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Modeling non-uniform thermal environment of stratum ventilation with supply and exit air conditions

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ABSTRACT

The information (e.g., indoor air temperature and velocity distributions) of the non-uniform thermal environment is the base of the proper operation control of stratum ventilation for thermal comfort and energy efficiency. The current practice of modeling the non-uniform thermal environment requires inputs of the wall temperatures/heat fluxes, which increases the cost and complexity of the sensors because the building management system generally does not monitor the wall temperatures/heat fluxes. This study proposes to model the non-uniform thermal environment with the supply and exit air conditions as inputs. The supply and exit air conditions (i.e., the supply air temperature, supply airflow rate and exit air temperature) can be obtained readily from the building management system. Twenty-eight experiments of two stratum ventilated rooms with different geometries, heat source distributions and air terminal layouts have demonstrated that the proposed method can accurately predict the vertically and horizontally non-uniform distributions of the indoor air temperature and velocity, with root mean square errors (RMSEs) between 0.13 °C and 0.22 °C and between 0.008 m/s and 0.039 m/s respectively. For the dynamic control of stratum ventilation, the models of the indoor air temperatures from the experiments under steady states are found to apply to the dynamic variations of the indoor air temperatures from around 24 °C–30 °C, with RMSEs between 0.28 °C and 0.37 °C. The proposed method has also been experimentally validated to apply to displacement ventilation.

1. Introduction

The air distribution is widely used to create satisfactory indoor thermal environments [1,2]. Mixing ventilation, as the conventional air distribution, aims to uniformly condition the entire space. For better thermal environment and energy efficiency, air distributions with a non-uniform thermal environment are preferred to condition only the occupied zone, e.g., personalized ventilation [3] and stratum ventilation [4]. Stratum ventilation is one of the collective air distributions that serve a group of occupants [4]. Stratum ventilation supplies the cool air horizontally to the head level, with the lowest indoor air temperature and highest indoor air velocity around the head level [5,6]. Air distributions with a non-uniform thermal environment have been reported to possess an energy saving potential from 20% to 75% [2,7].

Existing studies on the air distributions with a non-uniform thermal environment mostly focused on the feasibility studies by subjectively and objectively evaluating the quality of the non-uniform thermal environment [8–10] and simulating the energy performance [4,11]. The effects of the design parameters (e.g., air terminal types and layouts) [12–14] and operation parameters (e.g., supply air temperatures, supply airflow rates, outdoor weather conditions) [6,15,16] on the ventilation performances were also investigated. Additionally, new evaluation methods of the quality of the non-uniform thermal environment were concerned (e.g., the modified PMV model [17], model of heat removal efficiency [18], modified effective draft temperature [19] and equivalent uniform temperature [20]), as well as the energy performance evaluation method [21,22]. However, the proper operation control of the non-uniform thermal environment of the collective air distributions remains a challenge. The control of personalized ventilation theoretically is not a problem because it is controlled by the occupant according to the personal preference [23]. In the following context, the non-uniform thermal environment refers to that created by the collective air distributions.

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The information (e.g., the indoor air temperatures and velocities) of the non-uniform thermal environment is the key to the proper operation of the non-uniform thermal environment [17,18]. Zhang et al. [17,18] modeled the indoor air temperature and velocity of stratum ventilation based on the heat removal efficiency. However, these studies concerned only the averaged air temperature and velocity at the height of 1.1 m. The averaged air temperature and velocity were inadequate to control the non-uniformity of stratum ventilation, when differentiated thermal preferences were concerned [24,25]. Direct measurements of the non-uniform thermal environment require additional sensors in the occupied zone, which increases the cost and complexity of the sensor system and might disturb the space usage [26].

Modeling the non-uniform thermal environment is a promising solution in practice [27]. CFD simulations have been used to model the distributions of the indoor air temperature, indoor air velocity etc. to evaluate the ventilation performances of stratum ventilation [8,13,14]. Nodal models (also termed as multi-node models) have been developed to predict the vertical indoor air temperature distribution of stratum ventilation [28,29]. Compared with the nodal models, CFD simulations can provide more detailed information about the non-uniform thermal environment but requires high computational load [27,30]. The zonal models are the medium of CFD simulations and nodal models regarding the information adequacy of the non-uniform thermal environment and computing time [31]. Additionally, simplified methods based on the assumption of a fixed flow field have been proposed to predict the non-uniform distribution of indoor air temperature rapidly, e.g., the contribution ratio of indoor climate indices [22] and transient accessibility indices [32]. All of these methods require the inputs of wall temperatures/heat fluxes mainly to reflect the disturbance from the ambiance (i.e., the variations of the outdoor weather). Measuring the wall temperatures/heat fluxes would also require additional sensors compared with the operation control of the uniform thermal environment. The operation control of the uniform thermal environment only measures the supply and exit air conditions [33]. The additional sensors for the wall temperatures/heat fluxes increase the cost and complexity for the operation control. Moreover, the number and positions of the additional sensors are difficult to determine for the adequate measurements of the wall temperatures/heat fluxes. This contributes to the relative large deviations between the simulated and measured information of the non-uniform thermal environment, e.g., errors in the indoor air temperature of stratum ventilation from CFD simulations up to 2 °C [24] and errors in the indoor air velocity of stratum ventilation from CFD simulations up to 0.2 m/s [8].

