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ESTIMATIONS OF COOLING LOAD AND SUPPLY AIR PARAMETERS OF NON-UNIFORM AIR DISTRIBUTION USING RATIOS TO UNIFORM AIR DISTRIBUTION

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ABSTRACT

Cooling load and supply air parameters are the essential inputs of energy performance evaluation of the air condition system. Non-uniform air distribution (NUAD) benefits energy-efficient provision of comfortable and healthy indoor environment, but leads to increased complexities in the estimations of cooling load and supply air parameters. The non-uniformity-to-uniformity surrogation methodology enables the fully mixed air model to accurately estimate the cooling load and supply air parameters of NUAD, which is technologically convenient and computationally efficient. This study contributes to enriching the non-uniformity-to-uniformity surrogation methodology, which proposes a direct non-uniformity-to-uniformity surrogation by quantifying the ratios of NUAD to UAD regarding the cooling load as well as the supply air temperature/supply airflow rate for the constant-air-volume system/variable-air-volume system. The ratios to UAD are derived as the functions of the outside surface temperature of exterior wall, reference room air temperature and supply airflow rate/supply air temperature of UAD using data-driven modelling (Gaussian process regression). The proposed method is tested on an energy efficient NUAD, i.e., stratum ventilation. Compared with the conventional method which ignores the non-uniformity of stratum ventilation, the proposed method improves the estimation accuracy of the cooling load and supply air parameters by at least 89.1%.

Keywords: cooling load, supply air parameters, non-uniformity-to-uniformity surrogation, ratios to UAD

NONMENCLATURE

Abbreviations	
NUAD	Non-uniform air distribution
UAD	Uniform air distribution
GPR	Gaussian process regression
Symbols	
Q_{cl}	Cooling load
R_{CL}	Cooling load ratio to UAD
R_{SAT}	Supply air temperature ratio to UAD
R_{SAR}	Supply airflow rate ratio to UAD
T_{ow}	Outer surface temperature of exterior wall (°C)
T_{r}	Reference room air temperature (°C)
T_{s}	Supply air temperature (°C)
V_{s}	Supply airflow rate (ACH)

1. INTRODUCTION

Non-uniform air distribution (NUAD) is getting more and more attention because of its energy efficient provision of satisfactory indoor thermal environment [1]. Conventionally, uniform air distribution (UAD), i.e., mixing ventilation, is widely used for indoor air quality and thermal comfort. Different from UAD which targets at the whole room space, NUAD targets at the occupied zone [2]. For example, stratum ventilation supplies conditioned air horizontally into the occupied zone to efficiently cool the most sensitive body part (i.e., head) to thermal comfort with a fresh air layer in the breathing

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zone [3]. Compared with UAD, stratum ventilation was found to save annual cooling energy of the office, classroom and retail shop in Hong Kong by at least 44% [4].

However, the non-uniformity of NUAD increases complexities in the estimations of cooling load and supply air parameters. Accurate estimation of the cooling load and supply air parameters are indispensably required for the provision of indoor thermal comfort [5] and the energy performance evaluation of the air conditioning system [6]. Compared with UAD, the estimations of cooling load and supply air parameters for NUAD are more complexed. Regarding the cooling load, the non-uniformity affects the heat transmission from the ambiance by affecting the convective heat transfer between the room air and the inside surface of the exterior wall [7]. Regarding the supply air parameters, the non-uniformity makes the exit air temperature different from the reference room air temperature (i.e. the air temperature indicating thermal comfort in the occupied zone), and the exit air temperature and cooling load together affect the estimations of the supply air parameters.

The conventional method ignores the non-uniformity of air distribution, and could result in large errors in the estimations of the cooling load and supply air parameters [3]. Co-simulations of non-uniformity of air distribution and building energy can accurately estimate the cooling load and supply air parameters of NUAD, but are computationally deficient and technologically inconvenient in practice [8]. The non-uniformity-to-uniformity surrogation methodology enables the fully mixed air model to accurately estimate the cooling load and supply air parameters of NUAD, which technologically convenient and computationally efficient [3]. The recent non-uniformity-to-uniformity surrogation methodology achieves the non-uniformity-to-uniformity surrogation in an indirect way by quantifying an equivalent room air temperature between NUAD and UAD [3].

