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Experimental study on air change effectiveness: Improving air distribution with all-air heating systems

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ABSTRACT

A major challenge of all-air heating applications is poor air distribution, which is often associated with a high temperature stratification. The two metrics that are commonly used for design and assessment of supply air distribution in the space are: air distribution performance index (ADPI) and the Air Change Effectiveness (E), respectively. All-air heating systems often produce stagnant air in the occupied part of the room. In this case, E may be very low while relatively uniform temperature in this occupied zone results in acceptable ADPI. Since ventilation design is based on ADPI, many all-air heating systems often produce very low E. This experiment based study identifies situation with very low E and provides simple strategies to improve it. The study provides additional design criteria to the ADPI diffuser selection guide that helps with optimal diffuser selection and adjustments. The results show that additional design criteria significantly improve E as well as temperature distribution, measured by temperature effectiveness ($\mathcal{E}_T$), with all-air heating systems. Appropriate adjustment of the diffuser may improve E and $\mathcal{E}_T$ up to 30%, while the lower supply-room air temperature difference may increase E and $\mathcal{E}_T$ in average 75% and 45%, respectively. Also, proper return air inlet location significantly improves E and $\mathcal{E}_T$ for all-air heating. However, there are certain trades off as: the diffuser adjustment also may require seasonal adjustment for cooling and heating operation, lower supply air temperature difference requires more fan power, and floor exhaust placement may need more space for duct work.

1. Introduction

Mixing ventilation is the most common type of air distribution, used much more than alternative air distribution strategies such as piston, displacement, stratum, and personalized ventilation [1]. Achieving the ideal mixing in the room depends on an air distribution design; it can apply various types of supply air diffusers and return air inlets (exhaust) to create a mixing ventilation in different space types [2]. The impact of supply air diffusers on room air temperature and velocity under cooling applications are well studied [3], while there is much less information on the impact on the fresh air dispersion in heating applications. Also, there is very little information on the impacts that location of exhaust has on the air distribution. A major challenge of mixing ventilation is in heating application (all-air heating) as it causes poor air distribution due to a high temperature stratification [4–8]. Fisk et al. [4] conducted experiments that used overhead all-air-heating system that supplied minimum air supply flow rate of typical VAV systems. The air change effectiveness was significantly lower than 1.0 in each experiment. The measured air change effectiveness was in the range of 0.69–0.91 with mean value of 0.81. Offermann et al. [5] measured ventilation effectiveness and ADPI under heating conditions. For the ceiling supply/return configuration, ventilation effectiveness was 0.73 when temperature difference of supply air temperature and room average temperature was 8 °C. Krajcik et al. [6,7], measured air change efficiency and temperature effectiveness in a test chamber with various combinations of radiant floor heating and mixing ventilation. Theses all-air heating systems often produce stagnant air in the occupied space of the room with relatively uniform low temperature in this stagnant zone. However, with stagnant cold air in occupied zone, the fresh hot supply air short circuit in the upper part of the room causes very poor ventilation effectiveness in the occupied space.

In any application, it is important to consider both thermal

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comfort of occupants and effective distribution of supply air to the occupants not only for cooling but also for heating. An effective air distribution improves indoor air quality by providing fresh air in all areas of the occupied zone and thermal comfort by providing uniform temperature distribution and acceptable velocities [9]. The widely used design method for indoor air distribution is Air Diffusion Performance Index (ADPI) [11]. The index, percentage of the whole occupied zone with acceptable air velocity and temperature ranges, quantifies the performance of supply air diffusers to create a uniform thermal environment in the occupied zone. ADPI provides engineers and practitioners a simple tool to design air distribution that is usually associated with complex heat transfer and fluid dynamics [12]. The concept of ADPI first introduced and developed the correlations between diffuser properties and indoor air distribution performance for five types of terminal diffusers at cooling conditions. Recent studies have updated the ADPI metric to include 15 diffuser types [3,13–15]. Also, these studies removed the deficiency of ADPI method related to applicability to only cooling systems; the new ADPI guideline is valid for both heating and cooling conditions. Furthermore, the studies identified the conditions where poor ventilation effectiveness appears in all air heating. Specifically, when warm supply air is delivered in the room with a weak jet momentum, the supply air short circuit in the ceiling level generating stagnant air in the occupied zone.

