Building and Environment 45 (2010) 1441–1447

Contents lists available at ScienceDirect

Building and Environment

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

A CFD-based test method for control of indoor environment and space ventilation

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ARTICLE INFO

Article history:
Received 25 August 2009
Received in revised form
20 October 2009
Accepted 8 December 2009

Keywords:
Computational fluid dynamics
System simulation
Ventilation control
Temperature stratification
Online control test

ABSTRACT

System dynamic simulation has been adopted to test and evaluate the local and supervisory control of air-conditioning systems for over twenty years, while the modeling of the space ventilation was usually simulated using perfect mixing models. However, the complete-mixing air model fails to consider the impact of non-uniform air temperature stratifications. This paper presents a CFD-based virtual test method for control and optimization of indoor environment by combining a ventilated room with a ventilation control system. The ventilated room and its dynamic ventilation control system are represented by a computational fluid dynamics (CFD) model and models of the temperature sensor, PID controller and actuator and VAV damper model respectively. The ventilation and its control system are programmed using the user defined function program and interfaced with the CFD model. A space temperature offset model is developed to improve the accuracy of temperature measurement and control at the occupied zone as a virtual sensor. Case studies show that the ventilation control models can interoperate with the CFD simulation of the space online which presents a new application approach of CFD simulation for testing and developing control and optimal control strategy before a system is constructed practically. The use of the virtual sensor can effectively compensate the effect of non-uniform stratification on the temperature control and improve system control reliability in a mechanical ventilated room.

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1. Introduction

The operation and control of heating, ventilating and air-conditioning (HVAC) system are essential for ensuring satisfactory indoor comfort and indoor air quality (IAQ). Over the last decades, there have been increasing interests in studying how to maintain appropriate indoor comfort level. Proper ventilation of buildings can create thermally comfortable environment by controlling indoor air parameters, such as air temperature. A low ventilation rate may cause deficiencies of the system performance such as poor mixing of supply and room air, poor indoor thermal comfort. To improve the indoor ventilation performance, it is essential to have a suitable tool to predict and test ventilation performance in buildings. Many local and supervisory control approaches of air-conditioning systems for the last twenty years are presented to evaluate and improve the ventilation performance.

Wang [1] developed several dynamic models of building and variable air volume (VAV) air-conditioning systems, which incorporate the thermal (i.e. indoor air temperature), hydraulic, environmental and mechanic characteristics as well as energy performance. These models can simulate the system using a model-based program to maintain satisfied indoor thermal comfort. Kwok and Wai [2] presented an adaptive interface relationship of indoor comfort temperature with outdoor air temperature in order to preset the indoor air temperature as a function of outdoor air temperature. This algorithm can improve the occupants' acceptance of thermal comfort. Feriadi [3] developed a thermal comfort prediction chart and fuzzy thermal comfort model suitable for naturally ventilated buildings in the tropics based on data collected through field surveys in Singapore and Indonesia. Wang and Jin [4] presented a supervisory ventilation control strategy to predict indoor air thermal condition and evaluate the ventilation performance of HVAC system based on TRNSYS simulation platform. Yuan and Perez [5] developed a model predictive strategy to access multiple-zone ventilation and temperature control performance of a single-duct VAV system. Chao and Hu [6] established a dual-mode demand control ventilation strategy targeting at use in buildings where the number of occupants varies frequently. Djuric et al. [7] presented an approach to improve building thermal comfort by use of computer-based tools.

All these simulation systems have taken the indoor air as "perfectly mixed" into consideration. Since the indoor dynamic property is simplified, these simulation systems cannot precisely feedback the spatial variation of the controlled variable. Such an

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doi:10.1016/j.buildenv.2009.12.007

assumption can be unrealistic in applications where controlled variables vary considerably over distances.

CFD model as a powerful tool have successfully been applied in the HVAC field [8]. Many researches on predicting detailed room air flow patterns, indoor temperature distributions, and pollutant transportation indoors have been studied [9–19]. Meantime, CFD is a useful tool in design practice for the verification and comparison of tentative building design alternatives [20]. In contrast to full scale ventilation performance test, the CFD method is a relatively inexpensive and alternative method. It is applicable to provide complete information concerning indoor environment and space ventilation control performance of a new developed control strategy before it is constructed.

It would be a significant step forward to integrate the simulation of the space ventilation and the indoor thermal stratification phenomena to a real-time ventilation control strategy for ventilation performance test purposes. This paper presents a CFD-based test method combining a ventilated room with a dynamic ventilation and control system. The ventilated room is built using the CFD model. The ventilation and control system is programmed using user defined function program interfaced with the CFD model. This approach of merging the traditional ventilation and control system with CFD simulation to test indoor ventilation performance is very challenging, but if it is successfully achieved, it will undoubtedly provide new possibilities for testing and evaluating the ventilation control processes in applications.

