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Development of polynomial regression models for composite dynamic envelopes' thermal performance forecasting

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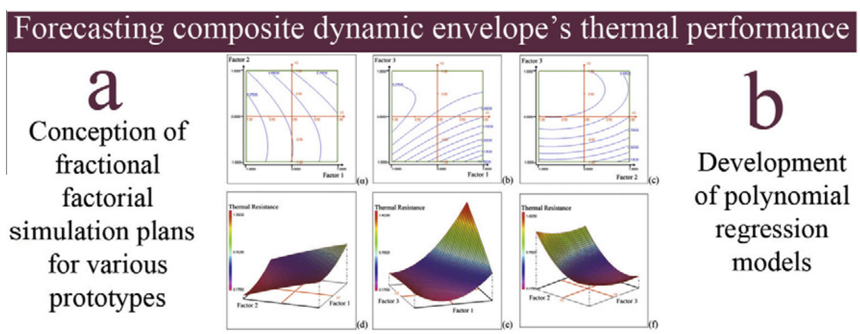
HIGHLIGHTS

- ▶ Original software for composite dynamic envelope's thermal performance forecasting.
- ▶ Construction of two hypothetical composite dynamic wall's prototypes.
- ▶ Different simulation scenarios based on fractional factorial simulation design.
- ▶ Development of polynomial regression models.
- ▶ Validation and evaluation of polynomial regression models.

GRAPHICAL ABSTRACT



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ABSTRACT

The building envelope's insulating efficiency is always a key element regarding the energy consumption control of the whole building. This article aims to propose a simple method based on classic and fractional factorial simulation plans to obtain regression models in the form of polynomial functions that link the angle, the thermal conductivity and the thickness of each envelope's component to the overall wall's thermal resistance. Original software that combines classic and novel modeling techniques has been used in order to have a precise and validated numerical investigation that focuses in a variety of possible composite dynamic wall's configurations. For the purposes of this study, the combined radiation/conduction heat transfer finite volume numerical model was updated complex enough to predict the temperature distribution and heat transfer in composite envelopes for a variety of inclination angles. The model takes into account the coupling between the solid conduction of both solid and fibrous systems and the gaseous conduction and radiation. The radiation heat transfer through each insulating layer has been modeled via the two flux approximation in order to take into account both optically thick and optically thin materials, as well as potential reflective surfaces currently used on composite wall's applications. Different simulation scenarios have been conceived according to basic fractional factorial simulation plans in order to obtain valid empirical polynomial functions. To validate this statistical forecast system, many simulation scenarios were carried out and the statistical results are in compliance with the numerical simulations. The regression models' results show that the error caused by simplification is acceptable in most conditions, and a lot of coupling calculation could be saved. Furthermore, the reduction of the complex numerical model to simple regression models in the form of polynomial equations aims to assist architects and engineers to directly obtain during the early design stages a high precision forecast of a composite envelope's thermal performance without mobilizing an expert's knowledge. Hence, having this knowledge they could optimize during the early design process the envelope's performance in order to finally achieve an integrated building design.

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Nomenclature

R	thermal resistance ($m^2\,K\,W^{-1}$)
S	surface of the composite wall (m^2)
T	temperature (K)
t	time (s)
ρc	volumetric heat capacity (J/(m^3 K))
k	thermal conductivity (W/(K m))
x	the spatial coordinate through the thickness of the composite wall (m)
q	thermal flux (W/m^2)
q_r	the total radiant flux in W/m^2 where $q_r = F^+ - F^-$
F^+, F^-	the incident radiant fluxes developing to the hot and the cold side of the material respectively (W/m^2)
l	length of each section (m)
f	solid fraction volume
R	radius of a fibrous material's fiber (m)
h_o, h_i	equivalent heat transfer coefficients including convection and radiation heat transfer on the boundaries (W/(K m^2))

Greek symbols

Δx	distances between the interfaces of the finite volume (m)
ΔT	temperature difference on composite wall's surface (K)
δx	distances between the grid points (m)
e	emissivity
β	absorption coefficient (m^{-1})
σ	Stefan–Boltzmann's constant
φ	inclination angle

