

Berrabah, Soukayna; Moussa, Mohamed Ould; Bakhouya, Mohamed

Article

Towards a thermo-mechanical characterization approach of buildings' envelope

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Berrabah, Soukayna; Moussa, Mohamed Ould; Bakhouya, Mohamed (2020) : Towards a thermo-mechanical characterization approach of buildings' envelope, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 1, pp. 240-245, <https://doi.org/10.1016/j.egy.2019.08.051>

This Version is available at:

<https://hdl.handle.net/10419/243739>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>

6th International Conference on Energy and Environment Research, ICEER 2019, 22–25 July,
University of Aveiro, Portugal

Towards a thermo-mechanical characterization approach of buildings' envelope

Soukayna Berrabah*, Mohamed Ould Moussa, Mohamed Bakhouya

International University of Rabat, FIL, ECINE, LERMA Lab, Sala El Jadida, 11100, Morocco

Received 29 July 2019; accepted 25 August 2019

Abstract

This paper investigates the numerical and experimental thermo-mechanical characterization of buildings' structure for energy efficiency. A finite element model (FEM) of a small-scaled building is carried out using mesh refining tools at thermal bridges zones. The latter is revealed towards infra-red (IR) camera measurements. Galvanized steel is the main material composing the building's walls in which heat transfer coefficients are determined based on measurements of external and internal averaged temperatures. Hence, the physical model includes thermal conductivity, heat convective and radiative phenomena. Results of computations, made with finite elements method, using the cast3m tool, show a good agreement compared to those obtained from experiments.

© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Keywords: Energy efficiency in buildings; FEM; Infrared camera; Materials; Thermo-mechanical characterization

1. Introduction

The building sector accounts for almost the third of overall energy consumption. However, in Morocco, it represents about 25%, of which 18% is devoted to residential [1]. This consumption is likely to increase in the coming years given the evolution of the building stock, resulting in a significant increase in the rate of household electrical appliances [2]. In order to cope with this situation, Morocco has adopted a thermal buildings' regulation, which aims to progressively include the building sector on the path of energy sobriety. Reducing energy consumption and subsequently CO₂ emissions while maintaining good occupants' comfort are the main aspects that could be taken into consideration for developing energy efficient approaches in buildings [3,4].

The research presented in this paper targets the aspect of integrating local and energy efficient materials including all house's envelope constraints (e.g., orientation, material characteristics, glazing, shading) and focuses mainly on thermo-mechanical characterization of buildings. As a case study, we characterized a small prefabricated office

* Corresponding author.

E-mail address: soukayna.berrabah@uir.ac.ma (S. Berrabah).

<https://doi.org/10.1016/j.egy.2019.08.051>

2352-4847/© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

baptized EEBLab (Energy Efficient Building Laboratory). This test site does not exceed 12m² of surface, 30 m³ of volume and is mainly composed of galvanized steel and two types of internal insulation; chipboard for the floor and polyurethane for the roof. We have used both temperature sensors to examine the surface temperatures and an infrared camera to detect areas where thermal bridges exist. Based on experimental results a finite element simulation model under the calculation code cast3m have been developed and validated.

2. Related work

Researchers have carried out various works concerning cavities with different geometries. Karatas and Derbentli [5] investigated combined natural convection and radiation in a rectangular closed cavity with one active vertical wall. The cavity is mainly constituted by aluminium for the cooled surface and plastic for the rest, even though, the emissivity is considered constant since the walls are all painted in white. Their work aimed at studying the effect of aspect ratio on the heat transfer in the cavity and the variation of the Nusselt number along with the cavity height. De Vahl Davis [6] described a study of a bi-dimensional movement of air in a square enclosed cavity. In order to generate the desirable movement, a gradient of temperature had been imposed on the right and left walls as a limit boundary conditions. De Vahl showed that a convergence of the results of the vorticity transport and energy equations can be obtained, in the case of square cavities, for values of Rayleigh number up to $2 \cdot 10^{-5}$. He also concluded that a Prandtl number in the range of 10^{-1} - 10^3 can be influencing as a stabilizing factor. Markatos and Pericleous [7] have developed a computational method used to obtain solutions of the buoyancy-driven laminar, turbulent flow and heat transfer in a square cavity with differentially heated side walls. A meshing refinement for the high Rayleigh number was taken into consideration. The results shown in their work are only available for rectangular cavities, with an aspect ratio of 1, a Prandtl number of 0.71 and for Rayleigh numbers up to 10^6 . However, the procedure is general and can be applied to other cases of cavities with different geometries.

