial sector represents 32% of it [1].

Several studies showed that the most efficient way to minimize the energy consumption in the building sector is the reduction of the heat losses by improving the insulation of the building envelope.

Thermal insulation materials are characterized by two fundamental parameters: thermal properties which are the thermal conductivity, the density and the thermal capacity, and also the thermal resistance which represents the material capacity to minimize heat transfer.

The application of thermal insulation varies with the types and ages of building and also with climatic conditions.

The application of insulation materials are varied for the types of buildings and structures and also climatic conditions.

Because of this variety, choosing the appropriate materials is vital not only for building's energy performance but also for reducing its impact on the environment [2].

In this context, new regulations for thermal insulation in the building sector lead researchers to investigate new insulation materials to create energy-saving systems. This research quickly turned to the use of bio-sourced insulation materials [5].

Hemp is among materials that are increasingly used in eco-construction. Its thermal properties may reduce energy consumption and costs.

The purpose of this paper is to investigate the thermal performance of three insulation materials.

Hemp as an ecological insulation material, wood and polystyrene as insulation materials that are widely used for thermal insulation, but are highly energy consuming [6].

The first section of our investigation consists on the experimental characterization of the thermal properties of the three samples studied, and then an evaluation of the thermal behavior of them is presented in the second section.

II. MATERIAL AND METHODS

A. *Thermal properties characterization: Boxes method (EI700 Device)*

Before studying the thermal behavior of our insulation materials (figure 1), we need to determine their thermal properties.

The characterization has been experimentally done by the EI700 Device, a unit developed by The Laboratory of Thermal and Solar Studies of the Claude Bernard University of Lyon. This device contains two boxes, the first one for the thermal conductivity measurement and the second one for the thermal diffusivity measurement (figure 2). The method used is called: the boxes method [7].

(a) (b) (c)

Fig. 1. Insulation material's samples: (a) Wood, (b) Polystyrene, (c) Hemp wool

Fig. 2. EI700 device : Boxes method.

II.A.1 Thermal conductivity measurement

The experimental measurement of the thermal conductivity consists in imposing a unidirectional heat flux through the studied sample. This one is placed between the cold isothermal capacity (A) of the device and the regulated heat source. Four thermocouples are used for the T_B, T_C, T_F and T_{amb} measurements. After approximately three hours, the steady state is reached, and temperatures are recorded. Thermal conductivity is deduced from the thermal balance:

$\varphi_j = \varphi_l + \varphi_c$ with:

- $\varphi_j = V^2 / R$ is the Joule Effect produced by the heating source.
- $\varphi_l = \beta\left(T_{B1} - T_{amb}\right)$ is the global heat losses through the box B1.
- $\varphi_c = \dfrac{\lambda S}{e}\left(T_C - T_F\right)$ is the conductive heat flux through the sample.

Equation (1) is used to deduce the experimental value of the thermal conductivity λ_{exp}:

$$\lambda_{\exp} = \frac{e}{S\left(T_c - T_F\right)}\left[\varphi - \beta\left(T_{B1} - T_{amb}\right)\right] \tag{1}$$

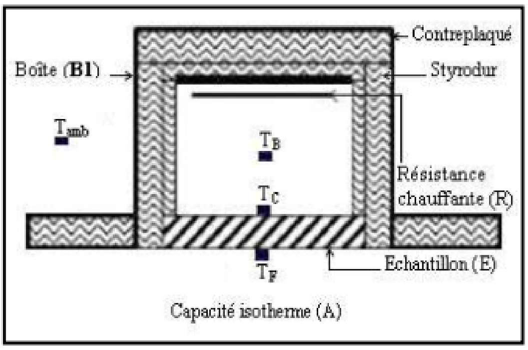


Fig.3. Schematic view of the box used for thermal conductivity measurement.

