International Journal of Heat and Mass Transfer 90 (2015) 246–253

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Synergic relationships between thermophysical properties of wall materials in energy-saving building design

Haie Huo [a], Chengjun Jing [a,*], Kai Li [b], Haibo Huo [c]

[a] College of Architecture and Environment, Sichuan University, Chengdu 610065, China
[b] National Microgravity Laboratory, IMCAS, Beijing 100190, China
[c] Ocean Engineering Research Institute, Shanghai Ocean University, Shanghai 201306, China

ARTICLE INFO

*Article history:*
Received 27 October 2014
Received in revised form 1 June 2015
Accepted 10 June 2015
Available online 4 July 2015

*Keywords:*
Synergic relationship
Inverse problem
Thermophysical properties
Numerical calculation
Improved genetic algorithm (IGA)

ABSTRACT

Synergy design is a novel concept in designing energy-saving buildings. Its main objective is to optimize building material combinations, energy-saving technologies and other relevant properties, ensuring that the energy consumption of the building meets the energy-saving demand. This constitutes an inverse problem, which cannot be solved by conventional methods. Therefore, using a new model that combines numerical calculations with an improved genetic algorithm, we elucidate the synergic relationships between thermophysical properties of wall materials. The investigation is conducted on a south-facing wall under the extreme climatic conditions of Chengdu, China. The results confirmed the existence of these synergic relationships. In particular, the thermal conductivity is a linearly increasing function of insulation thickness; however, if the thermal conductivities of two materials of fixed thickness are simultaneously optimized, increasing one conductivity nonlinearly reduces the other conductivity. These two cases confirm the efficiency and reliability of the proposed model in solving inverse problems related to insulation technology. The identified synergic relationships are also very useful in engineering applications, because the designer can select the combination of thermophysical properties most suited to the energy-saving requirements and local market conditions.

## 1. Introduction

Increased energy consumption has created serious energy and environmental problems in China. Building energy consumption accounts for approximately 25–40% of China's total commercial energy consumption. In addition, buildings are responsible for approximately 18% of energy-related $CO_2$ emissions [1,2]. As the economy develops and environmental awareness becomes more widespread, energy-saving is becoming increasingly adopted in building design. Therefore, studies related to energy-efficient buildings are of great significance in China.

As an exterior building enclosure, the external wall plays a critical role in the energy consumption of the building. Studies on improving external wall performance and reducing its heat transfer can be grouped into three categories:

(1) Developing new types of external walls. Examples are Trombe walls [3–5] and double-skin shades [6–9].
(2) Constructing the external wall from materials having variable thermophysical properties; for example, phase-change materials [10–13].
(3) Optimizing combinations of external wall materials. For example, selecting materials with appropriate thicknesses and the correct assemblage order in the design.

This study focuses on the third category. As is well known in energy-saving building design, the same energy-saving rate is yielded by multiple combinations of different wall materials. Therefore, synergic relationships might exist between the thermophysical properties of the materials, which could be exploited in energy-saving building design and engineering applications. However, such relationships have not been thoroughly analyzed in the published literature. Many researchers have focused on the effect of material combinations on the thermal performance of walls [14–17], but these studies are limited to specific materials. Mahlia et al. [18] analyzed the correlation between thermal conductivity and the optimum insulation thickness of the building walls using conventional methods. They reported a nonlinear relationship between these two parameters, which satisfied a polynomial function. However, they investigated only six kinds of insulation materials, and their function was obtained by curve fitting alone.

---

* Corresponding author. Tel./fax: +86 28 85401015.
*E-mail address:* chengjunjing1@163.com (C. Jing).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.06.029
0017-9310/© 2015 Elsevier Ltd. All rights reserved.

**Nomenclature**

| | |
|---|---|
| $a$, $b$ | binary substring of an individual (representative of a parameter) |
| $c$ | specific heat (J/kg K) |
| $D$ | sum of cooling and heating days (days) |
| $ESR$ | load-saving rate of external wall (%) |
| $ESR_D$ | $ESR$ in the building energy-saving design (%) |
| $ESR_G$ | $ESR$ specified in relevant standards or norms (%) |
| $h_i$ | heat transfer coefficient at the indoor wall surface (W/m$^2$ $K$) |
| $ho$ | heat transfer coefficient at the outdoor wall surface (W/m$^2$ K) |
| $I_T$ | total solar radiation (W/m$^2$) |
| $k$ | thermal conductivity (W/m K) |
| $q_i$ | heat flux at indoor wall surface (W/m$^2$) |
| $Q$ | total yearly transmission load (MJ/m$^2$) |
| $Q_B$ | total yearly transmission load of the standard external wall (MJ/m$^2$) |
| $Q_E$ | total yearly transmission load of the energy-saving external wall (MJ/m$^2$) |
| $Q_i$ | daily cooling or heating transmission load (MJ/m$^2$) |
| $r$ | uncorrelated exponent |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $T_e$ | sol–air temperature (°C) |
| $T_i$ | indoor air temperature (°C) |
| $T_o$ | outdoor air temperature (°C) |
| $x$ | space coordinate (m) or vector |
| $x_i$ | the $i$th gene (binary coding bit) of individual $X$ |
| $y$ | vector |
| $y_i$ | the $i$th gene (binary coding bit) of individual $Y$ |
| $X$, $Y$ | individuals in the population |

