ΔΙΕΡΕΥΝΗΣΗ ΤΗΣ ΣΥΝΕΙΣΦΟΡΑΣ ΤΩΝ ΠΟΛΥΣΤΡΩΜΑΤΙΚΩΝ ΜΟΝΩΤΙΚΩΝ ΣΤΗΝ ΜΕΙΩΣΗ ΤΗΣ ΕΝΕΡΓΕΙΑΚΗΣ ΚΑΤΑΝΑΛΩΣΗΣ ΤΩΝ ΚΑΤΑΣΚΕΥΩΝ

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Περίληψη

Οι περιβαλλοντικές επιπτώσεις των μονώσεων σε κτιριακές εφαρμογές υποτιμώνται πολλές φορές, παρ' ότι η κακή θερμομόνωση του κελύφους του κτιρίου αποτελεί ένα από τα κύρια αίτια θερμικών απωλειών. Αυτός είναι και ο λόγος που η θερμομόνωση των κτιριακών εφαρμογών αποτελεί ένα πολύ σημαντικό παράγοντα βιοκλιματικού σχεδιασμού. Τα πολυστρωματικά μονωτικά αποτελούνται από συνδυασμό επιφανειών αλουμινίου που εναλλάσσονται με στρώματα ινωδών θερμομονωτικών υλικών. Πρόκειται για δυναμικά υλικά που βρίσκονται σε διαρκή αλληλεπίδραση με το κτιριακό περιβάλλον και λειτουργούν ως φραγμοί της υπέρυθρης ακτινοβολίας που εκπέμπουν τα δομικά υλικά (radiant barriers). Ο κύριος στόχος της παρούσας εργασίας είναι να διερευνηθεί η συνολική συνεισφορά των μονωτικών αυτού του τύπου στην μείωση της ενεργειακής κατανάλωσης των κτιρίων. Ο συνδυασμός των φαινομένων μεταφοράς θερμότητας με αγωγή και ακτινοβολία, όπως εμφανίζονται στο εσωτερικό των πολυστρωματικών μονωτικών, μελετάται πειραματικά και αριθμητικά. Προκειμένου να εκτιμηθεί πειραματικά η θερμική απόδοση των πολυστρωματικών μονωτικών, χρησιμοποιήθηκαν οι τεχνικές των «*guarded hot box*» και «*guarded hot plate*». Εν συνεχεία, δημιουργήθηκε αριθμητικό μοντέλο το οποίο λαμβάνει υπόψη του και τους τρεις τρόπους μεταφοράς θερμότητας, δηλαδή τη θερμική αγωγή, τη συναγωγή και την ακτινοβολία. Η τελική εξίσωση μεταφοράς θερμότητας επιλύεται στους στοιχειώδεις όγκους στους οποίους διαμοιράζεται το μονωτικό υλικό, ενώ όσο αφορά στην ακτινοβολία, εφαρμόζεται στο μοντέλο η μέθοδος της «προσέγγισης των δύο ροών» (two flux approximation). Λαμβάνοντας υπόψη τους θορύβους των μετρήσεων και την πολυπλοκότητα των φυσικών φαινομένων που συμμετέχουν, η σύγκλιση των πειραματικών και των αριθμητικών δεδομένων, θεωρείται άκρως ικανοποιητική.