This study contributes to enriching the non-uniformity-to-uniformity surrogation methodology in a direct manner. The method proposed in this study directly quantifies the ratio of the cooling load and supply air parameters of NUAD to those of UAD using data-driven modeling. The proposed method is explained in Section 2. The effectiveness in the estimations of the cooling load and supply air parameters for stratum ventilation is demonstrated in Section 3.

2. METHODOLOGY

The proposed method defines three ratios to UAD, i.e., the cooling load ratio to UAD as the ratio of the cooling load of NUAD to that of UAD, the supply air temperature ratio to UAD as the ratio of the supply air temperature of NUAD to that of UAD, and the supply airflow rate ratio to UAD as the ratio of the supply airflow rate of NUAD to that of UAD. With the three ratios to UAD, the cooling load, supply air temperature and supply airflow rate of NUAD can be calculated from those of UAD using Equations 1-3, respectively. Thus, the core task of the proposed method is to quantify the three ratios to UAD.

$$Q_{\mathrm{cl,NUAD}} = Q_{\mathrm{cl,UAD}} R_{\mathrm{CL}} \tag{1}$$

$$T_{\mathrm{s,NUAD}} = T_{\mathrm{s,UAD}} R_{\mathrm{SAT}} \tag{2}$$

$$V_{\mathrm{s,NUAD}} = V_{\mathrm{s,UAD}} R_{\mathrm{SAR}} \tag{3}$$

where $Q_{\mathrm{cl,NUAD}}$ and $Q_{\mathrm{cl,UAD}}$ are the cooling loads of non-uniform air distribution (NUAD) and uniform air distribution (UAD), respectively; R_{CL}, R_{SAR} and R_{SAT} are the ratios of cooling load, supply airflow rate, supply air temperature to UAD, respectively; $T_{\mathrm{s,NUAD}}$ and $T_{\mathrm{s,UAD}}$ are the supply air temperatures of NUAD and UAD, respectively; $V_{\mathrm{s,NUAD}}$ and $V_{\mathrm{s,UAD}}$ are the supply airflow rates of NUAD and UAD, respectively.

For the constant-air-volume system, the supply airflow rate ratio to UAD is one since the supply airflow rate setting is the same for NUAD and UAD. The remaining two ratios to UAD are quantified as Follows. For a given room, with the inputs of the outer surface temperature of exterior wall (representing outdoor weather condition), reference room air temperature (representing indoor environment) and supply airflow rate setting (representing design of the constant-air-volume system), the model of NUAD (e.g., multi-node model [7] and CFD simulation [8]) outputs the cooling load and supply air temperature of NUAD, and the model of UAD (i.e., the fully mixed air model) outputs the cooling load and supply air temperature of UAD. Then, the ratios of cooling load and supply air temperature to UAD can be obtained. With database of the ratios of cooling load and supply air temperature to UAD, outer surface temperature of exterior wall, reference room air temperature and supply airflow rate, data-driven modelling (e.g., Gaussian process regression and support vector machine) can be used to develop the model of the cooling load ratio to UAD and the model of the supply air temperature ratio to UAD as the functions of the outer surface temperature of exterior wall, reference room air temperature and supply airflow rate.

With the developed models of the cooling load and supply air temperature ratios to UAD, the cooling load and supply air temperature of NUAD for the constant-air-volume system can be estimated using the fully mixed air model as follows. Given the inputs of the outer surface temperature of exterior wall, reference room air temperature and supply airflow rate, the cooling load and supply air temperature of UAD can be calculated by the fully mixed air model, and the ratios of cooling load and supply air temperature can be calculated by the developed data-driven models of the cooling load and supply air temperature ratios. And then, the cooling load and supply air temperature of NUAD can be calculated by Equations 1 and 2, respectively.

