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A novel energy simulation approach for thermal design of buildings equipped with radiative panels using inverse methodology

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ABSTRACT

The purpose of this research is to present a novel approach to estimate thermal design parameters with unknown values in a building equipped with radiative panels with the use of inverse methodology. A direct model is selected to analyze thermal behavior of building components in order to determine indoor temperature field using direct numerical modeling. Using inverse analysis, three thermal design parameters with unknown values, such as conductivity, internal and external convection and total heat transfer coefficients, are estimated using Levenberg–Marquardt and conjugate gradient methods with the knowledge of temperature field resulted from direct modeling. To illustrate the sufficiency of inverse technique, the results of both noisy and non-noisy estimations are presented using sensitivity analysis. To verify the accuracy of the present study, the results of inverse analysis are compared with those of numerical simulation presented in the literature, which indicates a good agreement between numerical and inverse solutions. It is shown that inverse analysis can be used as an applicable approach to increase computational precision in building thermal design phase.

1. Introduction

There are many different factors that play essential role in building thermal design; one of which is based on energy consumption in residential zones. During the last three decades, the concern about energy consumption rate in building sector of each society has become a vital requirement for human beings, which varied from 30% to 40% of its annual energy use in many European countries and increased as a result of the rise in standards of living, rise in population and universal climate change all over the world [1]. A considerable portion of this energy is consumed for heating/cooling indoor environment in residential buildings. One possible reason for this high unnecessary amount of energy use is the absence of computational precision in building thermal modeling [2]. From energy point of view, it seems essential to introduce new computational tools to reduce energy waste in the building sector.

Over the last two decades, there has been a growing demand to present applicable approaches for building energy analysis with reasonable accuracy [3]. These applicable approaches have had to be capable of calculating building thermal design parameters with acceptable precision and the least possible financial and computational design cost. Generally, thermal design parameters are mainly determined using experiment inside buildings, which is commonly known as an efficient approach in building design problems [4]. However, the results of experimental data may sometimes not be as precise as the exact solution due to error in measurement. Moreover, building thermal design parameters can sometimes not be easily calculated using experiments due to the intense financial cost regarding measurements in several special issues especially in some constructions such as ancient monuments, historical sites and antique buildings [5]. According to these limitations in using experiments, the use of computational codes and simulations are becoming more popular for estimation of building thermal design parameters such as conductivity and convection coefficients [6]. One of its commonly used approaches is known as inverse analysis that can work as an efficient tool to estimate unknown thermal design parameters in buildings [7].

Throughout the last four decades, there have been a number of impressive researches published on energy modeling and building thermal analysis in the open literature. Early works were conducted by ASHRAE[1] in 1963. Stephenson and Mitalas [8] investigated cooling load calculations by TRM method. With the development in new technologies and use of personal computers in the early

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[1] American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