II.A.2 *Thermal diffusivity measurement*

For the thermal diffusivity measurement [8], the sample is placed into the second box (B2) and heated from the bottom using an incandescent lamp with 1000W radiant power. After few seconds of heating, temperatures values of the sample top face are recorded. The times corresponding to the 1/3, 1/2, 2/3, and 5/6 fractions of the maximum value of the recorded temperatures are then identified. The experimental thermal diffusivity of the material is then deduced by averaging the three values calculated by the following expressions:

$$\left\{\begin{array}{l} \alpha_1 = \dfrac{e^2}{t_{5/6}^2}\left[1,15\cdot t_{5/6} - 1,25\cdot t_{2/3}\right] \\ \alpha_2 = \dfrac{e^2}{t_{5/6}^2}\left[1,15\cdot t_{5/6} - 1,25\cdot t_{1/2}\right] \\ \alpha_3 = \dfrac{e^2}{t_{5/6}^2}\left[1,15\cdot t_{5/6} - 1,25\cdot t_{1/3}\right] \end{array}\right\} \tag{2}$$

$$\alpha_{\exp} = \frac{\alpha_1 + \alpha_2 + \alpha_3}{3} \tag{3}$$

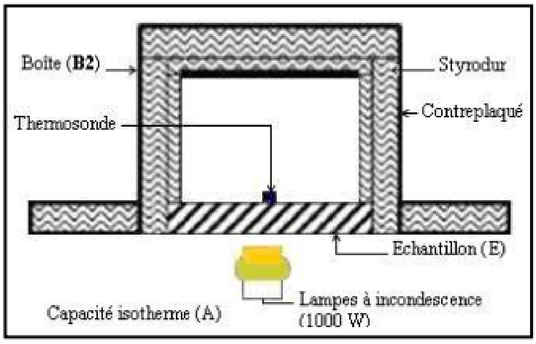


Fig.4. Schematic view of the box used for thermal diffusivity measurement.

II.A.3 Density and Specific Heat

After experimental measurement of the thermal conductivity and thermal diffusivity of the samples, their density and specific heat Cp are calculated using the following equations:

$$\rho = \frac{m_{sample}}{V_{Sample}} \tag{4}$$

$$Cp_{\exp} = \frac{\lambda_{\exp}}{\rho_{\exp} \cdot \alpha_{\exp}} \quad (5)$$

B. *Thermal Behavior Evaluation*

After the characterization of our three insulating materials, we had studied their thermal behaviour.

For this aim, a model house with replaceable side walls was used for determining the transient profile of the inside and outside temperatures of the wall which are measured at a constant interior and outer air temperature and then calculating the thermal resistance R.

II.B.1 Experimental device description

→ *High insulation house*

The high insulation house is a dimension casing of 400 mm × 400 mm × 400 mm, ground insulated through a 5 cm thick Styrofoam plate.

It consists of a thermally insulated base rack with removable lid, measuring walls, exterior insulation and heating.

Side walls are with square apertures (210 mm × 210 mm); and the measuring walls are set in from the inside and pressed by two screws against the aperture gasket.

Each of the exterior walls carries a profile and a small eccentric plate to hold supplementary insulating material. Every angle pillar has a hole to introduce temperature probes. The hole is sealed off with foam material. The lid is insulated by a 5 cm thick Styrofoam plate, fixed to the angle pillars of the base rack with 4 knurled screws which cannot be lost.

→ *Thermal regulation*

The thermal regulation is ensured by a regulating unit in plastic casing with plug to connect heating and a knob for selection of temperature.

Its maximum switching power is of 100 W, and its regulating accuracy is about ± 2°C.

The unit is equipped with a connecting cable with 5 pole diode plug linked with a temperature probe (NTC resistance) in an open metallic protective tube.

→ *Heat transfer service unit H112*

The bench mounted Hilton Heat Transfer Service Unit H112 contains a variable power supply with all associated electrical circuits protected by a residual current circuit breaker and overload cut outs. The rear panel contains a power socket for the optional units and access for the data acquisition system.

Miniature type K thermocouple sockets allow the connection of up to 12 temperature sensors from the range of optional experimental units available. The unit has three digital displays on the front panel including a push button digital temperature indicator allowing all relevant parameters to be displayed. Parameters displayed on the Heat Transfer Service Unit H112 are temperature, voltage range 0-240 Vac and Current range 0-2 Aac.

→ *Data Acquisition HC113A*

The computerized Data Acquisition Upgrade HC113A consists of a 21 channel Hilton Data logger (D103), together with pre-configured, ready to use, Windows compatible educational software.

Factory fitted coupling points on the H112 Options allow installation of the upgrade to the unit at any time in the machine's extensive life.

The Hilton Data logger (D103) connects using the cable supplied to a standard USB port on the user supplied PC.