The work presented in this paper puts more emphasis on the combination of natural convection, conduction within the materials and external radiation in a cavity filled with air. This allows achieving a numerical model compassing all thermal phenomena with more accurate results. In fact, temperature sensors have been used to examine the surface temperatures. We then used an infrared camera in order to detect areas with thermal bridges [8]. A finite element simulation model is developed and simulated using cast3m [9]. Simulation results are obtained and compared to those from experimentation.

3. Modelling and results

This section presents the computational model we have built using the finite element method and simulated using CAST3M tool. Experimental results have been introduced to show the accuracy of the proposed model.

3.1. Computational modelling

Indeed, we generate the geometry by respecting the real dimensions of the EEBLab to have more computational precision, where the number of elements is about 19768 and 41030 nodes (see Fig. 1). The implemented thermal model includes conductivity, natural convection and external radiation. It is worth noting that an iterative procedure is performed in order to linearize the radiative equivalent exchange coefficient. Thermal characteristics of the materials constructing the EEBLab are given in Table 1.

The conduction law is given by Fourier's model (Transfert thermique, métrologie et séchage, 2018), where k is the conductivity, ΔT the gradient of temperature, and n is the normal vector:

$$Q = \iint K \cdot \Delta T \cdot n \cdot dS \quad (1)$$

The spatial discretization of Eq. (1) on a finite element meshing, allows us to get Eq. (2), where C is the matrix of heat capacities, and T the temperature derivative.

$$C \frac{dT}{dt} + K \cdot T = Q \quad (2)$$

Table 1. Thermal characteristics of the EEELab's construction materials.

	Heat capacity [J/Kg K]	Density [Kg/m ³]	Conductivity [W/m K]
Galvanized steel	470	7800	0.499
Wood	2100	170	0.042
Plasterboard	1300	25	0.022
Glass	800	2530	0.93
Aluminium	900	2690	210

For natural convection, we need to define the amount of heat flux exchanged between the solid walls and the ambient air. For this, it is important to calculate the heat transfer coefficient, where Nu is the Nusselt number, L the characteristic length and K the heat conductivity.

$$h = \frac{Nu.L}{\lambda} \quad (3)$$

The calculus of heat flux is given following Eq. (4), where T_a is the ambience temperature, T the temperature of the wall, and S the air of the wall.

$$Q = h (T_a - T) S \quad (4)$$

In the formulation of the finite element problem, this type of transfer results in the addition of a convection matrix H, representing the coefficient h, to the conductivity matrix, and the addition of a term Q_c , representing the term $h \cdot T_a$, to the second member.

$$C \frac{dT}{dt} + (K + H) T = Q + Q_c \quad (5)$$

Radiant thermal transfer is given by the law of Stefan–Boltzmann; where ε is the emissivity of the used material and φ is the heat flux density.

$$\varphi = \varepsilon \sigma (T_a^4 - T^4) \quad (6)$$

3.2. Simulation and experimental results

The experimental setup consists of using three main equipment. An infrared camera has been used for visualizing the temperature distribution on the EEELab walls' surfaces and detecting areas where thermal bridges persist. For this, the camera has been directed to the front and left walls due to the diversity of components on them (i.e., door, window, beams, air inlet fan). Concerning the front facade, the camera was placed at approximately 24 m away to get a better view of the whole wall. However, the camera was placed at 4 m away from the left wall due to some infrastructure constraints. The experimental results served to determine the areas (i.e., thermal bridges) where the temperature sensors should be installed. DS18B20 temperature sensors have been deployed to provide temperature measurements in degrees C with an accuracy of ± 0.5 °C. Based on an already developed Internet of Things (IoT) platform [10], we have continuously collected walls' temperatures during different periods. Fig. 2(b) shows the sensors placements on the EEELab walls that have been symmetrically positioned on both internal and external facades. The temperatures' data are then transmitted in real-time via Wi-Fi to our IoT platform for processing and storage. Afterwards, we have analysed data from two main sources in order to validate the experimental results. A thermometer has been used to measure walls' surface temperature as well as the ambient indoor/outdoor temperature. Collected data are used as input for calculating the heat transfer coefficients, which remain important for modelling the thermal behaviour of the EEELab based on the finite element method on CAST3M.

Furthermore, horizontal test lines have been drawn on both facades (see Fig. 2(a)) to visualize the temperature distribution. As can be seen in Fig. 3(a), the temperature remains constant in steel and can reach about 307 K (A). However, when approaching the window and door borders, the temperature significantly drops to respectively reach approximately 297 K (B) and 300 K (C). Fig. 3(b) depicts the temperature of the left wall following the line 2 (see Fig. 2(a)). Fig. 3(b) (D) represents the corner beam section, (E) the galvanized steel, (F) the middle beam.