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Nomenclature

A	surface area, m^2
A_{fur}	furniture area, m^2
A_{sl}	area of incident solar radiation, m^2
B_r	the planck function for the spectral radiance of a black body
c_p	specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$
$c_{p,air}$	specific heat transfer coefficient of air, $J\,kg^{-1}\,K^{-1}$
$c_{p,fur}$	specific heat transfer coefficient of furniture, $J\,kg^{-1}\,K^{-1}$
$c(\tau)$	trial coefficients of a polynomial of $g(\tau)$
d	direction of descent
$D(\tau)$	trial coefficients of a polynomial of $F(s, \tau)$
e	error, K
E_i	emission flux, $W\,m^{-2}$
$F(s, \tau)$	time-space-varying temperature
F_{DS}	view factor of diffused surface
F_{SG}	view factor of earth
G_i	total radiation rate, $W\,m^{-2}$
$g(\tau)$	time-varying strength
h	thermal convection coefficient, $W\,m^{-2}\,K$
h_{fur}	thermal convection coefficient of furniture, $W\,m^{-2}\,K$
i	control volume numbers
I, I_B	time measurement numbers
I_b	direct radiation intensity to the walls, $W\,m^{-2}$
I_{dif}	diffused radiation intensity, $W\,m^{-2}$
I_G	earth diffused radiation intensity, $W\,m^{-2}$
J	sensitivity factor
J_i	radiosity factor, $W\,m^{-2}$
K	thermal conductivity, $W\,m^{-1}\,K^{-1}$
k	Iteration number
m_{air}	air mass, kg
M	sensor numbers
N	time measurements numbers
n	number of iterations
n_v	air change per hour
p	unknown thermal parameter vector
Q_{air}	air convection heat transfer, W
Q_{fur}	furniture convection heat transfer, W
Q_{gen}	convection heat transfer due to cooling equipment, W
Q_{infil}	infiltration heat transfer, W
q	heat source, $W\,m^{-2}$
q_i	net radiative flux, $W\,m^{-2}$
q''_{solar}	external solar flux, $W\,m^{-2}$
R_s	spectral radiance of the atmosphere
S	sum of the squared residuals
s	distance factor
T	temperature, K
T_{air}	ambient temperature, K
T_{fur}	furniture temperature, K
$T_{s,i}$	indoor temperature field, K
T_o	outdoor temperature field, K
T_r	radiative temperature, K
t	time, s
u	total heat transfer coefficient, $W\,m^{-2}\,K$
V	volume, m^3
x, y	Cartesian coordinates
Y	measured temperature, K

Greek symbols

β	search step size
ϵ	measuring instrument error
ε_1	iterative convergence tolerance
ϵ_r	radiative emissivity
ϵ_s	environment emissivity
η	radiative panel efficiency
θ	radiation angle, deg
λ	wave length, mm
γ	conjugate gradient
ρ	density, $kg\,m^{-3}$
ρ_i	reflectivity factor
σ_r	Stephan–Boltzman coefficient
σ	noisy coefficients
ψ	diagonal matrix
μ	damping parameter

Subscripts/superscripts

air	ambient air value
diff	diffused value
fur	furniture
G	earth
n	current iteration number
m	sensor measured temperature
r	radiative values
s	solid
T	matrix transpose form
1, 2, 3	arbitrary subscript temperature index

1980, energy modeling was remarkably investigated once again in buildings [9]. In this period, a considerable financial budget was dedicated to energy modeling in buildings by the United States Department Of Energy(DOE), which resulted in creating a number of different building energy simulation programs such as DOE-2 and TRNSYS [9]. Note that most of these programs remained unprofitable in research laboratories due to its complexity for use and rather high financial cost. To present a complete accurate load calculation, one had to consider all the complexities existing in building modeling [9]. This actuated researchers to use dynamic computer simulation in building modeling. Such example can be seen in works published by Pedersen et al. [10], Hensen et al. [11], Andersen [12] and Baoping et al. [13]. Then, the use of numerical algorithms, such as optimization methods, became popular and were investigated in the studies by Tzivanidis et al. [14], De Carli et al. [15], Neto et al. [16], Siddharth [17] and Cheng and Lee [18]. In addition, there have been a number of studies implemented on the solution of inverse simulation in building thermal energy performance; such as works published by Zhang et al. [19], where Zhang et al. showed how inverse technique could determine heating and cooling loads inside residential buildings. In the study by Fayazbakhsh et al. [20], it was demonstrated that conjugate and adjoint gradient inverse methods could be implemented to calculate heat gain in air conditioning and cooling systems. Moreover, inverse methodology can be used to analyze building energy and environment problems as it has been investigated by Zhang et al. [21]. Several studies investigated the results of unknown thermal design parameter estimation in building problems such as wall heat flux, thermophysical parameters like conductivity coefficient and thermal diffusivity. Such examples can be seen in studies by Ukrainczyk [22], Lei et al. [23], He et al. [24] and Chaffar et al. [25]. According to these papers, all thermal design parameters with unknown values were estimated in the wall of rooms and each parameter was calculated with the knowledge of temperature field determined from numerical simulation or experimental tests. As presented in the literature, several works studied heating and cooling load modeling inside buildings using inverse analysis or other computational tools like artificial