For the variable-air-volume system, the supply air temperature ratio to UAD is one since the supply air temperature setting is the same for NUAD and UAD. The ratios of the cooling load and supply airflow rate to UAD are modelled using data-driven modelling similar to the above processes of modelling the ratios of the cooling load and supply air temperature to UAD for the constant-air-volume system. With the developed models, the cooling load and supply airflow rate of NUAD can be predicted from those of UAD using Equations 1 and 3, respectively.

3. VALIDATION CASE STUDIES

3.1 Multi-node model of stratum ventilation

The multi-node model is employed to simulate the non-uniformity of stratum ventilation. Compared with CFD simulations, the multi-node model can more computation-efficiently simulate the non-uniformity for the estimations of the cooling load and supply air parameters of NUAD with reasonable accuracy [7]. The multi-node model includes the nodes of inner surfaces of the enclosure (i.e., ceiling, floor, interior partition and exterior wall), and the nodes of room air (air layers near the ceiling, floor, exterior wall and the core zone of the room). Since each node has the information of temperature, the multi-node model can reasonably simulate the non-uniformity of NUAD. Compared with the fully mixed air model with only one node for the room air, the increased nodes of the room air of the multi-node model explain the increased accuracy of the multi-node model for modelling NUAD.

The multi-node model is validated by the experiments in an environmental chamber (located at Xi'an Jiaotong University) configured as a stratum ventilated office with dimensions of 3.8 m × 2.8 m × 2.6 m (Figure 1). Figure 2 shows the vertical air temperature profile of stratum ventilation predicted by the multi-node model is close to that from the measurements, with the absolute error less than 0.3°C. More details about the multi-node model and the experiments can be found in Reference [7] and Reference [9], respectively.

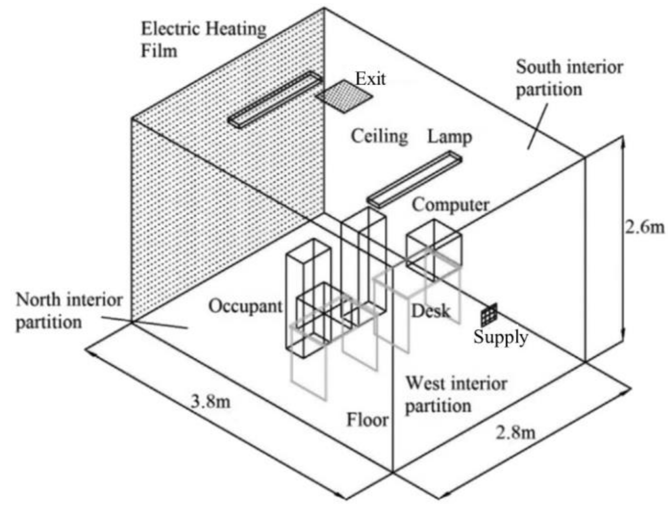

Fig 1 Experiment setup of stratum ventilation

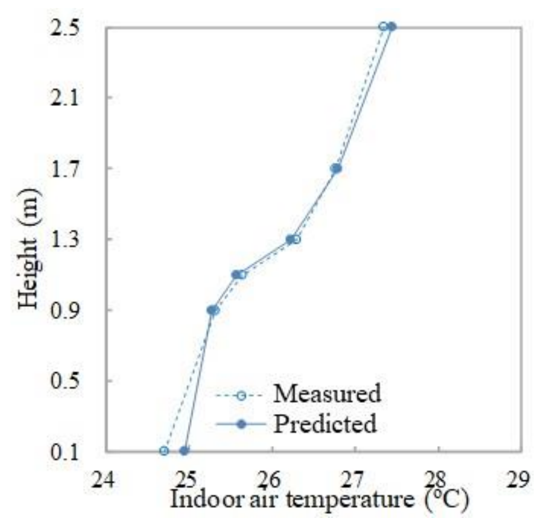

Fig 2 Comparisons of measured and predicted vertical temperature profiles for validation of multi-node model [3]