This study proposes to model the non-uniform thermal environment using the supply and exit air conditions as inputs. Both the supply and exit air conditions can be easily obtained from the building management system. Thus the proposed method can be conveniently employed in practice for the operation control of the non-uniform thermal environment, requiring no additional sensors for the wall temperatures/heat fluxes. The proposed method will be explained in Section 2.1. To demonstrate the effectiveness of the proposed method, steady-state experiments for two stratum-ventilated rooms with different geometries, heat source distributions, and air terminal layouts will be introduced in Sections 2.2 and 2.3. The results are presented in Sections 3 and 4. The robustness of the proposed method is discussed in Section 5 by applying it to other collective air distributions with non-uniform thermal environments and to the dynamic states.

2. Methodology

2.1. Modeling non-uniform thermal environment with supply and exit air conditions

The underlying principle of the proposed method to model the non-uniform thermal environment with supply and exit air conditions is explained as follows (Fig. 1). For an air-conditioned room with certain

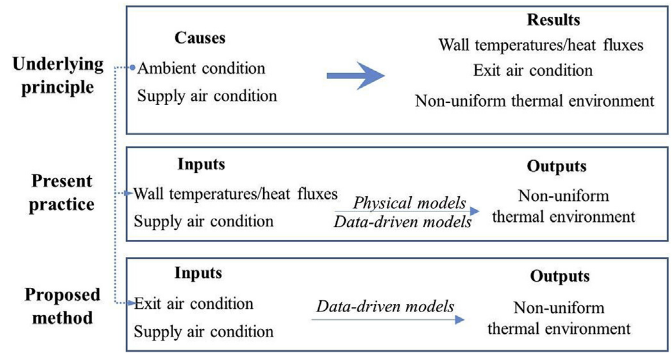

Fig. 1. Underlying principle of modeling non-uniform thermal environment using supply and exit air conditions as inputs.

internal heat sources, the supply air conditions (i.e., supply air temperature and supply airflow rate) and ambient condition (e.g., outdoor air temperature and solar radiation) co-determine the wall temperatures/heat fluxes, exit air condition (i.e., the exit air temperature and exit airflow rate) and indoor thermal environment [34,35]. The direct descriptions of the ambient condition are complex due to its diverse variations. Thus, in present practice, the ambient condition is not used as the inputs of the model of the non-uniform thermal environment [27,36]. Instead, wall temperatures/heat fluxes are used as the inputs (e.g., CFD simulations [27], zonal models [31], and nodal models [37]). This is because the wall temperatures/heat flues result from the ambient condition and can inversely reflect the ambient condition [28,29]. However, as introduced in Section 1, during the building operation, the wall temperatures/heat fluxes are not conveniently available. Particularly, in a non-uniform thermal environment, the wall temperatures/heat fluxes are also non-uniformly distributed [38]. Thus, multiple sensors are required to measure the non-uniform wall temperatures/heat fluxes, which increases the cost and complexity of the sensor system. This study proposes to model the non-uniform thermal environment using the supply and exit air conditions as inputs for two reasons. Firstly, similar to the wall temperatures/heat fluxes, the exit air condition also results from the ambient condition (Fig. 1). Thus, the exit air condition should also be able to reflect the ambient condition inversely. Actually, the exit air condition should be able to inversely reflect all the affecting factors of the indoor thermal environment, because the indoor air finally converges to the exit. Secondly, both the supply air condition and exit air condition are readily available from the building management system. This is consistent with the conventional application scenario of a uniform thermal environment [33]. In other words, with the proposed method, the building management system designed for the uniform thermal environment can also be used for the operation control of the non-uniform thermal environment without requiring more sensors.

There are mainly two types of models for the thermal environment, i.e., the physical models and data-driven models. The physical models are widely used in the design of both the uniform and non-uniform thermal environments, e.g., CFD simulations [27]. Compared with the data-driven models, the physical models are more time-consuming, especially for the non-uniform thermal environment [39]. Since the real-time thermal environment (especially the indoor air temperature distribution) is concerned in the operation control [40], the thermal environment model should be computationally efficient [30]. For computational efficiency, the data-driven model is recommended for modeling the non-uniform thermal environment. The polynomial model is one of the most efficient data-driven models and has been widely used in the field of thermal environment. For example, the polynomial model has been used to model the thermal environments of impinging jet ventilation [41], task/ambient air conditioning system [39] and ceiling fan [42]. Thus, in this study, the polynomial model is