Energy and Buildings 158 (2018) 950–963

Contents lists available at ScienceDirect

Energy and Buildings

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

An advanced simulation test bed for the stability analysis of variable air volume air-conditioning control system. Part 1: Optimal simplified model of building envelope for room thermal performance prediction

Zhi-Ming Yi, Hang Yu*, Qi Wei, Xiang-Yang Chu

School of Mechanical and Engineering, Tongji University, Jiading District, Shanghai 201804, China

ARTICLE INFO

Article history:
Received 24 July 2017
Received in revised form
13 September 2017
Accepted 22 October 2017
Available online 23 October 2017

Keyword:
VAV
Stability analysis
Joint computation
Computational fluid dynamics
Simplified wall model

ABSTRACT

This paper and its future companion papers, were aimed to develop a set of efficient and accurate enough modular tools to build a simulation test bed for the stability analysis of interacting VAV (variable air volume air-conditioning system) control loops. By providing the correlation equations between the heat flow and temperature of the two opposite surfaces, the wall model was expected to link adjacent zones effectively and efficiently. In part 1, the development of an optimal simplified 3R2C (composed of three resistances and two capacitances) thermal network model of building envelope, i.e., the wall model, was descripted. The verification showed that the simplification of one-dimensional heat conduction through a typical wall of heavy construction was acceptable. The accuracy of the optimal simplified 3R2Cmodel was satisfying, and outperformed that of the optimal 4R3C model as well as two 3R2C models which were normally used in practical applications. First and foremost, the room dimensions of the test bed with the boundary conditions in numerical scheme were designed under the principle of similarity. After validation of the numerical scheme with the high-cited scaled experiment, a series of numerical test cases simulating the potential oscillations in practical applications, were conducted. Then, the long neglected concerned frequency range within which heat flow transfer through extern wall, was determined. Finally, the part of solid wall was separated with the part of indoor air, and was developed into a flexible wall module of 3R2C model based on frequency domain regression.

1. Introduction

With the national industrial restructuring and upgrading, China is facing severe energy and environmental issues [1,2]. As to buildings, VAV with direct digital controllers, is universally accepted as means of achieving energy saving and comfortable zonal environment [3,4]. Included in the Chinese 13th Five-Year planning, China national Key R&D is working on the solution to heating and cooling of building in the Yangtze river region. An improved control strategy can reduce cooling/heating costs significantly without sacrificing the thermal comfort of the occupants, and the energy saving potential of VAV systems can still be improved substantially, by far [5]. However, the unresolved stability issues in VAV control systems, i.e., the VAV control system can easily fall into oscillation in the step response of room air temperature, need to be taken seriously in order to achieve high performance and low carbon emission. In the development phase of VAV controllers, a systematic approach to evaluating the stability by finding the stability region affected by the selection of set point values and control parameters, are called for. And the HVAC (Heating, Ventilation and Air-conditioning) field engineers desire to know how the stable conditions are affected to guide tuning of PID controllers. Unfortunately, with the lack of open research, these unsettled technical problems due to market monopoly have hindered the energy saving by VAV greatly.

Usually, the inherent interaction between control loops of room air temperature and supply air temperature are assumed to be essentially the source of the oscillation [6]. However, according to the existing open literatures of dynamic performance experiments and the reflections from HVAC filed operators, VAV control systems will encounter a lot of problems which are insignificant in constant air volume system, e.g., the airflow sensor in VAV terminal tend to be inaccurate and unstable at low airflow conditions [7–9]. There are few open studies on the low airflow performance of a VAV terminal unit, though it is believed that manufacturers of VAV boxes and controllers have conducted internal research activities to study

* Corresponding author.
E-mail address: tjyuhang@163.com (H. Yu).

https://doi.org/10.1016/j.enbuild.2017.10.076
0378-7788/

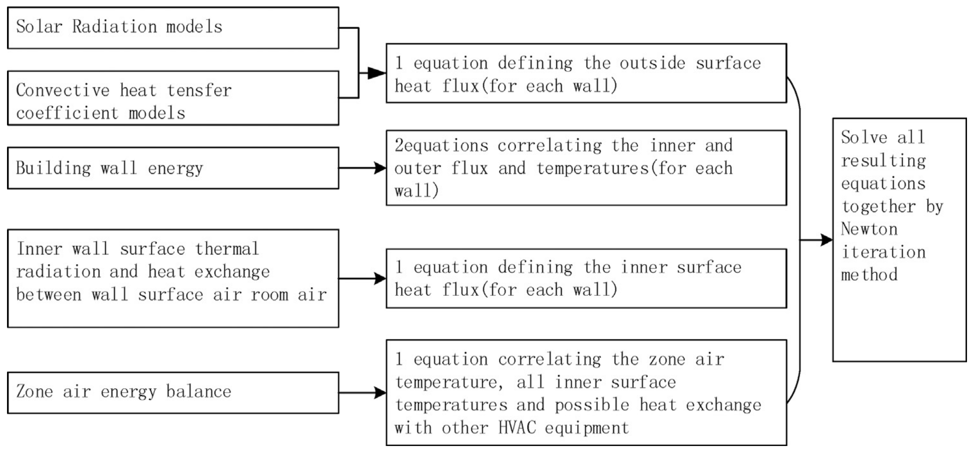

Fig. 1. modules used in thermal performance prediction and load calculation.