3.2 Gaussian process regression models of ratios to uniform air distribution

To generate the database for modelling the ratios to UAD, the full factorial design is used. The outer surface temperature of exterior wall is from 30°C to 50°C representing a wide range of the outdoor weather condition. The reference room air temperature is from 25°C to 29°C covering the general thermal condition of stratum ventilation. For the constant-air-volume system, the supply airflow rate setting is from 5 ACH to 15 ACH, and for the variable-air-volume system, the supply air temperature setting is from 17°C to 21°C, representing the general design setting of stratum ventilation. For each parameter, three values are considered, i.e., the lowest, the medium and the highest. Thus, 27 cases are obtained (i.e., the 27 combinations the three parameters with three values) for both the constant-air-volume system and the variable-air-volume system.

The algorithms of the regression learners (including the linear regression models, regression trees, support vector machines and Gaussian process regression models) are tested to develop the models of ratios to UAD. Gaussian process regression is selected because of the minimal root mean square error. This is consistent with results reported by Fang et al. [10] that Gaussian process regression was selected for the space cooling load modelling of a heat pump system for the good prediction performance. The ratios of the cooling load and supply air temperature to UAD of the constant-air-volume system predicted by the models of Gaussian process regression are close to those from the experimentally validated multi-node model, with the root mean square errors 0.01% and 0.03%, respectively. The ratios of the cooling load and supply airflow rate to UAD of the variable-air-volume system predicted by the models of Gaussian process regression are also close to those from the experimentally validated multi-node model, with the root mean square errors 0.47% and 0.05%, respectively. Due to the length limit of the paper, the model detailed information about modelling is not presented.

3.3 Estimations of cooling load and supply air parameters

To validate the proposed method, 10,000 validation cases are randomly generated, i.e., 10,000 different combinations of the outer surface temperature of exterior wall (from 30°C to 50°C), reference room air temperature (from 25°C to 29°C) and supply airflow rate setting (from 5 ACH to 15 ACH)/supply air temperature setting (from 17°C to 21°C) for the constant-air-volume system/variable-air-volume system. Thus, the validation cases are much wider than the training database of 27 cases (Section 3.2).

For the constant-air-volume system, Figure 3 shows that the proposed method accurately estimates the cooling load and supply air temperature of stratum ventilation. The absolute error in the cooling load estimation is less than 0.3% with the root mean square error of 0.09%, and the absolute error in the supply air temperature estimation is less than 4%, with the root mean square error of 1.31%. The conventional method has an absolute error in the cooling load estimation less than 6% with a root mean square error of 2.99% (Figure 4(a)), and an absolute error in the supply air temperature estimation up to around 30%, with a root mean square error of 12.19% (Figure 4(b)). Thus, compared with the conventional method, the proposed method improves the accuracy in the cooling load estimation and supply air temperature estimation for the constant-air-volume system of stratum ventilation by 97.0% and 89.3%, respectively.

