Impact of Transient Effect on Thermal Performance of Dynamic Insulated Wall

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ABSTRACT

This paper presents an analysis of the transient thermal performance of dynamic insulation. A model based on heat transfer through porous media is introduced, considering two types of boundary conditions: (1) indoor temperature and outdoor temperature are constant; (2) indoor temperature is constant while outdoor temperature changes. By solving the model numerically, it is found that for the first kind of boundary condition, the temperature profile in the wall will reach steady-state within one hour, when the porosity is high. It will take a longer time for this purpose if the porosity decreases. For the second kind of boundary condition, the results illustrate that the interior surface temperature of the dynamic insulation swings with the change of the environment temperature. Influenced by the transient effect, the interior surface temperature of the dynamic insulation is different with that under the steady-state. However, by comparing the heat loss obtained under the transient and steady-state condition, it is noticed that the difference is not significant. This means that heat transfer coefficients derived from steady-state analysis, such as dynamic *U*-value, are good approximations concerning the energy consumption of buildings with dynamic insulation, and are convenient tools for engineering implementation.

KEYWORDS

Building envelope, dynamic insulation, thermal performance, transient, analytical model

INTRODUCTION

Dynamic insulation intensively introduces an inward air flow through the building envelope. Due to the heat exchange within the envelope, the incoming fresh air can be pre-heated in the dynamic insulation. Therefore this technique is regarded as one possible method for reducing building envelope heat losses and achieving high indoor air quality.

Theoretical analysis has been performed to estimate the heat loss through a dynamic insulated wall. A steady-state one-dimensional model was presented by Taylor et al (1996). Based on the steady-state model, the dynamic-*U* value was derived, and it was regarded as a character of the thermal performance of dynamic insulation (Baker, 2003). The influence of convective heat transfer coefficient, which was neglected in the derivation of dynamic-*U* value, was discussed by Taylor and Imbabi (1997). The results showed that in the assessment of heat loss through dynamic insulation over the steady-state condition, the influence of both interior and exterior surface air films can be neglected. Considering the transmission and ventilation loss, the dynamic wall efficiency was defined by Morrison et al (1992) to represent the energy saving extent of dynamic insulation. Concerning the influence of transient effect, variation of heat load through a dynamic insulated wall was obtained by the Krarti (1994). However, the influence of the material property, such as porosity, was not included.

This paper presents a detailed numerical simulation for the thermal performance of dynamic insulation, under both steady-state and transient conditions, to investigate the impact of transient effect, taking into account the influence of the material property. Based on the analysis of the numerical results, a suitable tool of estimation of heat loss of dynamic insulation the engineering implementation is also presented and discussed.

NUMERICAL MODEL AND SIMULATION

Affected by the specific design of dynamic insulation, air flow and heat transfer in the dynamic insulation is nearly one-dimensional (Dimoudi et al, 2004). Therefore heat transfer process in the dynamic can be modeled as follows:

$$(\varepsilon\rho_a C_{pa} + (1-\varepsilon)\rho_s C_{ps})\frac{dT}{dt} + u\rho_a C_{pa}\frac{dT}{dx} = k_{eff}\frac{d^2T}{dx^2} \qquad (1)$$

Where T is temperature, ε is the porosity of the porous material, ρ_a and C_{pa} are the density and specific heat of the air, ρ_s and C_{ps} are the density and specific heat of the solid matrix, u is the velocity of the air flow, and k_{eff} is the effective thermal conductivity of the porous media.

Thermal performance of the dynamic insulation can be assessed based on the solution of this equation. To make the solution process and parameter study easier, the following non-dimensional form of equation is used:

$$\sigma\frac{d\theta}{d\tau} + \frac{d\theta}{dX} = \frac{1}{Pe}\frac{d^2\theta}{dX^2} \qquad (2)$$

where $\sigma = [(1-\varepsilon)(\rho C_p)_s + \varepsilon(\rho C_p)_a]/(\rho C_p)_a$ $\quad \theta = \frac{T - T_o}{T_i - T_o}$ $\quad X = \frac{x}{L}$ $\quad \tau = \frac{tu}{L}$

T_i is the indoor temperature, T_o is the outdoor temperature, L is the thickness of the dynamic insulation, $Pe = \frac{u\rho_a C_{pa} L}{k_{eff}}$ is the Peclect number.

Eqn.2 is solved by a numerical approach using finite difference method. A fully implicit scheme is used so that large time step can be adopted to correspond with the hourly change environment temperature in building simulation. TDMA algorithm (Patankar, 1980) is adopted to solve the algebraic equations.