these issues. The term stability limit analysis of VAV system was first systematically studied in the Japanese scholars' papers [10]. By means of normalized dynamic system models of the interacting systems and generalized parameter analysis, their pioneering works were to find the stability region affected by the selection of set point values and control parameters [6]. Briefly speaking, their principle work was to explore the possible existence of oscillations of room air temperature control system in the step input responses. However, on the key factor to instability, their conclusions were controversial and even contradictory with each other. Their arguments may due to the aggressive simplifications in the development phase of dynamical models of interacting systems. To accommodate the considerations of the non-uniform thermal profiles within the space where the sensors are set, more accurate modeling techniques, e.g., field experiment and computational fluid dynamics (CFD), are called for.

Field experiments can show more details about thermal performance of components, and can validate the new developed dynamic models. However, it was found that there were numerous factors contributing to the obvious error of the measurements by using a sensitivity analysis [11]. Besides, environment factors, e.g., outdoor climate, vary greatly from south to north and from east to west, in China. Consequently, it would be nearly impossible to guarantee the validity of all the data. Therefore, we need some ancillary methods, e.g. computational fluid dynamics (CFD) technique and joint calculation, to predetermine the main factors and to reduce the number of experiments. The simulation test bed in this paper was aimed to build a dynamic system of the interacting control loops. And the detection of the potential oscillation of room air temperature in the step response of which the time step is in minute level even in second level, is the principal component of stability analysis. There exists hundreds of building thermal performance prediction software based on integrated modules as shown in Fig. 1 [12]. Modular dynamic models have advantages of reusability and portability for only part of the modules need some adjustments to be reused in next case. Besides, it can make sure the modules are used appropriately as they are designed for. For example, a validated numerical scheme is an alternative to experiments to present the thermal conditions in an air-conditioned room, when the indoor air profiles were required. By far, it can only be used when necessary for it is time-consuming. Besides, we usually do not desire everything in trivial such as temperature profiles in solid wall every time.

By providing the correlation equations between the heat flow and temperature of both the surface of wall, the thermal model of the envelope can link adjacent rooms in an extremely flexible way. Unfortunately, the methods which were most commonly used in software (e.g. Energy Plus) of thermal load prediction, i.e., the CTF method and response factor method, are designed for building energy prediction with fixed time step (conventionally one hour) [13,14]. If we adjust the time step to minute level while maintain the accuracy, the key to success is the calculation of accurate, reliable condition transfer functions (CTF) [11], which was never easy [15]. As to the finite difference (FD) or finite volume (FV) method, reliable numerical accuracy could be expected and was used in some of the studies of room thermal performance prediction [16–18] in recent decades. However, the study of discretization scheme of the solid walls especially in the vicinity of the interface between adjacent different material layers, may need to be enhanced to guarantee the consistence of accuracy. Besides, the balance between the precision and computing resource consumption as well as the consistence of the coding of the components, was what the software must consider carefully, especially for the heavy calculation task in controller tuning simulation. In the late 90s, ASHRAE (American society of Heating, Refrigerating and Air-conditioning Engineers) Research Project 825 adopted a RC thermal network of wall model in a standard simulation test bed for the evaluation of control strategies [19]. The RC network thermal model (analog with circuit) of building envelope in that paper is showed in Fig. 2 [20]. Based on frequency domain regression, the RC network thermal model of building envelope, has received extensive researches, by far [20–22]. The modeling method itself was not difficult, yet the mathematical expression of RC model was very complicated as it contained many hyperbolic functions. Therefore, the relevant researches were mainly focused on the simplification of the modeling methods and development of new solving algorithms [20,23–25]. However, their concerned frequency range within which the simplified RC models were regressed, were far below the up limit frequency which was consistent with the oscillation frequency of room air temperature control loop. The prediction failure of heat flow through envelope within the time step of control systems by simplified RC network model was inevitable.

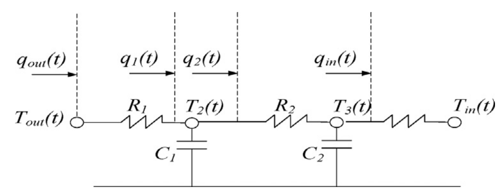

Fig. 2. Schematic of thermal network for 3R2C thermal model of building envelope.

Then, the determination of the concerned frequency range requires to know the limit frequency. As to the controversial up