Applied Thermal Engineering 84 (2015) 1–14

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Dynamic insulation of the building envelope: Numerical modeling under transient conditions and coupling with nocturnal free cooling

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HIGHLIGHTS

- Literature shows good energy performance of dynamic insulation in the cold season.
- Diversely, studies in transient conditions and for the warm season are poor.
- The study proposes a transient numerical model, tested and applied to the warm season.
- A feasibility analysis at three different latitudes has been performed.
- In our results, dynamic insulation improves nocturnal free-cooling potentials.

ARTICLE INFO

Article history:
Received 13 October 2014
Accepted 6 March 2015
Available online 1 April 2015

Keywords:
Thermal dynamic insulation
Porous media
Breathing walls
Free cooling
Numerical modeling
Transient conditions
MATLAB®

ABSTRACT

Dynamic insulation consists of building envelope components that are air-permeable. Presently, the scientific literature provides various studies on the achievable performance of this technology during the heating season and in steady-state conditions, showing energetic benefits due to the reduction of the walls' thermal transmittance.

Diversely, this paper investigates the behavior of dynamic insulation under transient conditions and is focused on the cooling season. In this study, a numerical model is proposed in order to evaluate the profiles of temperature and water vapor concentration, as well as the heat and vapor fluxes through air-permeable walls. This model is implemented in a home-made MATLAB® code, which adopts a finite difference method (FDM), and validated by comparison with: I) a simple case study from an authoritative literature reference; II) a CFD model run in COMSOL®, which adopts a finite element method (FEM). Then, the code is used to explore the benefits induced by dynamic insulation on nocturnal free cooling.

For this purpose, nocturnal free cooling potential is investigated in two cases: a) under the hypothesis of dynamic building insulation (i.e., airflow crosses the walls) and b) under the hypothesis of static insulation (i.e., the envelope is not air-permeable). The study shows the advantages of air flowing through the walls. In particular, a reduction of the indoor temperature is verified. The analysis is performed for three geographical locations (Cairo, Naples and Munich), characterized by different climates, in order to assess how the achieved benefits vary depending on the latitude.

1. Introduction

A common building envelope is impermeable to airflow, since air infiltrations cause a reduction of energy performance, above all during the heating period. However, the building cannot be completely airtight, because Indoor Air Quality (IAQ) must be regarded in order to ensure occupant comfort: from this point of view, air infiltrations can contribute to reduce the accumulation of indoor pollutants, risk of vapor condensation, risk of sick building syndrome.

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http://dx.doi.org/10.1016/j.applthermaleng.2015.03.039
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The dynamic insulation technology derives from the attempt to combine these two conflicting requirements. Indeed, it consists of building envelope components that are porous and air-permeable. It is noted that, in some cases, air-permeable walls are denoted as “breathing walls”. Precisely, the expression “dynamic insulation” refers to the variation of the system thermal transmittance due to the air flowing, while “breathing wall” refers to the flow of pollutants and moisture through the wall, mainly under concentration gradients. Since this study is mainly focused on the first phenomenon, the expression “dynamic insulation” (or more in general, porous wall) is used, although also the flow of water vapor is investigated.

Dynamic insulation systems give the two following main benefits:

- the IAQ is ensured by setting an adequate airflow through the walls, instead of introducing fresh air into the building by means of ducted air distribution as in conventional HVAC (Heating, Ventilation and Air Conditioning) systems [1], and the envelope works also as a highly efficient particulate filter [2];
- the walls act as a heat exchanger, since the flowing air is heated or cooled according to the operating conditions, and this phenomenon improves the energy performance of the entire building system [3].

Dynamic insulation systems work in pro-flux if airflow and conduction heat flux are in the same direction. In the opposite case, the system is classified as working in contra-flux [4]. The contra-flux insulation is more widespread, because it induces an increase of the wall's thermal resistance compared to an impermeable wall, while a reduction of the thermal resistance occurs in the pro-flux configuration.

Therefore, dynamic insulation generates a “smart” thermal envelope, which plays a great role in matter of energy conservation in buildings. Thus, for both stability of the indoor microclimate and energy savings during the heating and cooling operations, as well as for guaranteeing a proper conservation of building structures, proper studies are necessary for accurately evaluating the performance of the envelope elements. In this regard, recently, the authors [5] investigated the capability of a numerical model, based on the state-space representation, aimed at evaluating the transient heat transfer through thermal bridges. The method has been then validated by experiments carried out by means of a large apparatus, based on the use of thin film heat flux sensors [6].

