Building and Environment 85 (2015) 73–84

Contents lists available at ScienceDirect

Building and Environment

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

A novel concept to determine the optimal heating mode of residential rooms based on the inverse problem method

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ARTICLE INFO

Article history:
Received 21 August 2014
Received in revised form
21 November 2014
Accepted 24 November 2014
Available online 5 December 2014

Keywords:
Heating method
Optimization
Building energy efficiency
Inverse problem
Variation method

ABSTRACT

Because heating energy consumption is huge and it takes a large part of building energy consumption, techniques aiming at decreasing the heating energy demand are very important in today's world. While, there are few studies regarding the determination method of the optimal heating mode (i.e. convective, radiative or mixing) of a given house. A novel concept based on the inverse problem method to determine the optimal heating mode of residential rooms is put forward in this paper. By minimizing the additive heating energy consumption and keeping indoor thermal comfort simultaneously, the optimal heating mode of residential rooms is determined by the variation method. Some general conclusions are derived, such as the transition point of the convective and radiative heating mode and the influence of wall's thermophysical properties on the energy saving ratio. For illustrative purposes, a typical residential room in Beijing is analyzed. In addition, optimal heating modes of six typical room kinds in four representative cities in China are determined, which can guide the proper selection of the heating method in various places. The proposed method can be the first step to build the optimal indoor thermal network, and the new concepts can be used to deal with other similar problems in the built environment field.

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1. Introduction

Building energy consumption accounts for 25–40% of total energy consumption in China, in which most energy is used for space cooling and heating. Because of rapid urbanization and massive demand for buildings in new and old urban regions, over 1 billion square meters in area of new buildings have been constructed in China per year since 1996. In 2011, the total building energy consumption in China (biomass energy is not included) is 687 million tce, which accounts for 19.7% of the total domestic energy consumption [1]. Now the total building area in China has been 46,900 million m^2, and it is expected to be 60,000 million m^2 in the future [2]. The huge energy consumption required to construct and maintain buildings not only depletes the valuable fossil energy, but also emits tremendous amount of CO_2 and other pollution into the atmospheric environment. Therefore researches relating to energy efficient buildings are of great importance.

Most of the existing studies regarding air conditioning mode optimization are based on case studies, which can't derive some general conclusions. These studies can be classified as the following two parts: (a) Using numerical algorithms to get the optimal solution of a specific case, while these methods can't derive some general conclusions: Evins et al. [3] simulated the whole building by genetic algorithm (GA) (NSGA II), the results reveal that SAP is not efficient in building energy saving; Fesanghary et al. [4] simulated the whole building by Harmony Search Algorithm to minimize life cycle costs, the results reveal that Harmony Search can decrease life cycle costs effectively, but it just for a given case. (b) Addressing specific areas of sustainable building design: building envelope (including construction and form); HVAC systems; renewable energy generation; and holistic appraisals that cover several areas. Menon et al. [5] optimized the design of polygeneration systems in optimal control strategies to minimize energy costs; Hajabdollahi et al. [6] optimized under floor heating by GA and PSO to minimize total annual cost; Evins et al. [7] optimized CHP system by GA (NSGA II) to minimize energy cost.

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http://dx.doi.org/10.1016/j.buildenv.2014.11.030
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Nomenclature