INVESTIGATION OF THE CONTRIBUTION OF MULTIFOIL INSULATION IN THE REDUCTION OF ENERGY CONSUMPTION OF BUILDINGS

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Abstract

The environmental impact of building insulation is often underestimated, even though it is one of the most important factors of heat losses. That's why it is also a very important bioclimatic design parameter. The potential benefit of the multilayer insulation materials considered as radiant barriers is primarily in reducing building heating or cooling energy usage in warm and hot climates. These materials are usually consisted of reflective aluminium type foils and high-porous, semitransparent fibrous substrate materials. In difference with conventional insulation, they work by reducing heat transfer by thermal radiation across the air space between the walls, where conventional insulation is usually placed. The combined conduction/radiation heat transfer in multilayer thermal insulations (MTI) was investigated experimentally and numerically. The main purpose of the work is to understand the contribution of multilayer insulations on the reduction of heat losses of buildings. There are at present two kinds of techniques general used by accepted laboratories to measure thermal values: the guarded hot box and the guarded hot plate. Considering the measurements noise in both experimental platforms and the complexity of the factors which influence the performance of this type of materials, in order to investigate their detailed heat transfer characteristics and their real insulating efficiency, a transient, combined conduction, radiation and convection heat transfer numerical model was developed. The model takes into account the coupling between the solid conduction of the fibre system and the gaseous conduction of the gas in the pore space and is based on a two-flux approximation for the radiation, while the heat transfer finite difference equation is derived via the control volume formulation.

Λέξεις Κλειδιά: Βιοκλιματικός Σχεδιασμός, Μόνωση, Μεταφορά Θερμότητας, Κτήρια Χαμηλής Ενεργειακής Κατανάλωσης
Keywords: Bioclimatic Design, Green Buildings, Insulation, Heat Transfer, Renewable Energy

Subject Area: Environment – Natural Disasters

1. Introduction

In 2002, buildings used approximately 68 percent of the total energy consumed in the United States with 51% for residential use and 49% for commercial use. Also, 38% of the total amount of carbon dioxide in the United States and Europe can be attributed to buildings. It is true that globally since the beginning of the Industrial Revolution, the concentrations of most of the greenhouse gases have increased. For example, the concentration of carbon dioxide has increased by about 36% (from 280 to 380 ppmv), or 100 ppmv over modern pre-industrial levels. The first 50 ppmv increase took place in about 200 years, from the start of the Industrial Revolution to around 1973; however the next 50 ppmv increase took place in about 33 years, from 1973 to 2006 according to the Carbon Dioxide Information Analysis Center (2006) of the U.S. Department of Energy (DOE) which includes the World Data Center for Atmospheric Trace Gases.

Considering these statistics, reducing the amount of natural resources buildings consume and the amount of pollution given off is seen as crucial for future sustainability, according to the United States Environmental Protection Agency (EPA). In France after the petrol crisis of 1973, different thermal regulations have been established (1974, 1982, 1988, 2000, and 2005) in order to reduce at 75% the energy consumption of building applications and the greenhouse gases attributed to building applications in the time period between 1974 and 2020.

That's why first of all the concept guiding building design in any climate is the creation of an envelope, sealed as far as possible against the passage of energy. In this envelope there should be openings, allowing desirable (but controlled, both in time and in quantity) passage of natural energy from the building application outwards and vice versa. The construction should be massive with a relatively high thermal capacity. The first truth that should be refuted regarding building design is that the directional orientation of the building is the key to achieve thermal comfort. Any building being built according to a bioclimatic concept is largely insensitive to its orientation. But if the envelope is really well insulated and has a significant thermal capacity, there is not much difference in the thermal performance of a building facing south compared to buildings facing to other directions, because the envelope is, practically speaking, almost sealed to the passage of energy. Thus the popular opinion that the bio-climatic house must have a long southern exposure is not necessarily correct because a long south-facing elevation is needed only for positioning the south-facing windows and it should be large enough to enable just that.

Sealing the envelope against uncontrolled passage of energy should reduce to a minimum the possible overheating of the house in the summer and its cooling in the winter. In order to manage the energy economy of the house, no energy should be allowed to pass through the walls, as far as it is technically and economically possible. The building's significant thermal capacity should contribute to stabilizing the large daily temperature fluctuations and also should increase the building's thermal lag time, which is the time that passes, for instance, between the peak external temperature and the peak internal temperature. That's why in buildings an important factor is to achieve thermal comfort for its occupants and this is how the thermal insulation can work in order to minimize the thermal consumption of building applications.

