Energy Conversion and Management 105 (2015) 872–879

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Dynamic thermal reaction analysis of wall structures in various cooling operation conditions

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ARTICLE INFO

Article history:
Received 6 June 2015
Accepted 9 August 2015
Available online 1 September 2015

Keywords:
Envelop insulation
Thermal reaction
Heat transfer matrix
Cooling temperature
Operation time
Thermal performance assessment

ABSTRACT

This paper proposes a methodology of performance assessing of envelops under different cooling operation conditions, by focusing on indoor temperature change and dynamic thermal behavior performance of walls. To obtain a general relationship between the thermal environment change and the reaction of envelop, variously insulated walls made with the same insulation material are separately built in the same wall of a testing building with the four different structures, namely self-heat insulation (full insulation material), exterior insulation, internal insulation and intermediate insulation. The advantage of this setting is that the test targets are exposed to the same environmental variables, and the tests results are thus comparable. The target responses to two types of perturbations, cooling temperature and operation time were chosen as the important variations in the tests. Parameters of cooling set temperature of 22 °C and 18 °C, operation and restoring time 10 min and 15 min are set in the test models, and discussed with simulation results respectively. The results reveal that the exterior insulation and internal insulation are more sensitive to thermal environment change than self-heat insulation and intermediate insulation.

1. Introduction

In the hot summer and cold winter areas (China), there is a phenomenon that the residents are apt to intermittently use HVAC system, with one of the considerations that it is good for energy savings. Sometimes to obtain a swift decrease of indoor temperature, people will start cooling with a lower temperature. They may also turn up the temperature after a while of operation, or temporally close the cooling equipment. Since the phenomenon is often seen in reality, there are reasons for the wide range of investigations for the transient heat transfer mechanisms.

The consequential optimization perturbations are significant to the energy saving, thermal utilization and indoor thermal comfort [1]. Recently, a lot of work had been carried out to investigate the potential relationship and solutions for the issues of energy consumption, thermal performance and perturbations. The researchers obtained the results by numerical simulation methods or experimental ways. However, these results varied a lot, as the working conditions and the parameters of outdoor climate parameters, thermal characteristics of building envelop system, operation time and so on were different [2–5]. Therefore, with given functional and operational characteristics of the rooms and the building in target areas (climate), it is very challenging to achieve the relationship of energy consumption and the occupant comfort in the consideration of all variations. What's more, there is little evidence to support with the combined considerations of the occupants' perception and experiences and the energy consumptions in these buildings [6]. It is better to set constant comparative variations which are not mainly concerned in the research, in order to easily observe the desired relationships [7–9].

L. Pires found the special predominance of surface configuration in the heat transfer of internal walls, by using transition temperatures tests [10]. It was also found that surface structures could produce perturbations in the boundary layer that might lead to an early transition from laminar to turbulent regime, and the heat transfer would be influenced by some other parameters through observing the local changes occurred in the flow near to the structure surface elements [11–13]. Some researchers also studied the effects of heat dissipation in the perturbations, and proved that two main pre-conditions were decisive: the starting environmental temperature, and the efficient thermal coupling between the building and the environmental cooling sources [14,15].

Some other ways to research the energy consumption were also discussed, from intelligent buildings or intermittent control strategies and so on [16–22]. The methodology of dividing the

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http://dx.doi.org/10.1016/j.enconman.2015.08.018
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Nomenclature

q''_{in}	the heat fluxes of the internal surface (kJ h^{-1})
q''_{ex}	the heat fluxes of the exterior surfaces (kJ h^{-1})
t	the time
T_n	the finite difference nodal temperatures (K)
n	the number of nodes
T_{in}	the interior environmental temperatures (K)
T_{ex}	the exterior environmental temperatures (K)
A	status matrix
B	input matrix
C	output matrix
D	direct matrix

Acronyms

CFD	computational fluid dynamics
SSM	State Space Method
FR	frequency regulation
PWM	pulse width modulation

Greek symbols

κ	turbulent kinetic energy (J)
ε	turbulent dissipation (%)