→ *HDL Software*

The pre-configured menu driven Software supplied with the computer Upgrade HC113A allows all recommended experiments involving the electronic transducers and instruments on the H112 options to be carried out with the aid of computerized data acquisition, data storage and on-screen data presentation.

II.B.2 Experimental procedure

We begun the experience by placing the material on the side that we choose to study, we should make sure that the other sides are perfectly insulated and we don't have any thermal bridge.

Holes in the corner posts of the model house are used for the insertion of thermocouples -NiCr-Ni type K- to measure the interior and inside wall temperatures. The thermocouple used for measurement of the interior temperature is projected about 5cm into the house.

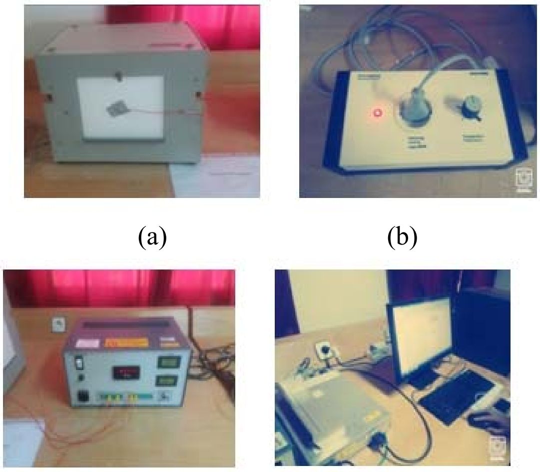
For measurement of the wall temperatures, the tip of the thermocouple should be firmly secured at the level of the lateral holes and as close as possible to the perpendicular centerline of the wall.

The leads must also be secured to the house structure to ensure strain relief.

For the heating purpose, a 100W incandescent lamp with a covering cap was used; the interior temperature was kept virtually constant by a heating thermostat. The temperature sensor of the thermostat is secured to the covering cap of the incandescent lamp and connected to the thermostat by means of a 5-pin socket on the floor and on the side of the house. The power supply for heating is introduced via the thermostat plug.

The cover of the house is then closed, and thermocouples are connected with the H112 heat transfer service unit that is linked to the acquisition card piloted by the HC112B software (figure 5).

A heat flux density is imposed and measurements are recorded until reaching the steady state.



(a) (b)

(c) (d)

Fig. 5. Experimental equipment: a) model house, b) thermal regulation, c) H112 heat transfer service unit, d) acquisition card D103, computer piloted by the HDL software.

III. Results and Discussion

Using the boxes method and the EI700 device, we have calculated the experimental thermal properties of our samples (Table 1).

TABLE I. Measured thermal properties of the insulating materials.

Insulation material	λ (W/m.°K)	ρ (Kg/m^3)	C_p (J/Kg.°K)
Wood	0.14	500	2500
Polystyrene	0.041	25	1500
Hemp wool	0.040	35	1000

We can note that these values are close to that found in the literature [9][10][11].

The thermal behavior of the insulating materials was evaluated by the representation of the transient profile of the inside and outside surface temperatures, and then by the determination of the thermal resistance of each material (Table 2).

For this purpose, we imposed three different heat flux densities with varying the thickness of each insulating material from 2cm to 4cm.

Figures from 6 to 14 show the transient profile of the inside and outside surface temperatures concerning the three insulating materials for different heat flux densities and different thicknesses.

We can note that for all the insulating materials, reaching the steady state differs from a heat flux density imposed to another. This is due to the thermal diffusivity of the material which is the heat propagation rate from the hot side to the cold side.

A. *Φ=20 W/m²*

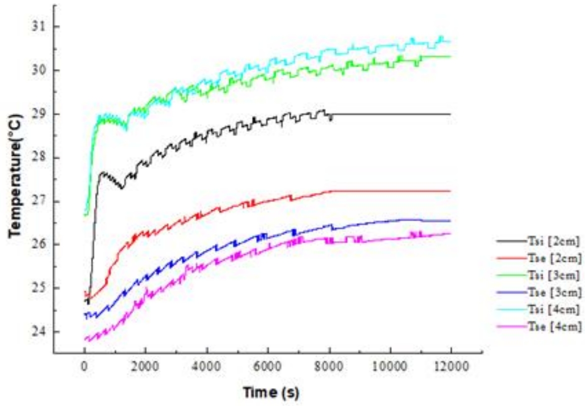


Fig.6. T_{si} and T_{se} transient profile for a wood wall wall with three different thicknesses.