2. Multi-foil Insulations and previous research

Multi-foil fibrous insulations are composed by layers of metallised polyester film; high strength polyester coated foils spaced with polyester wadding and closed cell foams. The low emissivity surfaces seem to be very effective in reducing radiant heat transfer. In fact the metallised foils can reduce the radiant heat transfer which is the primary mode of heat transfer in building applications. The research of Matthews, Viscanta, Incropera (1985) showed that radiation is an important mode of heat transfer, even when the opacity of a material is large. Also their calculations showed that radiation is the dominant mode of heat transfer in the front third of the material and comparable to conduction towards the back of the material. So knowing that the low emissivity surfaces of multifoil insulations seem to be very effective in reducing radiant heat transfer working as radiant barriers, it is believed that the use of multifoil insulations can reduce a lot the energy consumption of building applications because of the fact that radiant barriers inhibit heat transfer by thermal radiation. But as we commonly know thermal energy may also be transferred via conduction or convection, however, radiant barriers do not necessarily protect against heat transfer via conduction or convection.

The simulations of Reagan and Acklam (1979), Griggs and Shipp (1988) and Anderson (1989) show that a reflective surface or colour can cut cooling and heating loads by 10% to 60% in building applications. Also, the research of Daryabeigi (2001, 2002) for the NASA Langley Research Center showed that the use of 2 mm foil spacing and locating the foils near the hot boundary with the top foil 2 mm away from the hot boundary resulted in the most effective insulation design for space applications. In fact, in 1954, NASA invented a lightweight, reflective material composed of a plastic substrate with a vapor-deposited coating of aluminum.

The material, now commonly known as a "*space blanket*", is used to protect spacecraft, equipment, and astronauts from thermal radiation or to retain heat in the extreme temperature fluctuations of space. That's why during the decade of 1990 the worldwide industrialisation and commercialisation of multi-foil insulation was exploded. But, in the vacuum of space, heat transfer is only by radiation, so a radiant barrier is much more effective than it is on earth, where heat transfer can still occur via convection and conduction, even when an effective radiant barrier is deployed.

So in order to investigate the real performances of multi-foil insulations in building applications the combined conduction/radiation heat transfer phenomena were investigated experimentally by using the two kinds of techniques generally used by certified laboratories to measure thermal values (the guarded hot box and the guarded hot plate) and numerically by developing a transient, combined conduction, radiation and convection heat transfer numerical model.

3. Methodology

In order to obtain experimental data about the performances of multi-foil insulations, we realised multiple measurements using both the guarded hot box and the guarded hot plates of the Building Sciences Laboratory in ENTPE of Lyon.

The experimental phase started using the "guarded hot plates" test method (*Figure 1*) which is a *primary* measuring instrument that does not need to be calibrated with a known reference material and it is used to measure the thermal performance of insulations and other materials of high thermal resistance. Our guarded hot plate instrument is designed in accordance with ASTM C177 and ISO 8302 specifications and can be used to test materials from -170°C to 550°C, in various range increments, depending on the model.

Also, measurements of wall systems are typically carried out by apparatus such as the one described in ASTM C 236, Standard Test Method for "*Steady-State Thermal Transmission Properties of Building Assemblies by Means of a Guarded Hot Box*" [ASTM C-236]. At the Building Sciences Laboratory in ENTPE of Lyon different wall samples including multi-foil insulations were built and tested in a calibrated guarded hot-box (*Figure 1*) under steady state and dynamic conditions.

The precision of dynamic testing is close to the precision of the steady-state test method, which is reported to be approximately 8% [ASTM, 1989]. The dynamic test results were used to calibrate the transient, combined conduction, radiation and convection heat transfer numerical model that served in the analytical part of this project. The realized dynamic test typically consisted of the following two basic stages:

- Stabilizing stage (sample was kept under a set of boundary temperatures until steady state heat transfer occurs).
- Steady-state stage (steady temperatures on both sides of the wall)