HVAC systems into cooling zones and ambient zones or disturbed zones were also proposed [22]. The intermittent operation with Frequency regulation (FR) or pulse width modulation (PWM) control is popular for the temperature control of rooms [22,23]. It is a comprehensive evaluation of considering the prediction uncertainty of heat gains during operation by specifying respective bounds [6]. The relationship between the starting temperature and the zone initial temperature was studied, and the role of starting temperature was proved, in the transition from initial status to steady status and in temperature recovery in multi steady status [23]. The analysis from the perspective of multi steady status of the intermittent use was conducted too [24]. The multi steady status predicted the intermittent operation as a steady–transient–steady way, and released the pattern of heat change rate. More above, the multi steady status analysis quantitatively revealed the impact of the system's initial values on its final steady state [25].

In this paper, we propose a new comprehensive evaluation method, which comprises of comparisons in different boundary characteristics of envelope system, time control, and the various use of cooling. The temperature variation rate in the transient process is introduced and is used to judge the effect of systems' energy consumption.

2. Theoretical analysis of dynamic temperature change

2.1. Dynamic thermal reaction procedure of envelop walls

In this paper, the methodology of dynamic temperature change in a room is investigated, and then the applications are demonstrated for several working conditions in a combined field tests and numerical calculations. The temperature change is attributed by the comprehensive effects of the inner perturbations, outside perturbations and thermal characteristics of envelop systems [1]. The temperature change could be predicted in two situations. Firstly, operation time is long enough, so that the indoor temperature is stable. In this situation, the temperature of envelop systems could be assumed equal to the indoor temperature. In the turn on and off research, the conditions of the previous-off could be assumed to be the pre-conditions of the latter-on. Secondly, the operation time is short, thus the thermal stored in envelop is not completely transferred. In this situation, the conditions of the previous-off couldn't be assumed to be the pre-conditions of the latter-on. For the same indoor perturbations and outside perturbations, it is the thermal characteristics of envelop materials that decides the time.

Correspondingly, the thermal capacity of envelop is significant to regulate the indoor temperature at the conditions of intermittent use of HVAC systems. In the cooling operation, at the beginning of turn-on (pre-cooling), part of the cooling is utilized to lower the indoor air temperature, and part is mixed up with the heat through the inner surfaces of envelop. The proportion of the cooling consumed in lowering the indoor air temperature and balancing the heat obtained through the surface of envelop, is decisive to the operation time. After the cooling stops, the outside heat begins to transfer into envelop through the outside surfaces, and then released into the indoor air through the inner surfaces. Thus if we want to research the increase of indoor temperature, we also have to investigate the heat releasing of envelop. Therefore, the procedure of cooling dissipation of the envelop systems happens in the pre-cooling phase. Its dissipation rate strengthens when the cooling stops, and ends till the cooling has been dissipated over or the cooling starts again.

2.2. Thermal influence of wall sequence order

For composite walls made by more than two thermal materials, the different sequence order of thermal materials would result into a various procedure in the unstable heat transfer. The heat transfer matrix of the composite walls could be predicted as $[S] = [S_n]\,[S_{n-1}]\,[S_{n-2}]\ldots[S_1]$. Correspondingly, the heat transfer matrix of the composite walls is multiplied by the heat matrix of each wall. And the matrix multiplication does not conform to the exchange law. A different sequence order of the matrix in the multiplication could result into a different value. Hence in the unstable or dynamic heat transfer procedure, especially when the indoor or outside thermal environment changes, the temperature change of the two sides could be inhibited by the envelop walls, whose inhibiting performance is decided by the thermal characteristics and the sequence order of the envelop materials [26].

The State Space Method (SSM) based on the modern control theory could be applied to calculate the matrix equations of heat conduction of the envelop wall. Based on the matrix equations of state space, the reaction coefficients of the envelop wall could be obtained by multiplication operation. For the transient heat conduction equation of multilayer envelop wall, it could be solved by applying finite difference scheme to the various layer of materials [27]. Correspondingly, the node temperature is the state variables which could be eliminated, and the temperature of the internal surface and the exterior surface is the only input data which could be obtained by field tests. Hence, the matrix equations of heat flux are only related to the variables of surface temperature, as the thermal conductivity of each material is stable. The state