A	area of walls and window (m^2)
A_i	area of the internal wall
A_o	area of the external wall
A_w	area of the external window
ACH	air change per hour (h^{-1})
C	Expressions of the parameters of the room
C,C'	expressions of the parameters mainly about solar radiation
C_a	expressions of the parameters mainly about indoor air
C_i	expressions of the parameters mainly about inner wall
C_o, C'_o	expressions of the parameters mainly about external wall and external window
c_p	Specific heat (J kg^{-1} $°C^{-1}$)
$c_{p,a}$	specific heat of the air
$c_{p,i}$	specific heat of the internal wall
$c_{p,o}$	specific heat of the external wall
φ	heat flux(W m^{-2})
$\varphi_{i,i}$	heat flux of the internal surface of the internal wall
$\varphi_{i,o}$	heat flux of the outside surface of the internal wall
$\varphi_{o,i}$	heat flux of the internal surface of the external wall
$\varphi_{o,o}$	heat flux of the outside surface of the external wall
h	heat transfer coefficient (W m^{-2} $°C^{-1}$)
h_c	convective heat transfer coefficient of the human body
$h_{i,i}$	convective heat transfer coefficient of the internal surface of the internal wall
$h_{o,i}$	convective heat transfer coefficient of the internal surface of the external wall
$h_{o,o}$	convective heat transfer coefficient of the outside surface of the external wall
h_r	radiation heat transfer coefficient of the human body
$h_{r,o}$	radiation heat transfer coefficient between the internal and external walls
$h_{r,w}$	radiation heat transfer coefficient between the internal wall and the external window
h_w	heat transfer coefficient between the internal and external glass of the external window
$h_{w,i}$	convective heat transfer coefficient of the internal glass of the external window
$h_{w,o}$	convective heat transfer coefficient of the outside glass of the external window
L	wall thickness (m)
L_i	internal wall thickness
L_o	external wall thickness
$\dot{m}$	mass flow rate of the fresh air
q	heating flux (W m^{-2})
q_i	additional heating power for the internal surface of the internal wall
$q_{i,i}$	thermal radiation received on the internal surface of the internal wall
q_o	additional heating power for the internal surface of the external wall
$q_{o,i}$	thermal radiation of the internal surface of the external wall received
$q_{o,o}$	thermal radiation received on the outside surface of the external wall
$q_{w,i}$	thermal radiation heat flux received on the internal glass of the external window
$q_{w,o}$	thermal radiation received on the outside glass of the external window
Q	heating rate (W)
Q_a	air heating power
Q_{op}	minimal total heating power for a given room
Q_t	total heating power for a given room
Q_w	wall heating power
T	Temperature (°C)
T_a	indoor air temperature
$T_{i,i}$	temperature of the internal surface of the internal wall
T_{init}	initial temperature
T_{op}	operative temperature
$T_{o,i}$	temperature of the internal surface of the external wall
$T_{o,o}$	temperature of the outside surface of the external wall
T_{out}	temperature of the environment
$T_{w,i}$	temperature of the internal glass of the external window
$T_{w,o}$	temperature of the outside glass of the external window
T_{set}	lower bound operative temperature of indoor thermal comfort zone

Greek letters

λ	thermal conductivity (W m^{-1} $°C^{-1}$)
λ_i	thermal conductivity of the internal wall
λ_o	thermal conductivity of the external wall
ρ	density (kg m^{-3})
ρ_i	density of the internal wall
ρ_o	density of the external wall
κ	vector of heat flux ratios of different aspects and total heat flux

While, it is not possible to determine the best heating method using the above approaches. In addition, conclusions derived from such studies are only applicable to the specific building investigated. So in spite of the advantages in optimization algorithm, the designer will still face considerable difficulty to design the optimal HVAC system for a specific building. So the inverse problem method is introduced in the building design. Using inverse problem method, Zeng [8] optimized the material (specific heat) of the wall for a typical room in Beijing. The results reveal that, for passive solar room and positive room the best specific heat distribution is just like a Dirac delta function (δ function). Fabiano Cassol [9] also applied inverse problem method to illumination design of building. With the help of multi-objective optimization, optimal location and luminous power of the light sources are found to satisfy a prescribed luminance on the work plane with the constraint of lowest power consumption. The results reveal that inverse problem method is an effective way for illumination design and the generalized extremal optimization (GEO) algorithm decreased the power consumption effectively. While in spite of the introduction of inverse problem method, it is still used in case study.

So we determine a new way to solve the above mentioned problems, whereby the heating method, rather than the heating system, is investigated to clarify the relationship between optimal heating method and the parameters of the building envelope. In order to analyze the relationship between the optimal heating method and the parameters of the building envelope, a simplified room model is introduced in this article. In order to achieve the same indoor thermal comfort level, the heating method (i.e. radiative or convective) is optimized under various conditions in order to save the energy consumption. Some general rules and useful

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