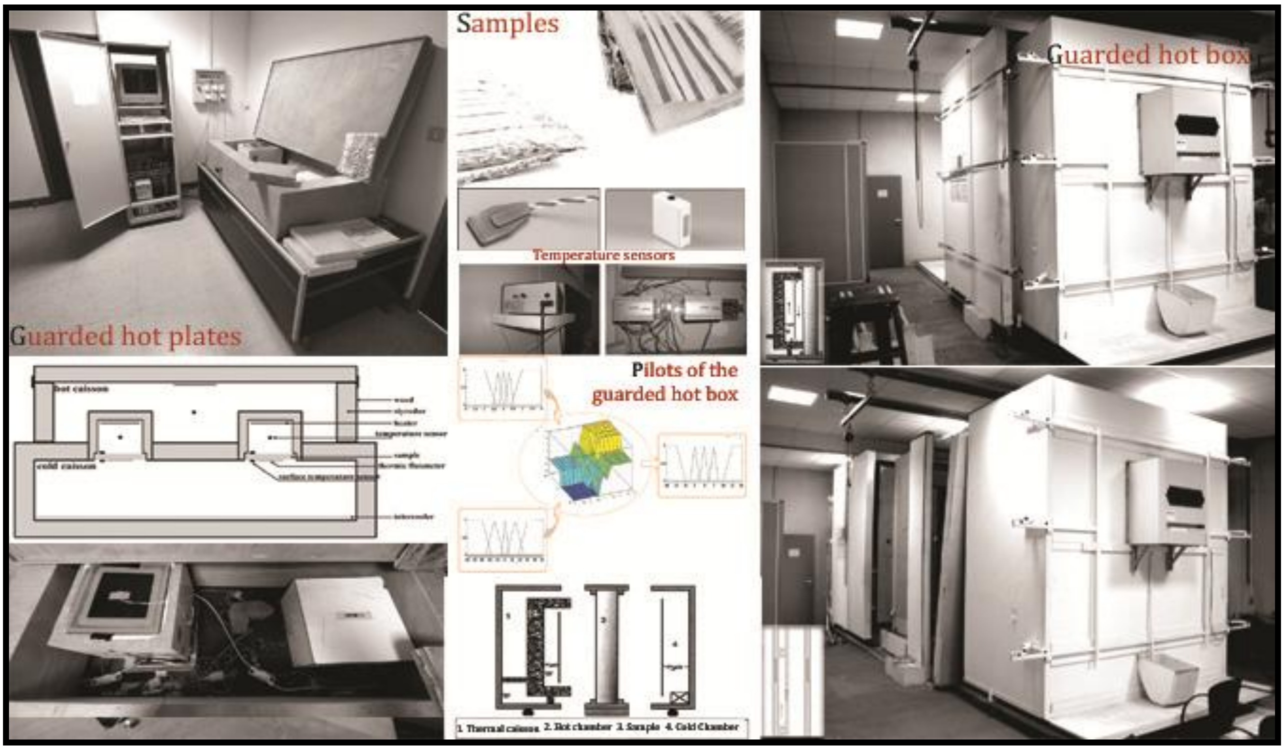

Figure 1: The experimental platforms which were used in order to measure the performances of multifoil insulations.

The multi-layer insulation sample that is studied in this research is consisted of seven reflective foils separated by layers of polyester fibrous insulation. The emissivity of each silver-coated foil is 0.2 for the exterior foils and 0.15 for the interior foils respectively. The six interior 1 mm thick insulation spacers were made by polyester with a volumetric specific heat of 39.586 kJ/(m^3K), while the two outer 2 mm thick fibrous spacers were made of polyester wadding with a volumetric specific heat of 45.821 kJ/(m^3K). On both sides of the multifoil product there were two 2 cm thick air gaps. The case of the insulating complex was built using 1 cm thick wood panel at each side.

The total thickness of the sample construction was 7.6 cm including the wood panels, the two air gaps and the multi-layer insulation sample. Both dynamic and steady-state tests were used in order to study the thermal behaviour of multi-layer insulations and to validate the numerical heat transfer model.

When the preliminary series of measurement were taken, the creation of a numerical model was necessary, in order to investigate the detailed heat transfer characteristics and the real insulating efficiency of multifoil insulations.

