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A hybrid dynamic modeling of active chilled beam terminal unit

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HIGHLIGHTS

- This paper presents the first reported ACB terminal unit model.
- The model encapsulates mechanical and thermal aspects.
- A compromise is made between underlying physics and suitability for applications.
- The model is obtained under the unique condition of ACB.
- The model is accurate and robustness.

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ABSTRACT

This paper proposes a hybrid dynamic model of active chilled beam (ACB) terminal unit. The model encapsulates mechanical and thermal aspects of the confined air jet and the cooling coil contained in the terminal unit and could be divided into two sub-models respectively. The models for the primary air, secondary air and mixing of them are together taken as the confined air jet sub-model. Another sub-model is the heat transfer description of the cooling coil. The model is kept simple and practical, avoiding sophisticated jet flow theories as well as heat transfer theories. Thus, in deriving the model using first principles and estimating it experimentally, a reasonable compromise is made between capturing exact underlying physics and suitability for engineering applications. Supported by experimental results from a pilot plant, unknown model parameters are identified by either a linear or nonlinear least-squares method. It is shown that static and dynamic performances of the model are satisfied, which reflect the effectiveness of this hybrid modeling technique as well. The model developed in this work is expected to have wide control and optimization applications.

1. Introduction

Heating, ventilation and air conditioning (HVAC) systems provide comfortable and healthy indoor environment for occupants, but they account for a lot of energy consumption. Compared with conventional variable air volume (VAV) all-air HVAC systems, air–water ones consume substantially less energy. One of the most promising options in air–water HVAC systems is active chilled beam (ACB) which has been used for more than 20 years in Europe and is becoming more and more popular as an outstanding means of managing large sensible cooling loads all over the world [1,2]. According to the energy saving figures of several energy retrofit projects in America [3], the total power demand of ACB is about 25–30% less than that of VAV. In terms of enhancing operation efficiency further, many practitioners have paid great efforts on control and optimal operation of ACB during recent years [1,2,4,5], while studies from the researchers and experts in HVAC field are still inadequate. As a consequence, in most of the existing applications, simple and model-free control and optimization strategies lead to much degeneration in energy performance. It is absolutely necessary for the researchers and experts to devote themselves into this field and develop advanced and model-based counterparts. Then, proposing a proper model of ACB terminal unit for such a purpose becomes the first task.

Preparatory to the review of related studies, schematic diagram of ACB terminal unit is depicted in Fig. 1. It comprises of a primary air plenum, dozens of specially designed nozzles, a mixing chamber and a cooling coil. A fixed pressure is maintained in the primary air plenum by a fan, so that a certain amount of cooled and dehumidified primary air is forced through the nozzles, through the mixing chamber and out into conditioned-zone. The nozzles are designed in such a way that a negative pressure kernel is generated in the region beyond the nozzle exit. It induces the

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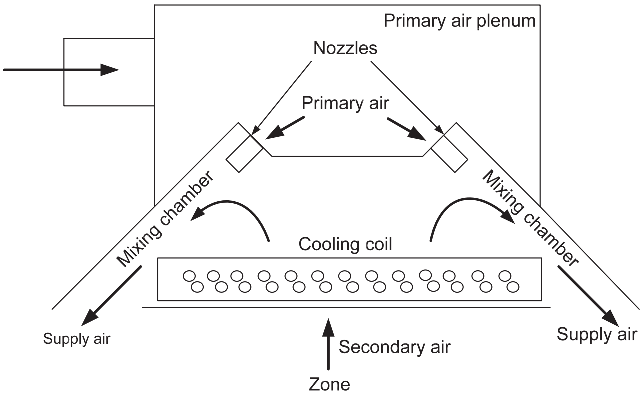

Fig. 1. Schematic diagram of an ACB terminal unit (Lateral Cross Section View).

flow of zone air known as secondary air through the cooling coil and into the mixing chamber. This induction of the secondary air by virtue of nozzle design is called entrainment effect, the better the design the stronger it is. Since the cooling coil is supplied with chilled water, the secondary air passing it is cooled. Finally, the cooled secondary air mixes with the primary air in the mixing chamber and the resultant supply air exits the unit into the zone.

