Energy Conversion and Management 86 (2014) 1–7

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Influence of user behavior on unsatisfactory indoor thermal environment

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ARTICLE INFO

Article history:
Received 24 January 2014
Accepted 1 May 2014

Keywords:
Heat-flux visualization
Energy-saving methods
Existing office building
User behavior
Indoor thermal performance
Temperature distribution

ABSTRACT

In areas of China that have hot summers and cold winters, the overall performance of HVAC systems in the poorly-insulated existing office buildings is generally not satisfactory, especially in extreme weather conditions. The reasons for the unsatisfactory indoor thermal environment were deduced, and to validate the findings, a methodology of numerical simulation for 3D heat-flux visualization was proposed. A full-scale model of a prototype office room was created, with representative working conditions for the characteristics of particular building. The results of the heat-flux visualization and temperature distribution showed that the overall effect was resulted from merged reasons, and that significance ranking of each reason varied when the outside environmental conditions changed. The simulation results were compared with the indoor occupant comfort levels of the volunteers who worked in the target room. Models of possible influential factors such as the outdoor temperature, opening or closing windows, and the effect of window shading devices (WSD) were set up. The influence of user behavior on indoor temperature in opening window, or not using WSD was proven to be significant in causing unfavorable indoor conditions. According to the visualized evaluation and analysis of the various factors, corresponding methods for both improving indoor thermal conditions and saving energy are proposed.

1. Introduction

In regions of China with hot summers and cold winters, the overall performance of HVAC systems in the poorly-insulated existing office buildings is generally not satisfactory, both in summer and winter. This is particularly true in certain rooms, especially when the weather is extremely hot or very cold. However, the HVAC systems can operate well in the transitional seasons. Since these problems often occur in practice, there is a need for a wide range of investigation. The consequential optimization restraints are important to thermal utilization, energy saving, airflow visualization and occupant comfort [1].

Energy consumption and occupant comfort are the result of different effects, such as heat sources, building envelopes, outdoor temperatures [2]. With increasing energy cost, and diminishing occupant comfort, there is a need for users to reduce energy consumption and to improve overall building performance in existing office buildings, without impairing indoor air quality [3]. Therefore, combined indoor air quality and occupant comfort are important considerations in the analysis and design in existing building energy-saving reconstruction [4].

The energy-saving reconstruction study undertaken aims to solve the problems of unsatisfactory indoor environment in certain rooms, which lie in the most unfavorable circuit points of the fluid pipelines, as well as to reduce energy consumption. The indoor temperature is only one aspect of the indoor environment, which consists of the air velocities and surface temperature as well [5]. As is well known, energy-saving reconstruction in existing buildings can be fulfilled through improving building envelope systems and retrofitting the HVAC system [6]. Many studies have been conducted to prove the effect of reconstruction of whole existing buildings, however, few papers have specifically solved the problems in particular rooms, as discussed above. The influence of opening windows on air conditioning efficiency is generally well known, but the significance of the user behavior is often ignored, or not applied into practice, as opening windows is a commonly-seen occurrence all over China, even in some extremely hot or cold areas.

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http://dx.doi.org/10.1016/j.enconman.2014.05.004
0196-8904/

Nomenclature

Q_i	convective internal loads (kJ h^{-1})
h_i	convective heat transfer coefficient of wall/window (kJ h^{-1} m^{-2} K^{-1})
A_i	surface area of wall/window (m^2)
T_{si}	surface temperature of wall/window (K)
T_{zi}	indoor zone temperature of air (K)
T_∞	ambient temperature (K)
T	temperature of indoor air (K)
m_i	mass of air (kg)
$m_{\inf}$	mass of infiltration air (kg)
C_p	specific heat of air (kJ kg^{-1} K^{-1})
Q_{SYS}	air systems output (kJ h^{-1})
ρ_{air}	air density (kg m^{-3})
C_T	sensible heat capacity multiplier (kJ K^{-1})

Acronyms

CFD	computational fluid dynamics
3D	three dimensional
WSD	window shading device

Greek symbols

κ	turbulent kinetic energy (J)