4. Transient, combined conduction, radiation and convection heat transfer numerical model

The governing conservation of energy equation (Ozisik, 1973) of the problem of combined conduction and radiation heat transfer through fibrous insulation bounded by two solid surfaces at specified temperatures is transformed (Ning Du et. al, 2007; Daryabeigi K., 2002) using the two flux approximation (Milne – Eddington approximation) into:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{\partial q_r}{\partial x} \overset{q_r=\left(F^+-F^-\right)}{\Rightarrow} \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{\partial\left(F^+-F^-\right)}{\partial x} \qquad \textbf{(1)}$$

where, T the temperature, t the time, x the spatial coordinate through the insulation thickness, ρ the density, c_p the specific heat, k the thermal conductivity, F^+ and F^- the incident radiation travelling forward and backward respectively and $q_r = F^+ - F^-$ the total radiant heat flux.

Because of the nature of the problem, the morphology of the physical domain and the experimental data, the initial and boundary conditions are the following, according to Georgantopoulou and Tsangaris (2007):

$$T\,(x, 0) = T_0(x) \qquad \textbf{(2)}$$

$$T\,(0_-,t) = T_1(t) \qquad \textbf{(3)}$$

$$T\,(L_+,t) = T_2\,(t) \qquad \textbf{(4)}$$

At the equations above with L is denoted the thickness of the insulation complex, $T_1(t)$ is the temperature variations at the warm side of the hot box close to the warm boundary of the insulation (this means the 0_) and $T_2(t)$ is the temperature variations at the cold side of the hot box close to the cold boundary of the insulation (this means the L_+). The silver coated foils are working like radiant barriers and that's why they impose boundary conditions for the radiation scheme in the inner part of the multifoil product. Figure 2 shows a sketch of the multilayered system, consisting of N sections (Radiation blocks) each one formed by the insulating material and the two reflected foils as boundaries, while again each section is subdivided in thin layers (finite volumes). Assuming that the bounding silver coated surfaces are diffuse emitting/reflecting surfaces, appropriate boundary conditions for the forward and backward radiant fluxes are obtained from radiant balances at the front (x=0) and back (x=l) faces of each section and are given by:

$$F^+(0) = e_1\sigma T_1^4 + (1-e_1)F^-(0) \qquad \textbf{(5)}$$

$$F^-(l) = e_2\sigma T_2^4(l) + (1-e_2)F^+(l) \qquad \textbf{(6)}$$

where, e is emissivity, l is the length of each section and the subscripts 1, 2 refer to the bounding surfaces at x =0 and x=l.

In order to calculate the temporal distribution of temperature on the domain, Eq. (1) was numerically solved using a finite volume technique (Patankar 1980) and, by superposing the radiant heat transfer flux, the discredited form yielded:

$$T_j^{n+1} = \frac{k_{B_j}}{(\delta x)_{j+1}}\frac{\Delta t}{\rho_j c_j \Delta x_j}T_{j+1}^n + \frac{k_{B_{j-1}}}{(\delta x)_j}\frac{\Delta t}{\rho_j c_j \Delta x_j}T_{j-1}^n + \left[1-\left(\frac{k_{B_j}}{(\delta x)_{j+1}} + \frac{k_{B_{j-1}}}{(\delta x)_j}\right)\frac{\Delta t}{\rho_j c_j \Delta x_j}\right]T_j^n + \\ +\left[\left(F^+-F^-\right)_{j-1} - \left(F^+-F^-\right)_j\right]\frac{\Delta t}{\rho_j c_j \Delta x_j} \qquad \textbf{(7)}$$

At the above equation the distances between the grid points are denoted with δx, T is the temperature, ρ is the density, c is the specific heat, Δx denote the distances between interfaces of finite volumes, Δt is the time step and K_B is the thermal conductivity at the boundaries of each finite volume. The subscript j represents the corresponding values at the jth grid point (the center of the jth control volume), while the superscript n represents the current time step.