The simulation is first carried out under a steady-state condition, i.e., constant temperature boundary condition:

$$X = 0 \qquad \theta = 0$$
$$X = 1 \qquad \theta = 1$$

The simulation is also performed under varying ambient temperature, which follows a sinusoidal function as

$$T_o = T_m + A_m \cos \omega t$$

The mean temperature T_m is 5ºC and the amplitude A_m is 6ºC, and the frequency ω is set up using a time step of 30s. The indoor temperature is constant, as that in the steady-state condition. To include the influence of air film near the wall, the convective heat transfer boundary condition is adopted.

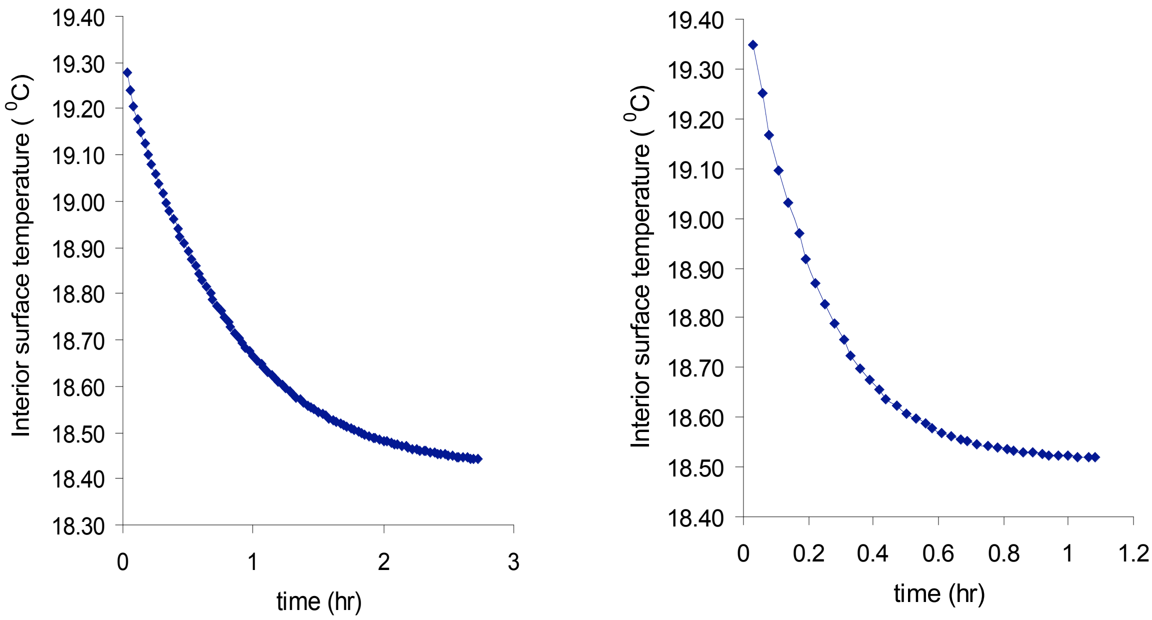
RESULTS AND DISCUSSION

The change of interior surface temperature with time under two porosity values is illustrated in Figure 1. The air velocity is 0.0005m/s, which is corresponds with ACH 0.4 for a 4.5m^2 by 2.5m high single room (Qiu and Haghighat, 2006). We can see under high porosity condition (ε=0.9), the temperature profile will reach the steady-state almost within one hour. Under medium porosity condition (ε=0.5), it will take more than one hour for the temperature profile to reach the steady-state. However, the absolute variation of temperature is not significant.

The change of interior surface temperature within one day is illustrated in Figure 2. It can be seen under the same indoor temperature as that in the steady-state condition, the interior surface temperature is not the same. It is also shown the influence of porosity can be neglected. As a matter of fact, by comparing the results under different flow rates, it is noticed that the extent of variation of the interior surface temperature is mainly influenced by the air flow rate.