The current scientific literature proposes several analyses of the energy performance of dynamic insulation under steady-state conditions and with reference to the heating season. In particular, these studies consider an introduction of outdoor air into the indoor environment through porous walls. In this way, an indoor air exchange is ensured and an energy gain can be also achieved. Indeed, the fresh air is preheated and then a rate of the heat normally wasted through the building envelope is recovered: this implies a reduction of the walls' thermal transmittance, which can theoretically be reduced to zero [7]. However, since the air velocity cannot be too high, Dalehaug [8] estimated that dynamic insulation can actually decrease conduction heat losses until 50%. Therefore, dynamically insulated walls can reduce the building thermal load around 20% [9].

A turning point in the study of dynamic insulation has been given by Taylor et al. [10], which presented an analytical method aimed at assessing the profiles of temperature and water vapor concentration as well as the heat and vapor fluxes through a dynamically insulated wall in steady-state conditions. These authors showed that the wall's thermal transmittance varies depending on air velocity and envelope thermal resistance in static conditions. Later, the model has been enhanced by considering more complex boundary conditions [11]. Taylor and Imbabi [12] also proposed a case of building design by using dynamic insulation; by referring to a multi-story office block; they demonstrated that such technology implies a potential reduction of initial and running costs for air supply and filtering. Gan [13] showed, by means of CFD, that, beyond the energy savings, dynamically insulated rooms could provide better thermal comfort if the system is carefully designed; nevertheless, problem of local discomfort can occur when the interior surface temperature is quite below the room air temperature. With reference to a real case study (i.e., a proper test-cell), Dimoudi et al. [14] explored the performance of the coupling between dynamic insulation and a ventilated façade, by showing the benefits of a flexible system that can operate both in pro-flux and contra-flux, depending on ambient conditions. An interesting application of dynamically insulated walls was also presented by Wong et al. [15], with reference to permeable concrete constructions; the authors investigated the thermal performance of APC (Air Permeable Concrete), by improving an analytical model, then validated by means of experiments with a hot wire method apparatus. A one-dimensional model for simulating porous materials, in order to improve the quality of energy calculations for buildings, has been proposed also by Steeman et al. [16], who focused on the buffering phenomenon induced by all hygroscopic materials that can be found in the building. On the other hand, dos Santos and Mendes [17] developed a two-dimensional model in order to predict how much the combined effect of heat and mass transfer affect the energy performance of a building, intended as both energy demand and achievable indoor comfort. Furthermore, the dynamic thermal insulation has been investigated also for other applications, lying outside of the building sector. For instance, Tinti et al. [18] evaluated, by experiments, the potentialities of polyurethane foams with micro-encapsulated phase change materials, designed in order to improve the transport of food in refrigerated vehicles; in their study, the dynamic insulating effect is based on the variation of conductivity of the layer due to the phase change and not to the air permeability.

The main original aspect of this paper concerns the analysis of dynamic insulation in transient conditions. A dedicated FDM (finite difference method) model is developed in order to evaluate the profiles of temperature and water vapor concentration as well as the heat and vapor fluxes through a porous (dynamically insulated) wall, in a dynamic regime. The aim is to ensure a higher accuracy in heat and mass transfer modeling through a permeable building envelope. The model – implemented in a home-made MATLAB® [19] code – is validated through the comparison with both the model of Taylor et al. [10] and a FEM (finite element method) model run in COMSOL®. The code is used to investigate the coupling of dynamic insulation with nocturnal free cooling. In fact, scientific literature is meager of studies concerning the behavior of this technology during the cooling season, although high thermal insulation levels can induce overheating risk, especially in presence of high internal and solar gains [20]. This problem can be overcome by using thermal inertia in an efficient way [21], by an adequate ventilation [22] or by a smart operation of dynamic insulation systems. In this regard, Elsarrag and Alhorr [23] showed that the adoption of dynamic insulation reduces the cooling demand of a Passive-House in the Gulf Region, and Imbabi [24] proposed a new Void Space Dynamic Insulation (VSDI) that eliminates the over-heating risk during extreme summer months; however, these studies assume steady-state conditions in the analysis of heat and mass transfer though dynamically insulated walls, while the proposed method uses an original dynamic approach. More in general, the effects of a porous building component (roof), on energy demand and thermal comfort during