The foils were treated as lumped masses in the solution process. Uniform nodal spacing was used in each fibrous layer region bounded by either two foils or a foil and a solid bounding surface, while it could vary between different layers (in this study δx=0.5 mm or 1.0 mm), which depends from the nature and geometry of the insulation layers. Finally, the time step was 0.5 sec, which satisfies the stability criterion for the explicit schemes:

$$\Delta t < \frac{\rho c(\Delta x)^2}{2k}$$

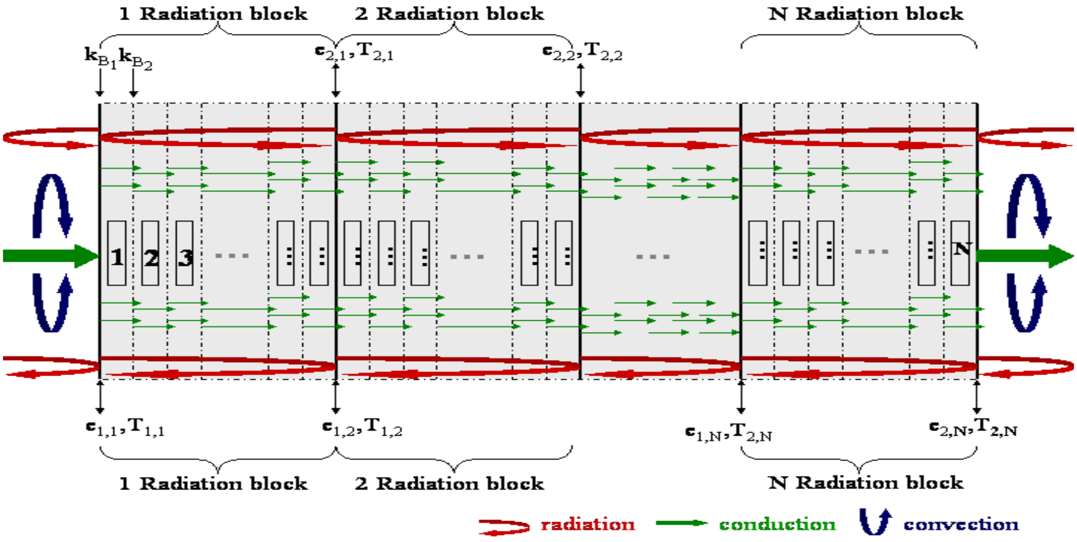

Figure 2: Separation of the multifoil insulation in N-radiation sections.

5. Results and Model evaluation

In order to simulate the transient and steady-state thermal test a linearly varying initial temperature distribution was assumed throughout the insulation thickness between the measured warm and cold side temperatures of the insulation complex (Eq. 2), while since the experimental data from the guarded hot box were applied as model inputs (Eqs. 3 and 4), constant temperature boundary conditions were used by specifying data from the steady-state conductivity apparatus and temporally varying boundary conditions were used by specifying data from the transient heat transfer apparatus.

Before the utilisation of temperatures of cold side as boundary conditions, they were smoothed statistically using the Spencer's 21-term moving average. The solution of the transient conservation of energy equation was marched in time for 10 days, which was the duration of the experiment; even if it could stop till a steady state condition was achieved. Data are plotted versus elapsed time from the initiation of the simulation.

The evaluation of the numerical model was based on the point-to-point comparison between model-generated values of temperature and experimental data. In Figures 3 to 4 is shown the comparison of predicted and measured temperatures for the multi-layer sample including two wood panels and two air gaps, at nominal temperatures between 25° C and 4°C. The agreement between predictions and measurements at apparent temperature differences in building applications presented a residual average of 0.00353 for the cold boundary of the insulation complex and 0.00234 for the warm one.

The maximum difference between the measured and numerically predicted temperatures was 0.57 ^{o}C (maximum relative difference of 2.56%) and 0.2 ^{o}C (maximum relative difference of 3.7%) for the warm and cold edge of the insulation complex respectively. In order to reduce temperature residuals, a temperature correction procedure was developed in the context of bias adjustment approach (Wilks, 1995).

To this end, standard mean error in the form of BIAS score (Papadopoulos and Katsafados, 2009) was estimated, reducing the average residual outputs to 0.00319 and 0.00114 for the cold and the warm boundary of the insulation sample respectively. The good agreement between the predicted and measured data indicates that the formulations used in the study have produced satisfactory results.