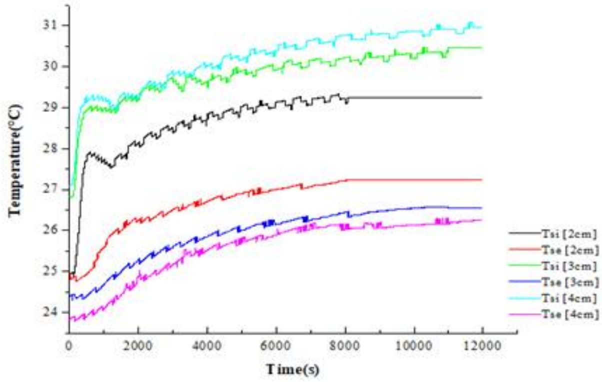


Fig. 7. Tsi and Tse transient profile for a polystyrene with three different thicknesses.

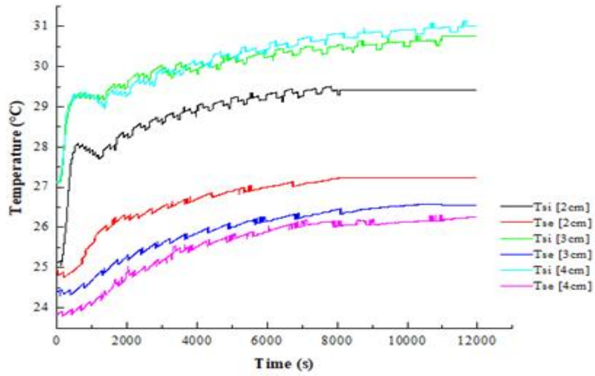


Fig. 8. T_{si} and T_{se} transient profile for a hemp wool wall with three different thicknesses.

If we compare the temperature's gradient between inside and outside surface, we can observe that it increases with the increase of the thickness of each insulating material and for all the heat flux density imposed.

For the wood, the temperature's gradient between inside and outside surface varies from 1,73°C to 11,35°C for the three thicknesses investigated and for the three heat flux densities imposed. For the polystyrene, the variation is from 2°C to 12,4°C, and for the hemp wool, it's from 2,18°C to 12,45°C.

B. *Φ=40 W/m²*

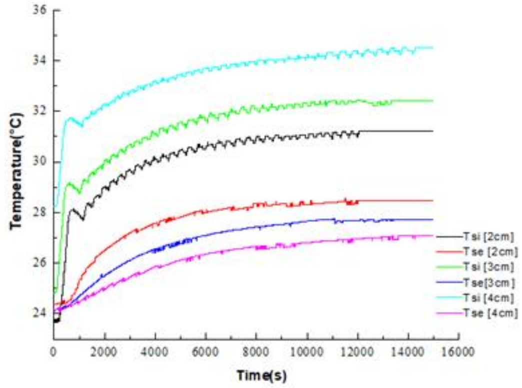


Fig.9. T_{si} and T_{se} transient profile for a wood wall with three different thicknesses.

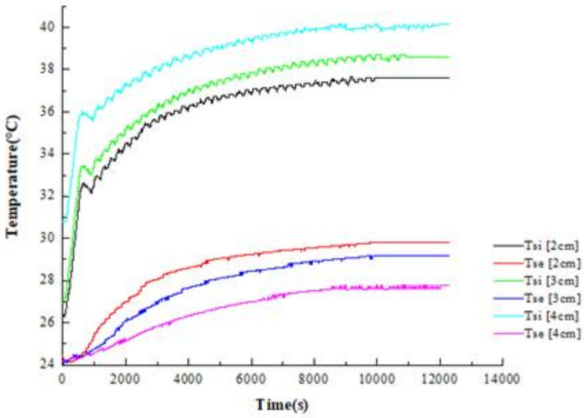


Fig.10. T_{si} and T_{se} transient profile for a polystyrene wall with three different thicknesses.

