Energy and Buildings 80 (2014) 598–612

Contents lists available at ScienceDirect

Energy and Buildings

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

Analytical optimization of the transient thermal performance of building wall by using thermal impedance based on thermal-electric analogy

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ARTICLE INFO

Article history:
Available online 18 June 2014

Keywords:
Transient thermal performance
Building envelope
Insulation material distribution
Heat transfer dissipation
Built environment

ABSTRACT

An effective analytical method for analyzing the transient thermal performance of building envelopes is very important to optimize their thermal performance design. However, the influence of thermal mass and insulation material distribution cannot be analyzed well by using the current steady state thermal resistance (i.e. *R* value) and thermal inertia index (i.e. *D* value). Moreover, the substitution effect between the thermal resistance *R* and the thermal capacitance *C* has not been theoretically studied before. A novel analytical approach based upon thermal impedance of evaluating the transient thermal performance of building envelopes is developed in this paper. By using that, the optimal material distribution (corresponding to the minimal space heating or cooling load due to building envelope heat loss or gain) can be analytically determined. In addition, the substitution relationship between *R* and *C* can be theoretically derived. The results show that putting concrete material in the middle and evenly distributing the insulating materials on the inside and outside surface can maximize the module of thermal impedance for given conditions. The proposed approach provides an effective way to theoretically optimize the transient thermal performance of building external wall.

1. Introduction

With the development of economy and increasing living standard, building energy consumption is growing rapidly in China. During 1980–2006, Chinese energy consumption increased by 5.6% annually, boosting the 9.8% annual economic growth [1]. Heating and air conditioning, accounts for 65% of the total building energy consumption. In 2011, the total building energy consumption (biomass energy is not included) is 687 million tce [2], which accounts for 19.7% of the total domestic energy consumption. This huge energy consumption not only consumes valuable fossil fuel resources, but also emits a huge amount of CO_2 and other pollutants into the atmosphere.

Good thermal performance of building envelops is very important to improve building energy efficiency. Currently, the main parameter of such performance in the building energy efficiency standard in China is the thermal resistance value (*R*-value). In fact, it is a steady state heat transfer measure, which does not capture the two important features of transient thermal performance proposed by Asan [3,4], i.e., the time lag and decrement factor. In order to address the problem, in the latest version of Chinese thermal design code for civil building (GB 50176 – 201X) [5], the thermal inertia index D is used to characterize the transient thermal performance. It is calculated as follows:

$$D = R \times S \tag{1}$$

Abbreviations: AC, alternative current; DC, direct current; FDM, finite difference method; GA, genetic algorithm; PCM, phase change material; *T* Matrix, transfer matrix.

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http://dx.doi.org/10.1016/j.enbuild.2014.05.023
0378-7788/

Nomenclature

Symbols

A	amplitude/area [m^2]
a	thermal diffusivity [m^2/s]
C_e	electric capacity [F]
C_h/C	thermal capacity [J/K]
c_p	specific heat [J/(kg K)]
D	thermal inertia index (dimensionless index reflecting the counteraction of exterior wall on fluctuations in temperature and heat flow)
h	surface coefficient of heat transfer [W/(m^2 K)]
k	thermal conductivity [W/(m K)]
I	current [A]
j	imaginary unit
L	wall thickness [m]
p	active power [W]
$Q_{dissipation,irr,AC}$	irreversible heat transfer dissipation of AC [J]
$Q_{dissipation,irr,DC}$	irreversible heat transfer dissipation of DC [J]
$Q_{dissipation,rev}$	reversible heat transfer dissipation [J]
q	heat flux rate [W]
q_r	reactive power [W]
R_c	thermal resistance of concrete materials [m^2 K/W]
R_e	electric resistance [Ω]
R_h	thermal resistance [m^2 K/W]
R_I	thermal resistance of insulation materials [m^2 K/W]
s	apparent power [W]
T	temperature [°C]
t	time [s]
U	voltage [V]
w_1	marginal price of thermal capacitance C
w_2	marginal price of thermal resistance R
X_c	thermal capacitive reactance [Ω]
x	length in the heat transfer direction [m]/relative ratio of external thermal resistance to the total amount
y	relative ratio of external capacitance to the total amount
Z	thermal impedance [m^2 K/W]

Greek letters

ω	frequency [rad/s]
ρ	density [kg/m^3]
φ	phase angle of thermal impedance [degree]
η	performance index of real wall compared to ideal wall
β	distribution factor

Subscripts

AC	alternative current
con	constant
DC	direct current
equ	equivalent
in	indoor
irr	irreversible
m	layer number
n	number of node
out	outdoor
opt	opt
rev	reversible
real	real
var	variable
0	basic
1	inlet
2	outlet

Superscripts

$\sim$	variables changing with time
–	constant variables