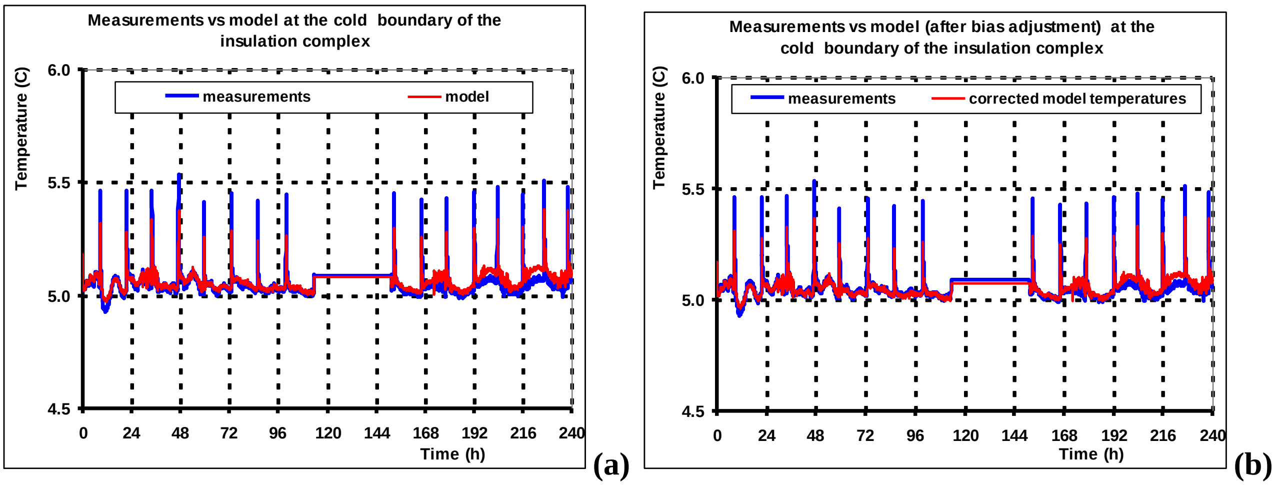

Figure 3: Comparison of predicted and measured temperature in the cold boundary of the multi-layer insulation complex: a) before bias adjustment, and b) after bias adjustment

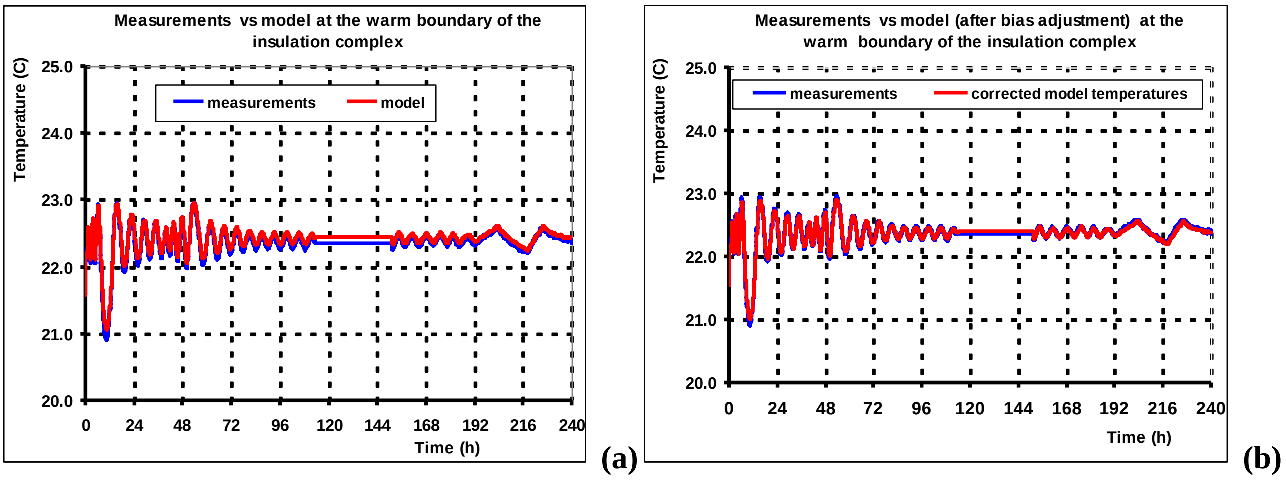

Figure 4: Comparison of predicted and measured temperature in the hot boundary of multi-layer insulation complex: a) before bias adjustment, and b) after bias adjustment