Occupant comfort provides insight into the operation of a particular building over a determined period of time, but occupant comfort does not enable that insight to be extended and used to predict the performance of other aspects [7]. The focus of this paper is to develop a methodology that can be used to evaluate and then predict the energy consumption performance. The development began with the monitoring and investigation of a room, lying in the most unfavorable circuit point of the fluid pipeline in an existing office building, with particular characteristics. Through modeling, and supported by data from the monitoring, together with the theoretical analysis, the operation of a building under certain environmental conditions could be understood, and the reasons which led to the unfavorable indoor environment could be deduced [8]. By using data from a monitored building to calibrate the expected results of the numerical model through theoretical analysis, the model configuration then could be altered to determine what impact any changes in certain design characteristics would have under potential reconstruction strategies [9]. In addition, the theoretical analysis can provide a validation of the models using computational fluid dynamics (CFD) simulations [10]. It would offer a better understanding of energy consumption performance in existing office buildings and in improving current occupant comfort [11].

2. Assumptions and theoretical analysis

2.1. Assumptions for thermal derivations

Generally speaking, the variants that were directly related to the building thermal environmental analysis consisted of outdoor air temperature, outdoor air humidity, solar radiation intensity, land surface temperature, effective sky temperature, wind velocity and wind direction [12]. In a situation having the same energy consumption and a constant heat source in the building, it is the effect of these variants that determine the quality of the indoor environment [13]. Compared with rooms having good occupant comfort in the same building, the unsatisfactory rooms had specific building characteristics, such as poor window orientation with large size, and top floor location [14]. In regions of China with hot summers and cold winters, occupants are apt to open the windows to improve the ventilation in the room, throughout the year [15]. This phenomenon of opening windows was also followed in the target room, so the reasons thus could be established for this behavior, especially as air conditioning was provided [1,16].

2.2. Governing equations of energy balance

HVAC systems provided cold air to rooms to meet the cooling loads [17]. Using the assumptions above and the effectiveness algorithm, an equation can be obtained to establish the relationship between the indoor thermal environment and the outside conditions (Eq. (1)) [18]. The essential analysis for the room and HVAC system integration is to formulate an energy balance for the indoor air and to solve the resulting ordinary differential equations using a predictor–corrector approach [19–20].

$$C\frac{dT}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surrfaces}} h_i A_i (T_{si} - T) + \sum_{i=1}^{N} m_i C_p (T_{zi} - T) + m_{\inf} C_p (T_\infty - T) + Q_{SYS} \tag{1}$$

where $\sum_{i=1}^{N} Q_i$ = sum of the convective internal loads; $\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T)$ = convective heat transfer from the room surfaces; $\sum_{i=1}^{N} m_i C_p (T_{zi} - T)$ = heat transfer due to air mixing; $m_{\inf} C_p (T_\infty - T)$ = heat transfer due to infiltration of outside air; Q_{SYS} = air systems output; $C\frac{dT}{dt}$ = energy stored in the indoor air; $C = \rho_{air} C_P C_T$; ρ_{air} = air density; C_P = air specific heat; C_T = sensible heat capacity multiplier, which can be ignored [10].

3. Numerical methods

3.1. Prototype office room

The prototype building for developing the research approach was located in Chengdu, in southwest China. This location has hot summers and cold winters, with an average temperature of 5.9 °C, and a lowest temperature of –2.1 °C in January, and with an average temperature of 29.9 °C, and a highest temperature of 37.9 °C in July. The target office room (7.15 × 6 × 3 m) was located on the top floor of the building, which has eight floors in total. The only door was located in the east of the room, with a size of 0.9 × 2 m. The window was in the west of the room, with a size of 2.85 × 6 m, and the corresponding WSD was of the same size

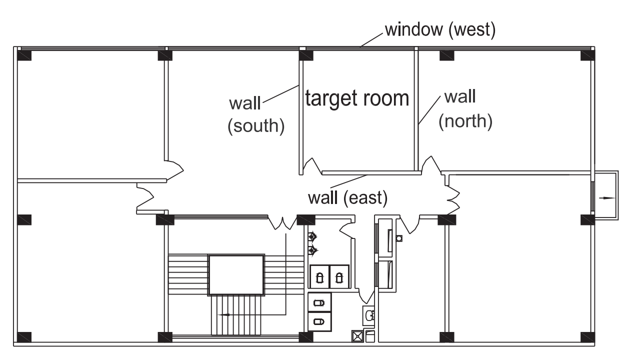

Fig. 1. Plan view of the target office room.