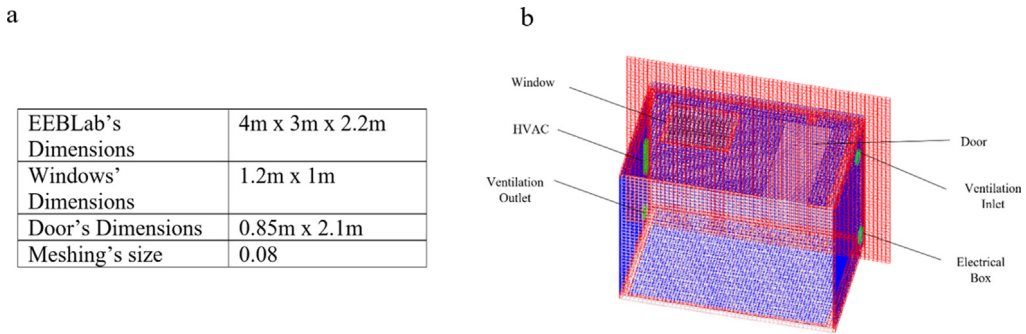


Fig. 1. Geometry and Meshing (a) Dimensions (b) Rotational view.

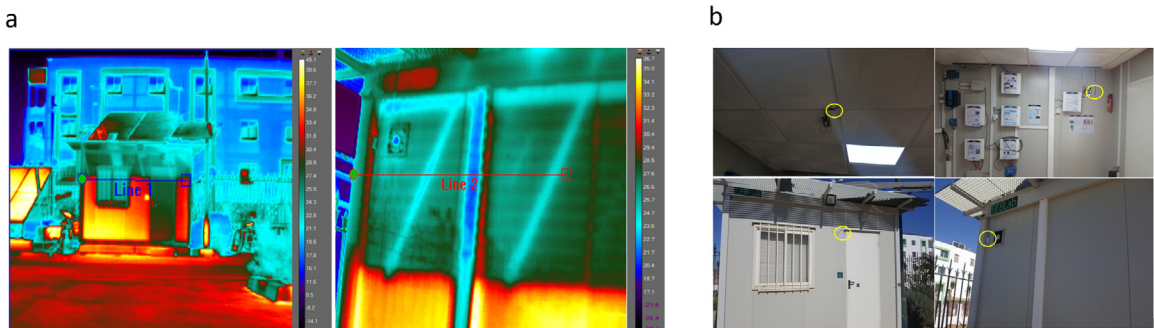


Fig. 2. (a) Temperature distribution using thermography (b) Examples of the placement of thermal sensors.

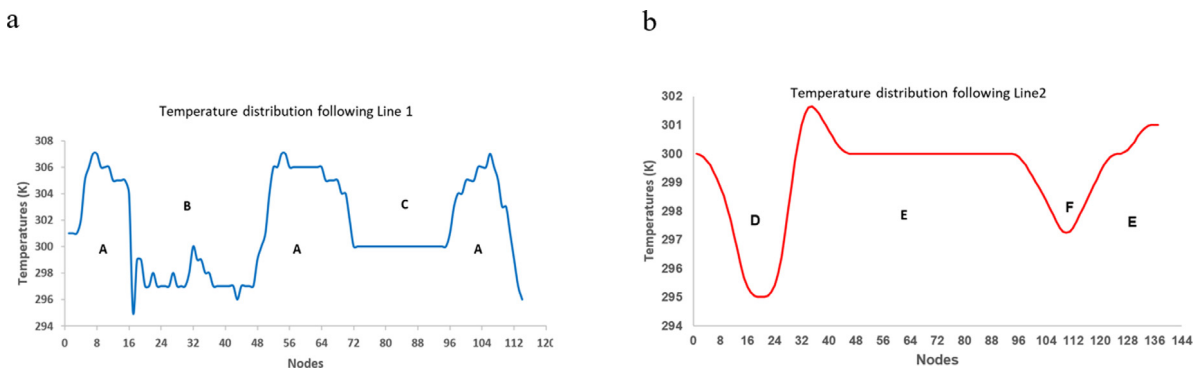


Fig. 3. (a) Temperature distribution following test Line 1 (b) Temperature distribution following Line.

Passing between these sections, we notice a drop of temperature at beam level while it remains constant otherwise. From these results, we can conclude that thermal bridges persist in areas where variable materials co-existent, and the contact is not perfect. This can be explained by the fact that the conductivity of materials varies and affects the internal temperature by allowing air exhaust through the materials and zones of infiltration.