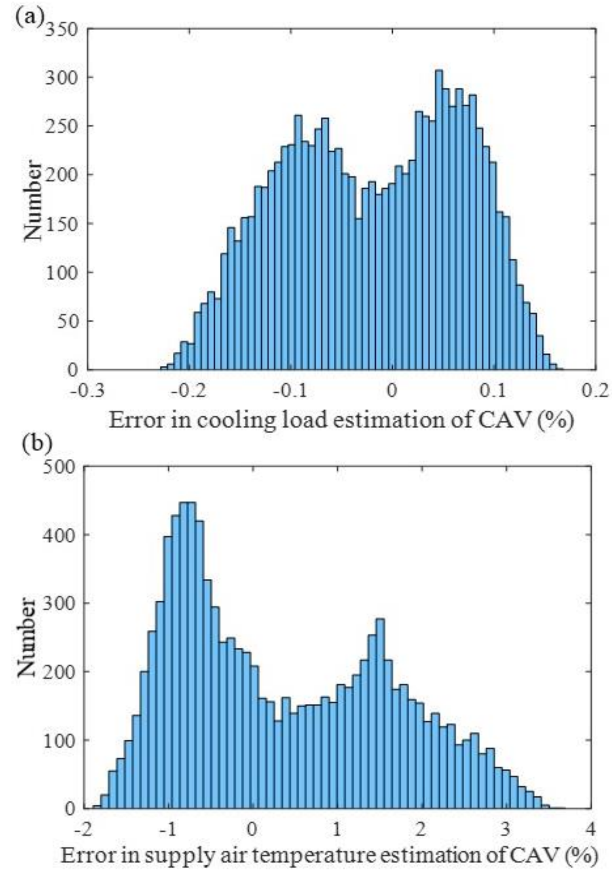

Fig 3 Errors in estimations of cooling load and supply air temperature by proposed method for constant-air-volume system (CAV)

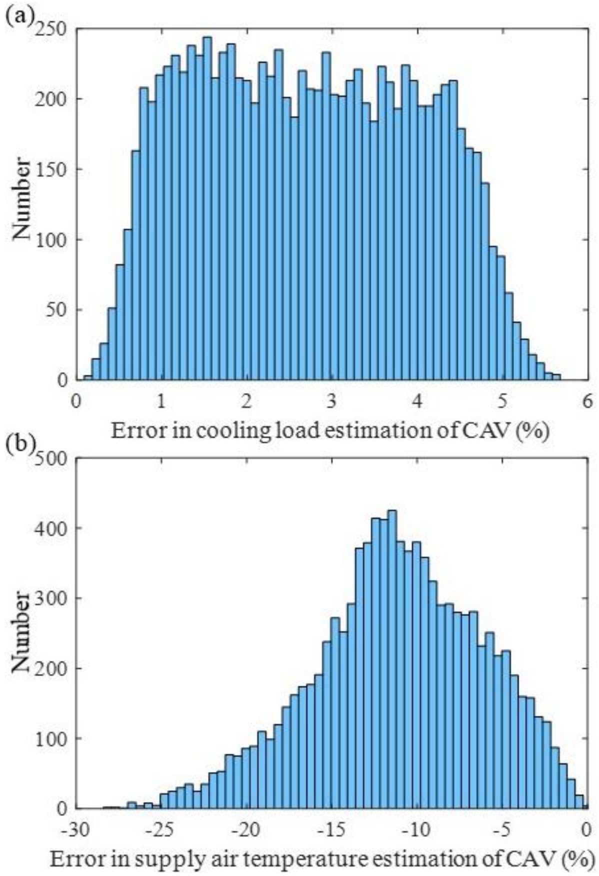

Fig 4 Errors in estimations of cooling load and supply air temperature by conventional method for constant-air-volume system (CAV)