Locations of supply air diffuser and exhaust impact air distribution and their ventilation effectiveness in the space have been investigated by many researchers [16–18]. Sinha et al. [16] compared impact of different inlet and outlet locations using models and computational fluid dynamics. The study found that the most effective combination of inlet and outlet positioning is with inlet near the floor and exhaust near the ceiling. When considering position of air supplies in the upper part of the room, Lee et al. [17] experimentally compared high wall jet from grill diffusers with typical ceiling diffusers. Their results show that the air inlet position and type are important determinants in the distribution of airborne contaminant concentrations. Overall, the ceiling diffuser produced more efficient ventilation than the wall jet air inlet. In Khan's study [18], the arrangements of wall inlet and outlet greatly influence contaminant concentration. However, the influence of the outlet location is minimal with ceiling diffuser inlet. Since the air near exhaust is not driven by jet momentum but by negative pressure in the air, the velocities near exhausts are relatively small. Therefore, the effects of the exhaust location on room airflow pattern are relatively small in most applications. However, the exhaust location influences Air Change Effectiveness and Contaminant Removal Effectiveness [2]. Location of exhaust is even more important when mixing ventilation provides heating. ASHRAE standard 62.1 [19] assumes Air Change Effectiveness (E) of 0.8 when a 0.8 m/s jet does not reach to the lower part of the room or when the supply-room temperature difference is larger than 8 °C. In the literature, Ventilation Effectiveness is defined as description of air distribution system's ability to remove internally generated pollutants from a building zone or space, while the E is an air distribution system's ability to deliver ventilation air to occupied zone or space [10]. In the following section of the paper, we will use E as the index that describes quality of the air distribution and the ventilation effectiveness.

Our previous study [20] conducted extensive experiments on E in mixing ventilation. These data combined with the results from the latest ADPI study [3] and provided comprehensive data set on diffuser performance considering both uniformity of the temperature field and range of E in the both cooling and heating applications. E and temperature effectiveness (ε_T) were slightly higher than 1.0 in cooling applications. However in heating application, E was significantly decreased at small $T_{0.25}/L$ even though ADPI was in acceptable range (ADPI higher than 80%); this poor E due to the short circuit of the supply air. E within the acceptable ADPI range of $T_{0.25}/L$ (recommended range) was 0.56–0.87. This short circuiting of hot air puts performance of many diffusers in the range that is lower than specified value in ASHRAE standard 62.1, $E > 0.8$.

To overcome the challenges of poor ventilation under heating conditions, this study examines simple strategies that may improve E and ε_T under heating conditions, while maintaining acceptable ADPI; specifically, it evaluates the impacts of diffuser deflector adjustment with linear slot diffusers and adjustable blades grills, room-supply air temperature difference with vertical flow of linear slot diffusers, and exhaust locations with adjustable blade grill. In addition, it provides new diffuser selection data in the form of the ADPI for diffusers with a vertical jet projection (vertical flow) categorized as Group E in ASHRAE Handbook [21].

The following section briefly summarizes indices utilized to evaluate the performance of the mixing ventilation systems used in this study. It is followed by the methodology section that describes experimental setup and matrix of experiments. The results section compares different indices to evaluate impacts of analysed ventilation performance strategies, while the conclusion section synthesizes major findings.

2. Theoretical background and description of used indices

This section explains three indices: Air Diffusion Performance Index (ADPI), Air change effectiveness (E) and Temperature effectiveness (ε_T), that are most commonly utilized to evaluate air distribution performance. It provides short overview of variables and physical phenomena and explains the basics for interpretation of the tables and graphs in the results section.

2.1. ADPI

ADPI is defined as the percentage of the occupied zone that maintains acceptable velocity and temperature. The region of acceptable velocity and temperature is determined by local Effective Draft Temperature (EDT) that combines air temperature difference and air speed [22–24]. EDT for cooling condition is defined as,

$$EDT(\theta) = T_i - T_a - 8.0(V_i - 0.15)[^{\circ}C] \tag{1}$$

where T_i is temperature at the test point, i; T_a is spacious average temperature (°C) and V_i is local air speed (m/s). EDT for heating condition is defined as [3,13].

$$EDT(\theta) = T_i - T_a - 9.1(V_i - 0.15)[^{\circ}C] \tag{2}$$

ADPI incorporates the throw and the characteristic length, and it provides design variables for selecting diffusers. The dominant diffuser property for air distribution is the supply jet throw length at which the jet velocity decreases to a selected terminal value of 0.25 m/s ($T_{0.25}$) [25]. The characteristic length (L) describes the room geometry in the form of the distance at which jet travels. The ratio $T_{0.25}/L$ is a dimensionless number that characterizes a supply diffuser momentum (including capacity of a diffuser to mix/entrain surrounding air) for given flow rate. $T_{0.25}/L$ has the largest impact on ADPI, and together $T_{0.25}/L$ and ADPI are used in the diffuser selection guideline provides by ASHRAE Handbook [11]. The guideline lists the relationships between ADPI and a dimensionless ratio of $T_{0.25}/L$ for various diffuser types at different thermal loads. One is able to design an HVAC terminal system, such as diffuser selection and layout, by ensuring $T_{0.25}/L$ of the system renders ADPI greater