*Greek letters*

| | |
|---|---|
| $\alpha$ | solar absorptivity of outdoor wall surface |
| $\rho$ | density (kg/m$^3$) |
| $\delta$ | insulation thickness (m) |

Exploring the synergic relationships between the thermophysical properties of the external wall materials subject to certain constraints (in our case, the specified saving percentages of the total yearly transmission load of the external wall) constitutes an inverse problem. The conventional approach solves the saving rate, given the combinations and thermophysical properties of the wall materials. In contrast, the inverse problem seeks the combination and thermophysical properties of the wall materials that satisfy the specified saving rate. To this end, we adopt a variant of an iterative stochastic search method called the genetic algorithm (GA). GA is widely used for solving uncertainty problems and is a powerful mathematical tool for solving nonlinear inversion problems [19–24]. Here, we develop an improved genetic algorithm (IGA) and combine it with numerical calculations.

## 2. Methods

### 2.1. Description of the problem

China aims to implement a 65% energy-saving rate for residential buildings in hot summer and cold winter zone. This type of climate is mainly found in the Yangtze River Basin, where the winter is damp and cold while the summer is damp and hot. Indeed, the climate conditions are more extreme in the Yangtze River Basin than at other same-latitude regions worldwide. The total energy per unit floor area consumed for cooling and heating is even higher in this zone than in the cold zones of China [25]. Therefore, ensuring that new buildings meet strict energy conservation standards is especially important in this zone. Therefore, it is important to explore the synergic relationships between the thermophysical properties of the wall materials, which engineers can then apply in practice. This study focuses on Chengdu as a representative city within the hot summer and cold winter zone. The total transmission load of a multilayered external wall is determined from both steady-state and transient heat transfer models.

### 2.2. Mathematical and numerical formulation

#### 2.2.1. Mathematical model

A composite wall comprising $M$ parallel layers of different thicknesses and physical properties is schematized in Fig. 1. The outside surface of the wall is exposed to solar radiation and the local environmental temperature. The inside surface is exposed to room air at the designed temperature.

The steady-state and transient one-dimensional heat conduction equations for a multilayer wall are given by

$$\text{steady state}: \quad k_j \frac{\partial^2 T_j}{\partial x^2} = 0 \quad j = 1, 2, \ldots, M \tag{1}$$

$$\text{transient}: \quad \rho_j c_j \frac{\partial T_j}{\partial t} = k_j \frac{\partial^2 T_j}{\partial x^2} \quad j = 1, 2, \ldots, M \tag{2}$$

where $x$ is the spatial coordinate, $t$ is the time, and $T_j$ is the temperature. The parameters, $\rho_j, c_j, k_j$ and $k_j$ are the density, specific heat and thermal conductivity of the $j$th layer, respectively.

The boundary conditions are

$$\text{outdoor}: \quad -k_1 \left(\frac{\partial T}{\partial x}\right)_{x=0} = h_o(T_e(t) - T_{x=0}) \tag{3}$$

$$\text{indoor}: \quad -k_M \left(\frac{\partial T}{\partial x}\right)_{x=L} = h_i(T_{x=L} - T_i) \tag{4}$$

where $h_o$ and $h_i$ are the combined heat transfer coefficients at the outdoor and indoor wall surfaces, respectively. $T_i$ is the indoor air

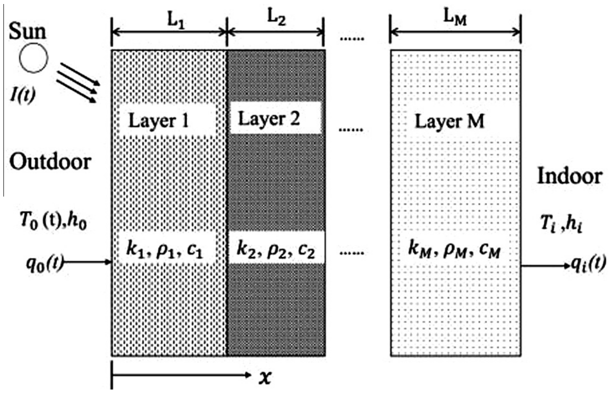

**Fig. 1.** Physical model of an M-layered composite wall.