1. Introduction, general context and objectives

With two-fifths of the final energy consumption and a quarter of the global CO_2 emissions, the building sector seems to be a priority target for energy saving actions. The building envelope's insulating efficiency is clearly a key component of this overall energy consumption control. Regarding the envelope's treatment of both new construction and existing buildings' rehabilitation activities the obtained thermal performance depends on the employed materials themselves, the principles of implementation that should respect the building's design, the high quality of the setting work, the eventual changes of the characteristics of material or product that could occur with the passing of time as well as their sensitivity to various physical or climatic parameters.

Insulation systems of today can already achieve the required insulation levels provided by the European and International normative standards only when they receive an adequate design and a careful implementation. It is noteworthy that even if there are always singular points such as thermal bridges, air parasites intakes or defects of implementation that may constitute a significant share of losses the envelope design and construction remains the most important factor that can influence on the energy consumption of the whole building.

Today, the building market is characterized by the existence of numerous different thermal insulation systems based on organic (wood wool, cork, straw, and technical hemp) and/or inorganic (foam glass, glass and mineral fibers) materials. The appearance of such insulating materials has led to the development of a specific research area. The main purpose of scientific research in this field is the analysis of the real performances of such insulating materials and different insulation systems [1–13]. On the other side, in the course of such a scientific and technological development, dynamic reflective insulation systems appeared. Such insulation systems work as a radiant barrier inside the building's envelope because they are intended to block the infrared radiant heat transfer and for this reason their resistance to heat flow depends on the heat flow direction. For this purpose they became the object of an international discourse regarding their insulating performances [2,14–20]. In addition, many methods were developed to estimate the thickness of the thermal insulation required to arrive at a desired heat flow or surface temperature for flat surfaces, ducts and pipes [21–24]. On the other side integrated building automation systems have become increasingly popular, and many research works focus on remote control technologies to enable real-time monitoring of the energy consumption by energy end-users, life cycle assessment of building's components as well as the application of renewable energy sources on buildings [25–32].

However, even if nowadays we have the potential and the knowledge to sufficiently study the contemporary insulating systems as a function of the envelopes' design, there are few studies that try to treat the envelope heat losses' physical problem in a holistic way. It is generally accepted that a major energy reduction of the envelope's heat losses can be achieved only if the envelope is correctly designed by engineers and architects. Towards this direction there is a need to develop digital tools to assist on decision making regarding the design of efficient insulating composite envelopes, by allowing the architects to explore large areas of formal solutions in the early phases of the design process in order to ensure a proper level of insulating performance.

The main objective of the research work presented here is concerned with the means to make informed decisions in energy consumption management of the building's envelope elements. The first part presents the modeling techniques to obtain the detailed composite walls' resistance profiles which are further used in an overall insulating performance evaluation analysis. For this purpose a validated-according to the experimental and theoretical framework sketched from the last international norms of standardization- and original combined conduction, convection, radiation numerical model that resulted from an intensive past study on dynamic insulating materials has been employed. The numerical model has been modified in order to be accurate with the needs of the study presented here.

The second part treats the issues related to a detailed screening analysis of the thermo-physical properties that influence on the thermal resistance of a composite wall, from the estimation to the impact factors. At this level it is described a new simple methodology developed to estimate the thermal resistance of a composite wall, using polynomial regression models obtained from a database of values that were calculated by dynamic simulations. The proposed prediction models show promising features to be easy and efficient prediction tools for comparing the thermal resistance of different composite walls configuration. The statistical models regarding the thermal resistance of a composite wall obtained in this study could be used by architects and engineers during the early design stage of their project, instead of using more complicated and time consuming simulation software, with the aim to arrive at forecast the insulating performance of the composite envelope and propose the most efficient solutions.

2. Materials and methods

Since new insulating products (such as multilayer thermal insulation) appeared on the market in recent years, the scientific debate on the thermal performance of a composite dynamic wall