The close agreement between measured and simulated temperatures validated the numerical model for predicting the transient thermal performance of multifoil insulating complexes subject to conditions similar to building applications. A first parametric approach was used to determine the optimum insulating performances of multi-foil insulations. It was found, as seen in Figure 5, that the influence of the cold boundary starts at the 37th grid point which is placed in the cold air gap. All the other grid points which are located in the inner part of the multi-foil insulation or in the hot air gap hold their dependence from the hot boundary.

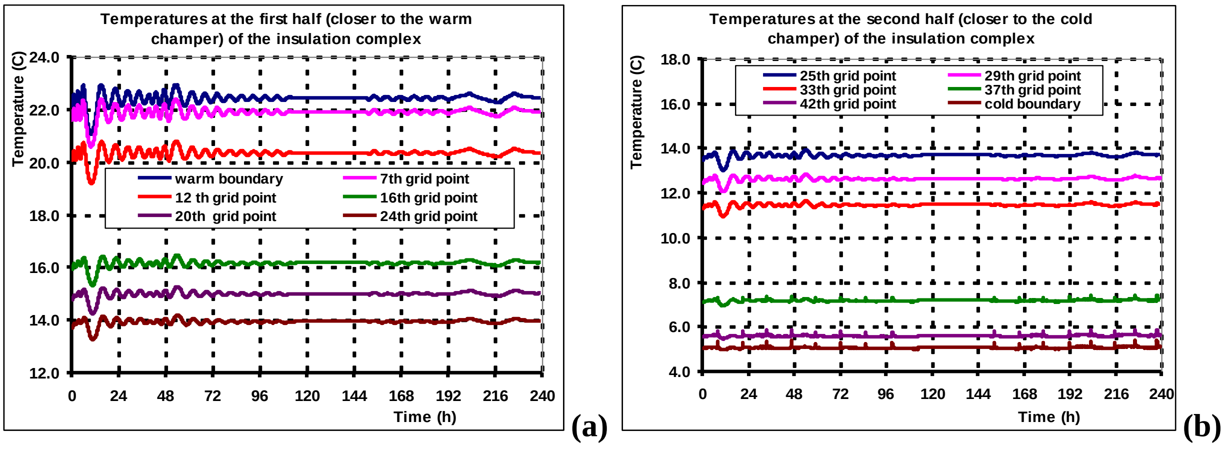

Figure 5: Time variation of predicted temperatures a) at the first half of the multi-foil insulating complex, and b) at the second half of the complex.

6. Concluding remarks and perspectives

In order to investigate the performances of multi-foil insulations, multiple measurements were realised using both the guarded hot box and the guarded hot plates of Building Sciences Laboratory in ENTPE of Lyon. The experimental phase started using the "guarded hot plates" test method and continued in a calibrated guarded hot-box where different wall samples including multi-foil insulations were built and tested under steady state and dynamic conditions.

After finishing a series of measurements, a numerical model was developed for modeling combined radiation/conduction heat transfer in high – porosity fibrous insulation. The radiation heat transfer was modeled using the two flux approximation. The accuracy of the model was validated in a first phase by point-to-point comparison between model-generated values of temperature and experimental data. The results showed close agreement between measured and simulated temperatures validated the numerical model for predicting the transient thermal performance of multifoil insulating complexes subject to conditions similar to building applications.

Even though, considering the non-linear nature of this problem and because of the presence of multiple factors which influence the heat transfer intrinsic phenomena, it is necessary to continue the evaluation of the numerical model by realising multiple tests in the same experimental platforms varying the parameters which influence the efficiency of these materials. But at least, the use of reflective materials in building applications seems to be an attractive option to refining buildings insulation and reducing the energy consumption of the constructions.

7. Acknowledgements

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