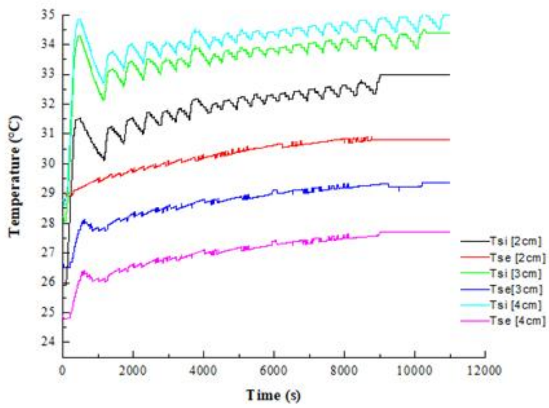


Fig. 11. T_{si} and T_{se} transient profile for a hemp wool wall with three different thicknesses.

C. *Φ=60 W/m²*

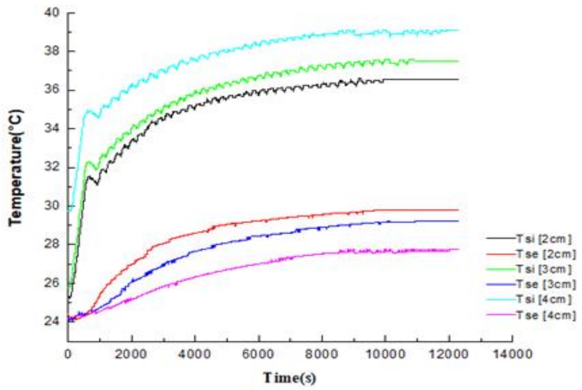


Fig. 12. T_{si} and T_{se} transient profile for a wood wall with three different thicknesses.

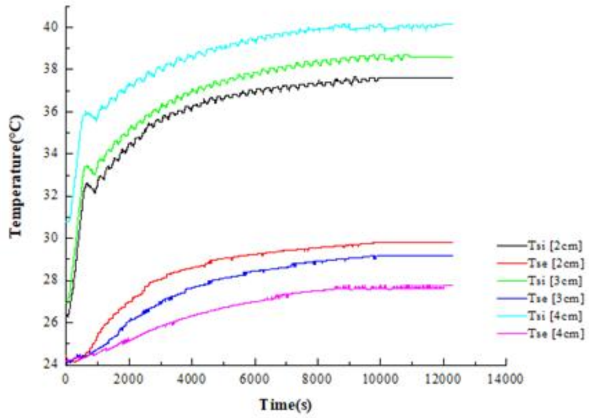


Fig. 13. T_{si} and T_{se} transient profile for wood wall with different thicknesses.

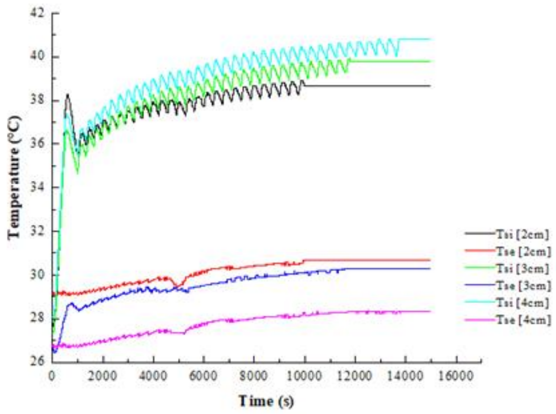


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Fig. 14. T_{si} and T_{se} transient profile for a hemp wool wall with three different thicknesses.

By calculating the thermal resistance [12] [13] (figure 15), we can see that, for each insulating material, it increases with the increase of the thickness [14].

If we compare between the three insulating materials, it’s clearly shown that we have a slight superiority for hemp wool followed by polystyrene and then by wood.

These experimental results are in good agreement with literature because the increase of the thickness of an insulating materiel until reaching its critical thickness influences positively the thermal performances of walls [15], by increasing its thermal resistance first; and also by having influence of its thermal inertia, despite of the fact that an insulation material don’t have a higher thermal inertia for the heat storage, its lower thermal inertia plays a crucial role for comfort by providing thermal phase lag, especially in summer [16].