2. Description of virtual ventilation test method

2.1. Overview of the ventilation test method

In the design of ventilation test system, evaluating the indoor air environment has been the main target of the analysis from the start of CFD application. Based on our experiences in applying CFD to HVAC system, we have refined the following two major components which are indispensable for indoor ventilation performance test: (1) simulated ventilation room, (2) ventilation and control system. Both of these have become essential tools in the analysis of indoor environments and space ventilation.

2.1.1. Simulated ventilation room

Experimental measurements are reliable for providing sufficient data to test ventilation performance but need large labor-effort and time. In the proposed ventilation test method, the CFD simulation is used to represent the room as a virtual ventilated room model [21].

2.1.2. Ventilation and control system

The next critical step in applying CFD for ventilation and control test is the development of a ventilation and control system. The components of the ventilation and control system in this study include a temperature sensor model, a space temperature offset model, a PID controller model, an actuator model and a VAV damper model, which are programmed using user defined function program (UDF) and interfaced with the CFD model.

At this stage, the CFD-based online ventilation control test technique combined CFD simulation with the ventilation and control system has developed into a preferable test tool. The schematic diagram of the virtual online ventilation control test method is shown in Fig. 1.

The indoor air temperature near exhaust air is monitored by a temperature sensor as the actual indoor air temperature measurement. Fig. 2 describes the typical pressure-dependent VAV ventilation control system used in this study, in which the supply air temperature was set as constant and the indoor temperature is controlled to a predefined set point. The manipulation of the supply air flow rate is done through a VAV damper according to the control signal given by a PID controller.

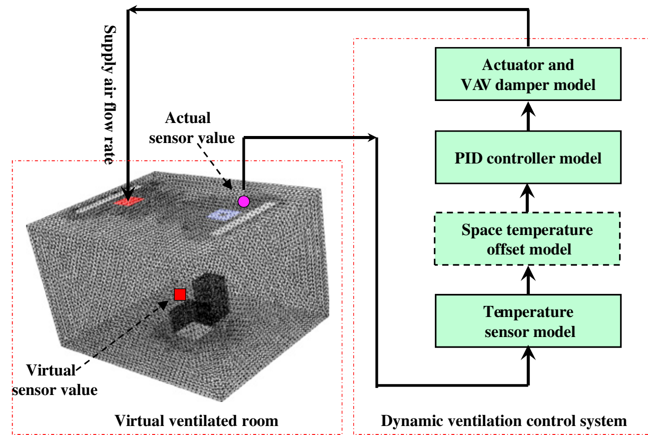

Fig. 1. Configuration of virtual online ventilation control test system.

2.2. Ventilated room model

CFD model is an alternative for representing the room as a virtual ventilated room model. Choosing a proper numerical model for CFD simulation is also necessary to obtain accurate data. The detailed introduction is explained as follows.

The size of ventilated room is 3.0, 3.0 and 2.5 m in length, width and height respectively. In this room, the actual temperature sensor is located near exhaust air, while virtual sensor is located in occupied zone shown in Fig. 1.

2.2.1. CFD theoretical model

Computational accuracy can be improved significantly by adopting a reasonable numerical model. Chen [14] compared five different k–ε models, including the standard k–ε, the LR k–ε and the RNG k–ε models, which concluded that the RNG k–ε model is the most appropriate model that characterizes the flow field in a ventilated space. The form and coefficients of the RNG k–ε model can be found in Ref. [21].

In this study, the continuity, momentum and energy conservation equations were solved by employing the finite volume, the second-order upwind scheme and the SIMPLE algorithm. The air was assumed to be incompressible and its physical properties are assumed constant. The residuals of continuity, momentum and turbulent kinetic energy and its dissipation rate were set to be 1×10^{-4} in magnitude for convergence, while the residual of energy should reach 1×10^{-7} in magnitude.

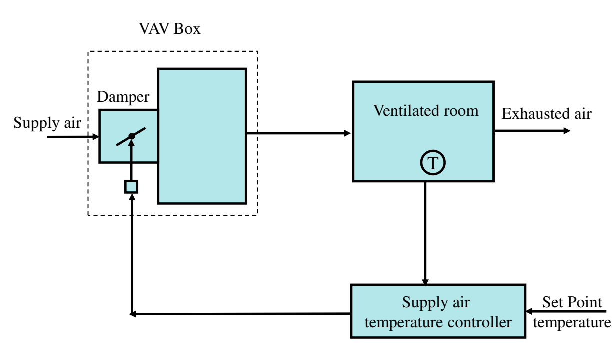

Fig. 2. Control schematics of pressure-dependent VAV system.

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