Fig. 4 shows the evolution of the external and internal temperature from 11 AM to 2 PM on the 21st March 2019. This will allow us, in addition to the results from the camera, to make the comparison with the simulation and validate the model. We notice that temperatures of the four walls at the same ambiances evolve in the same way. A small offset is seen at the external temperature on the front facade since the sun is directly exposed to it during this time of the day.

Furthermore, the average resulted in temperatures and heat transfer coefficients on the internal and external facades as well as ambiances are depicted in Fig. 5(a). We can notice that the respective difference temperature

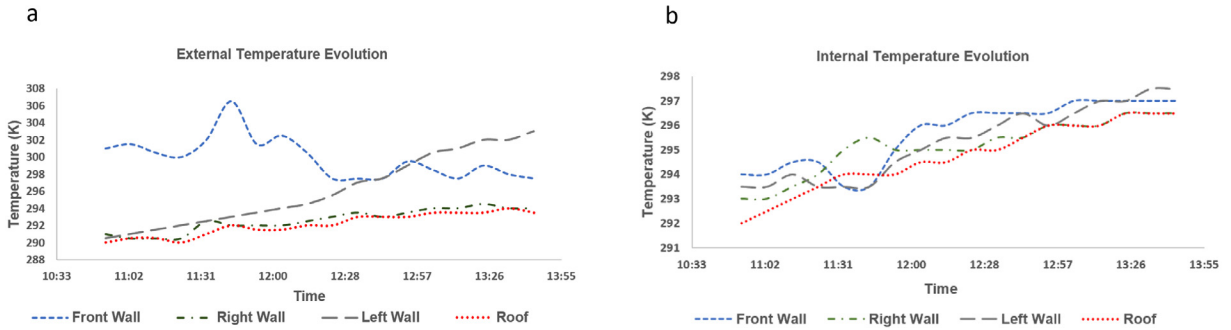


Fig. 4. (a) External temperature evolution (b) Internal temperature evolution.

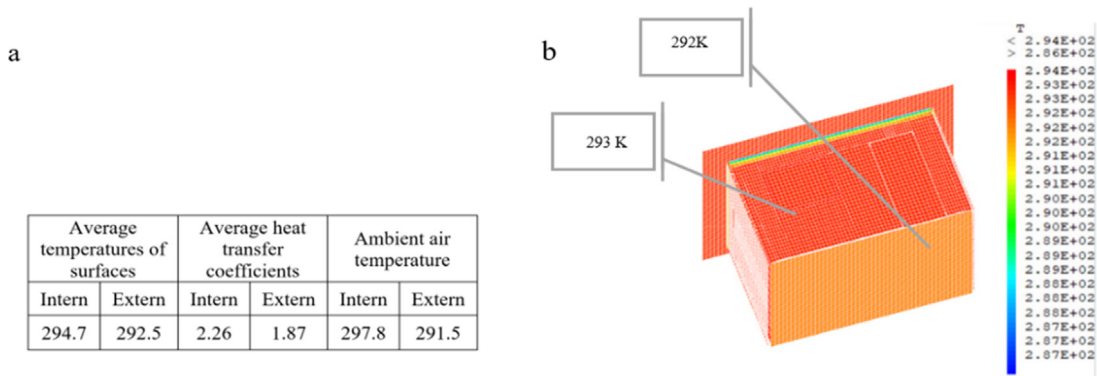


Fig. 5. (a) Results issued from the use of thermometer (b) spatial temperature distribution under cast3m.

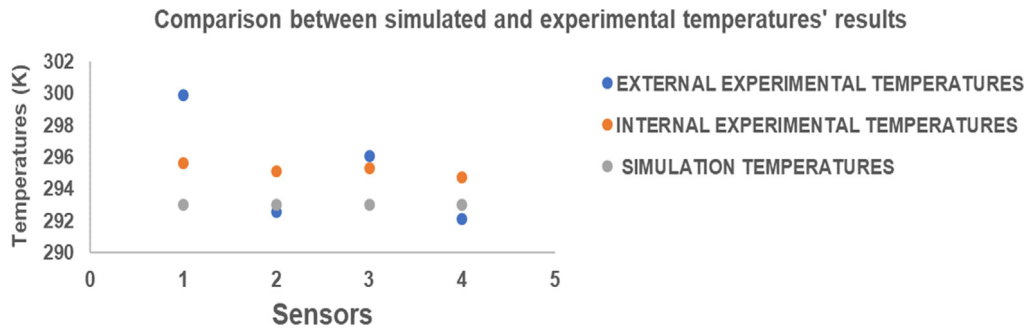


Fig. 6. Comparison between simulation and experiments.

between the internal and external ambient air is about 6.3 °C and the one between the two sides of the surfaces is about 2.2. We can say that the equilibrium is almost attended due to the small thickness of the walls (from 50 to 80 mm) and the type of construction materials. The results reported in Fig. 5(a) have been used as input parameters in the simulation. Simulation results are presented as spatial temperature distribution on the surfaces of the EEBlab’s envelope on a precise period (steady state). As shown in Fig. 5(b), facades’ temperatures are almost uniform and vary between 290–293 K.