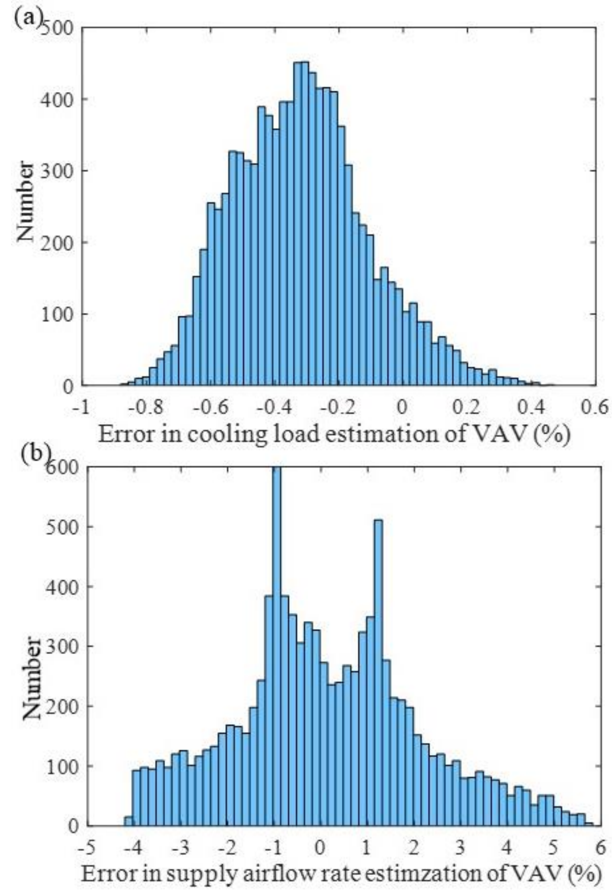

Fig 5 Errors in estimations of cooling load and supply airflow rate by proposed method for variable-air-volume system (VAV)

For the variable-air-volume system, Figure 5(a) shows that the absolute error in the cooling load estimation by the proposed method is less than 1% with a root mean square error of 0.38%. Figure 5(b) shows that the absolute error in the supply airflow rate estimation by the proposed method is less than 6%, with a root mean square error of 2%. The conventional method reasonably predicts the cooling load with an absolute error less than 7% with a root mean square error of 3.5% (Figure 6(a)). However, the conventional method would result in an inaccurate supply airflow rate estimation, with an absolute error up to 90% and a root mean square error of 57.61% (Figure 6(b)). Compared with the conventional method, the proposed method improves the accuracy in the cooling load estimation and supply airflow rate estimation for the variable-air-volume system of stratum ventilation by 89.1% and 96.5%%, respectively.

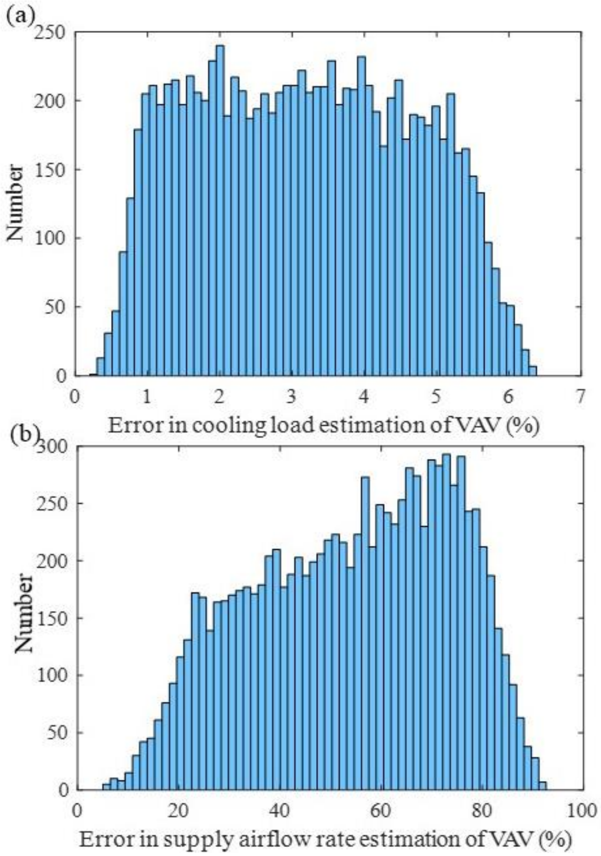

Fig 6 Errors in estimations of cooling load and supply airflow rate by conventional method for variable-air-volume system (VAV)

4. CONCLUSIONS

This study proposes a new non-uniformity-to-uniformity surrogation method to enable the fully mixed air model to accurately estimate the cooling load and supply air parameters of NUAD, which is technologically convenient and computationally efficient. The proposed method defines the ratios of cooling load and supply air parameters to UAD, and models them using data-driven modelling (Gaussian process regression). With the developed models, the cooling load and supply air parameters of NUAD can be calculated from those of UAD. Case studies on stratum ventilation using the experimentally validated multi-node model show that proposed method estimates the cooling load and supply air parameters with the absolute error less than 6% and root mean square error not greater than 2%. Compared with the conventional method, the proposed method improves the accuracy in the estimations of the cooling load and supply air parameters by 89.1% at least.

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