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Temperature sensor placement optimization for VAV control using CFD–BES co-simulation strategy

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ABSTRACT

The popular optimal control approaches in the heating, ventilation and air conditioning (HVAC) system just focus on the energy consumption mostly. It usually simplifies the thermal comfort issue through using an indoor average temperature, which may result in the improper indoor temperature distribution. The co-simulation technology, which integrates the building energy simulation (BES) and computational fluid dynamics (CFD), can provide a possible solution to avoid the false optimization in the control process. In this paper, a simple co-simulation strategy is presented to integrate the BES and CFD techniques for the HVAC system. The energy simulation and thermal comfort calculation are coupled together and the indoor temperature distribution is embedded into the VAV control process. The CFD–BES co-simulation method is validated in the HVAC simulator of an office building located in Shanghai. With the CFD–BES co-simulation strategy, the indoor temperature sensor placement is optimized though considering the energy consumption and predicted mean vote (PMV) simultaneously. The results show that the commonly selected sensor position of indoor temperature is not always the best solution for the VAV terminal control.

1. Introduction

Indoor thermal comfort and energy efficiency have already become the two main issues in the heating, ventilation and air conditioning (HVAC) system. To obtain the higher energy efficiency, some energy simulation tools such as DOE-2 [1], EnergyPlus [2] and TRNSYS [3] are widely used to analyze the energy consuming process and then develop the optimal control strategies for the different buildings. Wang [4] developed a TRNSYS based simulator for the HVAC system in an office building. This HVAC simulator can be used to test different optimal control strategies for the possible energy saving potentials. Fan [5] developed the simulator for an airport HVAC system using EnergyPlus. He presented several optimal control strategies in the simulator to validate the potential energy saving of the airport. Perez-Lombarda [6] employed DOE-2 to evaluate the energy efficiency of HVAC system in an office building. Yuan [7] developed the model predictive strategy to realize the temperature control of multiple zones. Chao [8] developed a dual-mode demand control strategy to analyze the indoor air quality and the possible energy saving. These energy simulation tools including the detailed component models usually carry out the complicated control logic so as to obtain the better energy conserving results.

However, the capacities of these energy simulation tools are quite limited in the aspect of indoor thermal comfort analysis. During the energy simulation process, each room is usually considered to be one calculation node through assuming the indoor air to be well mixed. Since the indoor dynamic property is simplified, no detailed room temperature distribution but indoor average temperature can be provided. As a result, it cannot supply the spatial variation of temperature during the control process. Without the spatial temperature distribution, it is difficult to optimize the energy saving and thermal comfort comprehensively. Consequently, it is necessary to develop the optimal control embedded with spatial temperature distribution for the higher energy efficiency and better thermal comfort in the buildings.

Computational fluid dynamics (CFD) technique is a widely used tool for the thermal comfort calculation. Many applications have been applied in the building and HVAC system successfully [9–13]. Zhai and Chen [14] compared several coupling methods between CFD and energy simulation tools. The static and dynamic coupling approaches between CFD and energy simulation were presented

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Nomenclature

T	temperature (°C)
G	humidity (kg/kg)
CC	CO_2 or pollutant concentration (ppm)
C	thermal capacitance (kJ/°C)
R	thermal resistance (°C/kW)
Q	heat (kW)
S	moisture or pollutant generation rate
v	volume flow rate (m^3/s)
V	air volume (m^3)
M	air mass (kg)
A	area (m^2)
F	mass flow rate (kg/s)
P	pressure (Pa)
t	time (s)
H	control output
K	gain
e	difference of controlled variable and its setpoint
A ~ G	sensor position
PMV	predicted mean vote
HVAC	heating, ventilation and air conditioning
VAV	variable air volume
CFD	computational fluid dynamics
BES	building energy simulation

Greek symbols

ρ	air density (kg/m^3)
Ψ	sensible heat ratio
θ	variable of sensor
τ	time constant
Δ	drifting bias

Subscripts and superscripts

SA	supply air
RA	return air
str	non-transparent layer
win	transparent layer
inf	infiltration
exf	exfiltration
int	internal
plt	CO_2 or pollutant
in	inlet
ex	outlet
wt	water
C	coil
s	sensor measurement
r	real value
P	proportional item
I	integral item
D	derivative item
i, $i-1$	time

and tested in an office. Bartak [15] also integrated the energy simulation tool with the CFD models. This coupling strategy was validated in the university building. Djunaedy [16] presented an external coupling strategy between the energy simulation and CFD software. Through exchanging the necessary data, the energy simulation and CFD models were well coupled. Furthermore, Zhai and Chen [17] made the sensitivity analysis for an office building. They compared several coupling approaches between CFD and energy simulation tools through considering the building characteristic and calculation precision.

As to the comprehensive optimization, many control strategies have been delicately designed [18–21] in the HVAC system. However, the negligence of the key component such as the sensor may lead to the optimal target unreachable. Besides the accuracy of measurements, selecting a better sensor position should be also considered in the optimal control process. Although the sensor actually plays essential roles in the control loop, its placement optimization was not paid enough attention in the last few years. For the variable air volume (VAV) control loop in the HVAC system, the temperature sensor is usually placed at the return air inlet. Whether this placement method is always the best solution during the whole control process is an interesting but unsolved issue.

Recently, Fan and Ito [22] developed a BES-CFD integration approach to study various supply air location in an office building. With the co-simulation of CFD and energy analysis tools, the energy consumption using the different ways was analyzed. Sun and Wang [23] presented a CFD-based virtual testing method for the control of indoor environment. The virtual sensor was used to compensate the effect of nonuniform stratification on the temperature control process. This virtual sensor improved the control reliability in a mechanical ventilated room. Zhang [24] presented a contribution ratio of indoor climate (CRI) method for the building energy system. With the CRI method, the temperature distribution of an office using CFD was combined with its thermal load simulation.

The co-simulation between CFD and energy consumption has not been well developed in the VAV control process. It is also necessary to optimize the sensor placement in the HVAC system. In this paper, a simple CFD–BES (building energy simulation) coupling strategy is presented to co-simulate the energy simulation together with the thermal comfort analysis. The indoor temperature distribution is embedded into the VAV terminal control process. The temperature sensor placement is optimized through considering the indoor thermal comfort and energy consumption simultaneously.

2. System description

2.1. The HVAC system

The typical HVAC system in an office building is shown in Fig. 1, which can be partitioned into water side and air side. In the water side, the supply chilled water coming from the chiller is transported to the air handling unit by the 2nd level pump. The return chilled water passing by the air handling unit is circulated back to the chiller by the 1st level pump. Actually, the air handling unit is the heat exchanging place between the air and water.

On the other hand, the supply air, which is the mixture of the outdoor air and recycle air, is circulated to the air handling unit by the supply fan and exchanges heat with the chilled water. After being cooled down (in the summer condition), the supply air is circulated to the VAV terminals to meet the indoor requirement. With the return fan, the return air is divided into two parts: the exhaust air and the recycle air. The former is discharged into the outside space and the latter is reused to another air circle.

2.2. Pressure-independent VAV control

In the office building, pressure-independent VAV terminal control (Fig. 1) is employed to maintain the required indoor