A comparison between the temperature values, resulting from the simulation and those resulting from the experiments, was carried out (see Fig. 6). The test points have the same coordinates in both experimental and numerical issued points: ‘1’ on the front face, ‘2’ on the right face, ‘3’ on the left face and ‘4’ on the roof. Concerning the internal simulation temperatures and those gathered from the sensors, there is a maximum difference of about 3 °C. We have noticed a good agreement between the external experimental temperatures and the simulation

results at the level of sensors 2 and 4. However, there is a slight difference between the sensors 1 and 3 results which can be caused by the disturbances generated while gathering the data.

4. Conclusions and perspectives

This paper focused on the experimental and numerical study of the thermal behaviour of buildings. The usage of Infrared camera allowed us to observe the temperature distribution on the walls as well as areas of thermal bridges using thermography treatment. Based on theoretical correlations and the usage of thermometers, we were able to calculate heat transfer coefficients between facades and internal/external ambiances. These latter results were integrated into the simulation programme in addition to some thermal characteristics of the construction materials in order to visualize the temperature distribution under Cast3m simulation tool. The realized stationary thermal model showed an agreement with the experimental approach. It takes mainly into consideration the three classical thermal phenomena namely the conduction within the material, the natural convection and the external radiation. As future work, we plan to validate this numerical model on transient behaviour coupled with a mechanical model considering the own weight of the studied building as well as the weight of equipment installed on its roof. Afterwards, we will study the possibility to integrate some new functional materials [11] and investigate energy harvesting aspects.

Acknowledgements

Special acknowledgements are addressed to our EEELab team and especially the ICT members. They were of big help in creating a platform for real-time data monitoring (i.e., Temperature data). A special thank is also addressed to Professor Vincent Felix for his guidance and advice concerning the usage of Infrared camera.

This work is supported by MIGRID project, Morocco (grant 5-398, 2017–2019), which is funded by USAID under the PEER program.

References

- [1] Agence urbaine de Skhirat-Témara. Decrees of thermal regulation of constructions; 2019, http://www.aust.ma/images/aust/reglementation/Decreets/R%C3%A8glement_thermique_de_construction_au_Maroc.pdf.
- [2] Aderee. Thermal regulation of Moroccan construction, simplified version, Morocco; 2014.
- [3] Lachhab Bakhouya, Ouladsine, Essaaidi. Energy-efficient buildings as complex socio-technical systems: Approaches and challenges. *Ser Nonlinear Syst Complex* 2017;18:247–65.
- [4] Bakhouya NaitMalek, Elmoutamid Lachhab, Berouine Boulmrharj, Ouladsine Felix, Zinedine Khaidar, Elkamoune. Towards a context driven platform using IoT and big data technologies for energy efficient buildings. In: 3rd international conference of cloud computing technologies and applications. IEEE; 2017, p. 1–5.
- [5] Karatas, Derbentli. Natural convection and radiation in rectangular cavity with one active vertical wall. *Int J Therm Sci* 2018;123:129–39.
- [6] De Vahl Davis. Natural convection of air in a square cavity: a benchmark numerical solution. *Internat J Numer Methods Fluids* 1983;3(1983):249–64.
- [7] Markatos, Pericleous. Laminar and turbulent natural convection in an enclosed cavity. *Int J Heat Mass Transf* 1984;27:755–72. [http://dx.doi.org/10.1016/0017-9310\(84\)90145-5](http://dx.doi.org/10.1016/0017-9310(84)90145-5).
- [8] Bianchi Pisello, Baldinelli, Asdrubali. Infrared thermography assessment of thermal bridges in building envelope: Experimental validation in a test room setup. *Sustainability* 2014;6:7107–20.
- [9] Cast3m. Digital simulation software; 2019.
- [10] Nait Malek Kharbouch, El Khoukhi Bakhouya, Deflorio Elouadghiri, Latre, Blondia. On the use of IoT and big data technologies for real-time monitoring and data processing. *ICTH Procedia Comput Sci* 2017;113:429–34.
- [11] Ould Moussa. Modélisation du comportement dynamique non-linéaire des structures en matériaux à mémoire de forme [Ph.D. thesis], France: Ecole Polytechnique; 2012.