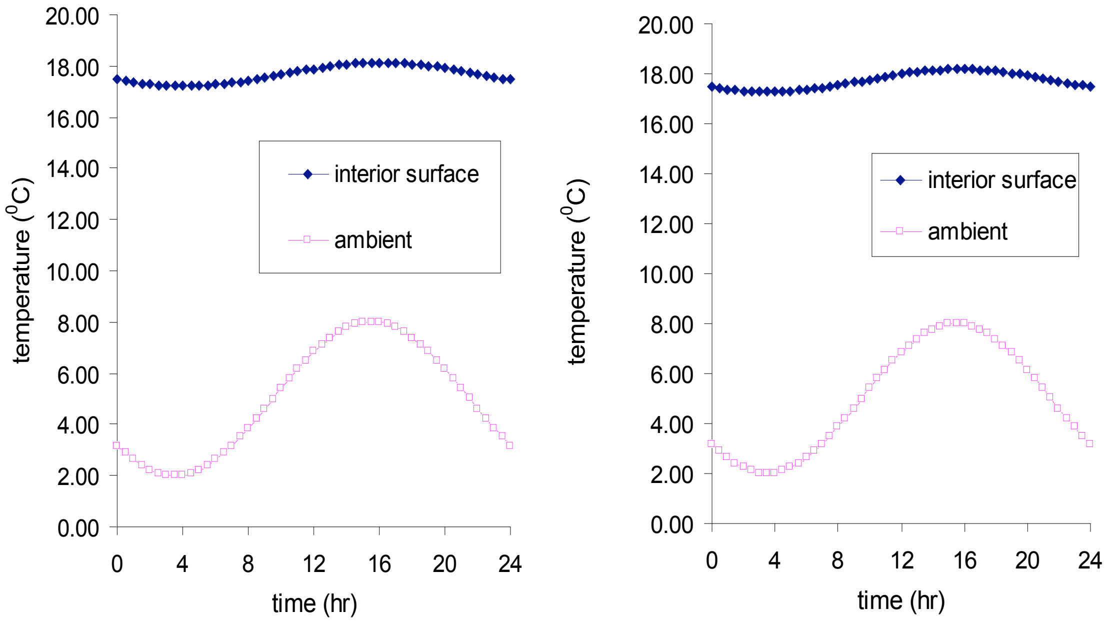
Figure 3 shows the heat flux obtained under the steady-state and transient boundary conditions, for the two porosity values. It can be seen that in each case, there is no significant difference between the results obtained by the steady-state and transient boundary conditions.

By analysis the variation of parameters in Eqn.2, it is easy to find that the heat capacity ratio σ will influence the time for the temperature to reach the steady-state. Thus the density and heat capacity of the solid matrix will affect the transient thermal performance of the dynamic insulation. Parametric study has been performed concerning the influence of this factor. As we concern more about influence of the property of the material to the energy consumption, the total heat loss is calculated and illustrated in Figure 4. It can be found the difference increase, however, is very limited. Detailed analysis finds that even at the highest air velocity, the total heat flux obtained under two conditions is within 10% of the total heat flux. Therefore concerning the energy consumption, the unsteady item in the left side of Eqn.2 has little influence on the results, and can be neglected. The steady-state is a good approximation to the transient model. This is good as though the model of Eqn.2 is simple; it is not suitable for engineering implementation because of the numerical method needed in the solution process.