For the modeling of such kind of terminal unit, there is no dedicated study yet. However, there have been some research works on the entrainment effect and cooling coil which may be able to be incorporated into the modeling. In fact, the turbulent merging confined jet phenomenon which happens in ACB is very complicated. In most cases, it is explored with the assistance of computational fluid dynamics software and massive experiments. Morton et al. [6] presented the entrainment effect as an incorporation of fluid from the surrounding into the jet by turbulent eddies generated by the shear existing between the two regions. Because the turbulent energy dissipation cannot be measured, some empirical hypotheses are employed to close the equation system in jet models. Based on entrainment hypothesis and spreading hypothesis, Enjalbert et al. [7] and Wang [8] individually derived the entrainment effect models for single turbulent jet from conservations of momentum and mass. Given Reichardt's hypothesis, the entrainment effect modeling becomes more powerful and flexible. Hodgson et al. [9] and Wang and Davidson [10] demonstrated some models of complex processes involving complicated boundary conditions and multiple jets by the method of superposition of particular solutions. Unfortunately, all these models require the details of system configurations, such as nozzle dimensions, arrangements and so on. More importantly, the independent variables of these models, spreading constant and virtual point, should be determined empirically with a lot of experiments as well. As a result, they are generally useful in active control of jets. Targeted at control and optimization applications rather than at developing innovative terminal units, such kind of confined air jet models are unsuitable here. Then, this paper captures the entrainment effect via an empirical model.

Considering the modeling of the cooling coil, a wide range of models is currently available. Lebrun et al. [11] and Brandemuehl et al. [12] developed two theoretical cooling coil models for ASHRAE HVAC Toolkits. The models require dimensions of the fin and the tube thickness, diameter, and spacing as inputs in order to calculate the heat transfer coefficients but present insufficient robustness. Stoecher [13] proposed an empirical model, which can predict the performance of a coil regardless of the type of fluid in the tubes with a given set of constants. Its defect is that for different fluids different sets of constants are needed. Either theoretical or empirical modeling approach has some inherent disadvantages. Conversely, a hybrid modeling approach takes advantages of both theoretical and empirical modeling approaches. It can offer acceptable accuracy and robustness with simple models. The model structures are derived from first principles, while the unknown parameters are identified by catalog or experiment data. A variety of models are achieved in this way. Braum et al. [14] established an effective model for cooling coils via introducing the concept of air saturation specific heat. Rabehl et al. [15] relaxed some of the assumptions and complications in Braum's model and capture the effect of geometry on performance. Furthermore, the model is simplified to several unknown lumped parameters without any geometry descriptions in Refs. [16–20].

It should be noted that most of the existing cooling coil models, including the referenced ones [11–20], are usually static models. They are not sufficient in many cases. For example, compared to controlling the fluid flow rate, controlling the exit temperature of the cold fluid with dynamic models is better to maximize the coil capacity. In other word, a dynamic model is more convenient to make full use of the coil cooling capacity in ACB application. Meanwhile, the condensation can be strictly avoided if the transient behavior can be predicted. The study on dynamic description of the fin-tube heat exchanger was first attempted by Shah [21]. General formulations of different problems, novel approaches and various techniques and so on were addressed step by step [22–24]. However, these comprehensive dynamic models are developed for computer simulation, which are too complex to be applied. Additionally, Wang et al. [25] presented a nonlinear dynamic model and designed a nonlinear controller, but the model performance was compromised because of ignoring several important heat transfer properties, such as variations of the heat transfer coefficients, heat storage of the coil and so on. Jin et al. [26] showed another dynamic model and the model is able to offer acceptable accuracy and robustness with five or six unknown parameters. In Refs. [27–29], similar dynamic models were also developed for automotive waste heat recovery systems, borehole and ground applications. Constrained by the ACB terminal unit, the secondary air outlet temperatures of and the coil temperature are very difficult to be measured. As a consequence, these available modeling techniques [25–29] become unfeasible here. This paper, however, tries to maintain the important characteristics and achieve a new dynamic model with less information.

In this paper, a hybrid dynamic model is presented, which is the first reported ACB terminal unit model. It is divided with two sub-models. The models for the primary air, induced secondary air and thermal and mechanical mixing of them are lumped together as one sub-model. Another sub-model is a thermal model of the cooling coil. Due to the necessary simplification of the entrainment effect, it is described by an empirical function. In contrast, tremendous effort has been invested on the detailed modeling of the cooling coil based on incomplete information. Using heat transfer mechanism and energy balance principle, a dynamic cooling coil model with no more than five parameters that represent the lumped geometric terms is developed. The unknown model parameters are identified by either a linear or nonlinear least-squares method with the experimental results from a pilot plant. Meanwhile, the experiment data and simulation results are compared to validate the model and illustrate its effectiveness.

2. Model development

Without loss of generality, some assumptions are adopted for ease of mathematical modeling:

1. The mixing of the primary and secondary air is considered instantaneous and homogenous.