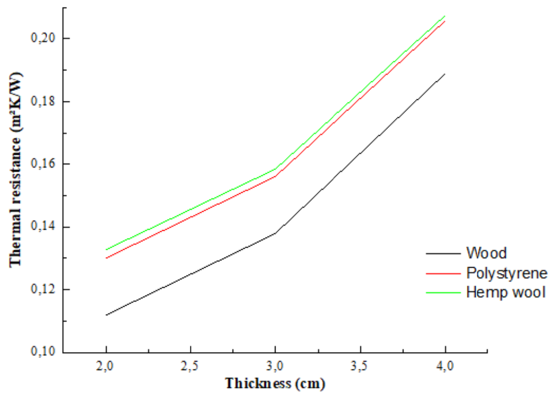

Fig. 15. Thickness influence on the thermal resistance for the three insulating materials

IV. CONCLUSION

In this paper, we have studied experimentally the thermal performance of three different insulating materials: wood, polystyrene and hemp wool. After the characterization of the thermal properties of these insulating materials, the thermal behavior of a wood, polystyrene and hemp wool walls was investigated. The experimental results obtained show that when the insulation material thickness increases the thermal resistance increases too which will have great influences on the reduction of the energy consumption and can improve the thermal comfort of a room.

NOMENCLATURE

Cp_{sample}	Specific heat J/Kg.K
e	Thickness, m
m_{sample}	Sample's mass, Kg
R	Electrical resistance, Ω
S	Sample's surface, m²
t	Time, s
T_{amb}	Ambient temperature, °C
T_{B1}	First box temperature, °C
T_c	Hot surface temperature, °C
T_F	Cold surface temperature, °C
V	Tension, V
V_{sample}	Sample's volume, m^3
Greek Symbols	
φ	Heat flux produced by the heating source, W
ρ	Sample's density Kg/m^3
λ_{exp}	Experimental thermal conductivity, W/m².K
α	Thermal diffusivity, m²/s

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AUTHOR PROFILE

Maryam Dlimi is a Ph.D student at Moulay Ismail University. She received her MSc. Degree in Renewable Energies and Energy Systems from the Hassan II University Faculty of Sciences Ain Chock of Casablanca. Her Ph.D subject is about modeling and experimental characterization of the thermal behavior of building envelopes isolated by multilayer walls.

Omar Iken is a Ph.D student at Moulay Ismail University. He received a first MSc. Degree in Photonics, Micro and Nanotechnologies and Time-Frequency from the University of Franche-Comté (France), and a second MSc. Degree in Instrumental Development for Micro and Nanotechnologies from the University of Lyon 1 (France). His Ph.D subject is about radiative thermal rectification applied to building thermal insulation. He is focused on thermo-chromic materials at nanoscale.

Rachid Agounoun is a senior lecturer at University Moulay Ismail, Morocco. He received the MSc. Degree (Magister) in mechanics and energetic system from the Université de Lorraine, Nancy, France and the Ph.D degree in science for engineers from the Université de Lorraine, Nancy, France. He is an active researcher at Thermal & Material Research Unit (advanced materials and energy system). His area of research includes Thermal Comfort, Building Thermal Simulation, renewable energy and Porous Media.

Khalid Sbai is a full professor since 2001 in Electronics. He received his M.sc. Degree in Electronics from Valencienne University (France) in 1996 and his Habilitation in Physics from Moulay Ismail University in 2008. His research interests include Structural studies, vibrational and electronic properties of carbon nanotubes.

Rachid Saadani is a senior lecturer at University Moulay Ismail, Morocco. Was born in Morocco in 1977. He received the MSc. Degree (Magister) in thermal and energetic system from the Universit Marne La Vallée, Paris Est, Paris, France and the Ph.D degree in science for engineers from the Universite´ Paris Est, Créteil, Paris. He is an active researcher at Thermal & Material Research Unit (advanced materials and energy system). His area of research includes Thermal Comfort, Building Thermal Simulation, renewable energy and Porous Media.

Amine Zoubir is a senior lecturer at University Moulay Ismail, Morocco. He received the MSc. Degree (Magister) in fluid mechanics from the University of Lyon 1 (France) and the Ph.D degree in Mechanics, Energetics, Civil Engineering and Acoustics of INSA Lyon (France). He is an active researcher at Thermal & Material Research Unit (advanced materials and energy system). His area of research are focused on the numerical modeling of convective heat transfer and around the diagnosis of energy performance in buildings.

Miloud Rahmoune is a full professor at Moulay Ismail University. He received his Msc. Degree in applied mechanics from Université Montpellier 2 (France) and his Ph.D. degrees in Mechatronics from Universit Montpellier 2 (France) and Universite´ Hassan II Mohammedia, in 1993 and 1996 respectively. His research interests include structural Dynamics, active control, and smart materials.