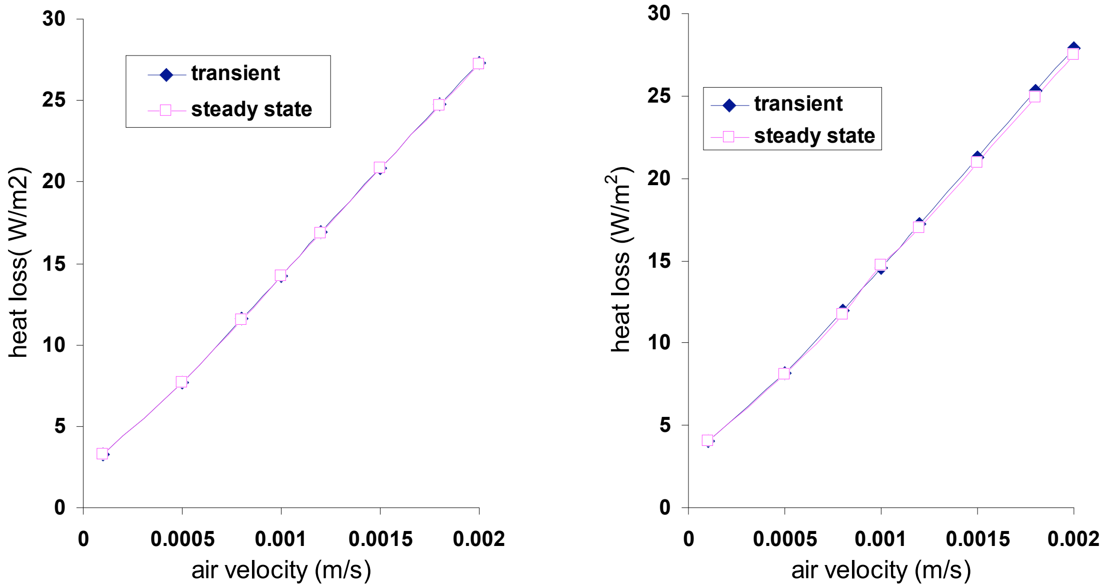
(a) ε=0.5 (b) ε=0.9

Figure 1: Change of interior surface temperature with time



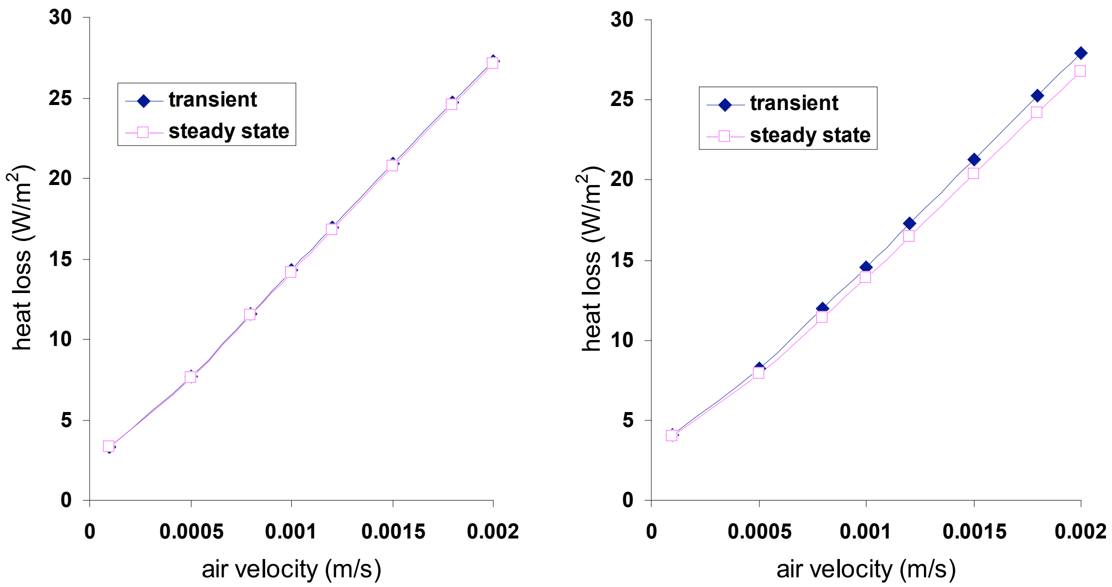
(a) ε=0.5 (b) ε=0.9

Figure 2: Change of interior surface temperature in one day



(a) ε=0.9, ρ_s=70kg/m^3, Cp_s=1000J/kg (b) ε=0.5, ρ_s=70kg/m^3, Cp_s=1000J/kg

Figure 3: Heat loss obtained under steady-state and transient condition



(a) ε=0.9, ρ_s=120kg/m^3, Cp_s=1500J/kg (b)ε=0.5, ρ_s=120kg/m^3, Cp_s=1500J/kg

Figure 4: Heat loss under different heat capacity condition

Under the steady-state condition, an analytical solution can be obtained. By deriving the heat flux in the exterior surface of the dynamic insulation, the following dynamic *U*-value expression can be obtained to represent the conductive heat loss:

$$U_{dyn} = \frac{Pe}{R(e^{Pe} - 1)} \tag{3}$$

where $R = \frac{L}{k_{eff}}$ is the effective thermal resistance of insulation material in the static condition.

The expression in this equation is different from the generally adopted equation in the literature (Taylor and Imbabi, 1998), which is actually the non-dimensional ratio compared with the steady-state *U*-value.

Using the dynamic-*U* value to calculate the conductive heat loss, and including the ventilation loss, if the incoming air temperature equals to the outdoor temperature, the total heat loss through a dynamic insulated wall can be conveniently estimated as

$$Q = Q_{cond} + Q_{vent} = U_{dyn} A\Delta T + \dot{m} C_p \Delta T = U_{dyn} A\Delta T + \rho_a u A C_{pa} \Delta T \qquad (4)$$

where A is the area of dynamic insulation, and ΔT is the indoor-outdoor temperature difference.

CONCLUSION

With the variation of outdoor environment temperature, the transient effect has an impact on the thermal performance of the dynamic, and its influence is affected by the property of the wall material.

Under the condition of high porosity, the impact of transient effect can be neglected. The influence of transient effect will increase with the decrease of porosity, and the increase of the density and heat capacity of the insulation material. However, concerning the energy consumption, the difference of results obtained under the steady-state and transient boundary conditions are within 10%, in the range of the material property values in the current simulation.

Therefore the steady-state analysis is a good approximation for the engineering implementation of dynamic insulation. By using the proposed dynamic-*U* value, the heat loss through the dynamic insulation can be conveniently estimated.

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