Numerical study on the performance of an Multiple PCMs unit for air distribution

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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 (ƐT), with all-air heating systems. Appropriate adjustment of the diffuser may improve E and ƐT up to 30%, while the lower supply-room air temperature difference may increase E and ƐT in average 75% and 45%, respectively. Also, proper return air inlet location significantly improves E and ƐT 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.

Keywords

Ventilation effectiveness; Mixing ventilation; ADPI; All-air heating; Diffuser adjustments.

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][5][6][7][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.

2. Experimental

The first part of the methodology section describes the diffusers tested in this study. The second part explains the two series of experiments: (1) experiments related to ADPI and (2) experiments related to E and ƐT. These two series of experiments were conducted in the same test room at the University of Texas at Austin and the testing methodologies followed previous studies procedures described greater details in Refs. [3][9][10][11].

Fig. 1a shows the linear slot diffusers (Model SDS75, frame size 190 mm × 1200 mm, Price Industries, Inc.) with vertical flow used in the experiments. The diffusers provide various airflow patterns by adjustabling deflectors. The performance of linear slot diffusers with horizontal projection can be found in the previous study related to air change effectiveness [11]. The vertical flow allows to supply primary air directly to the occupied space and may increase E and ƐT. However, a higher air velocity in occupied space may compromise ADPI.

Fig. 1b shows adjustable blade diffusers (Model 51DV, frame size: 150 mm × 600 mm, Nailor HVAC, Inc.) used as high side wall diffusers. This specific model is a good representative of all high side wall adjustable blade diffusers [3], [12]. The diffusers also allow different airflow directions by adjustment of blade angles. To evaluate the impact of adjustments on E and ƐT, blades angle were set three patterns: 0° horizontal, 45° Upward and 45° Downward. The ADPI with each adjustments was determined in our previous studies [3], [12]. In previous studies, 45° Upward projection allowed supply air to easily attch to the ceiling and slide along the ceiling due to Coanda effect, resulting in better ADPI under cooling conditions. However, it may cause higher thermal stratifications and lower E under heating conditions. 45° Downward projection directly supplies air to the occupied zone which may increase E. However, it may also cause lower ADPI because of higher velocity in occupied space. 0° Horizontal blade position was considered as the nominal setting, and different exhaust locations were tested with nominal setting.

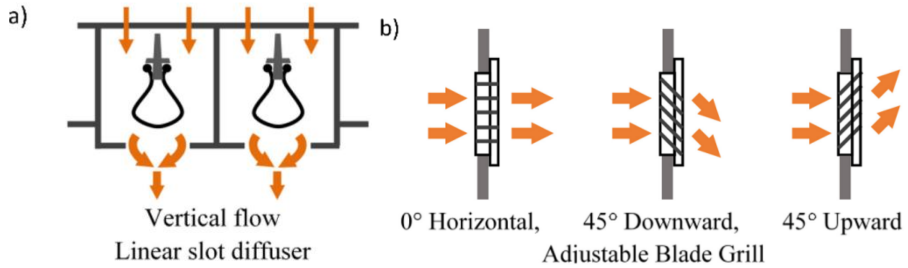

Fig. 1. Diffusers used in this study: a) Linear slot diffuser with vertical flow, b) Adjustable blade grill with 0° Horizontal, 45° Upward, and 45° Downward adjustment.

Fig. 2 illustrates experimental setups of the test room for ADPI measurements. ADPI measurements were conducted under the same chamber and setups as our previous studies [3][13], [14]. Heating load was simulated by adjusting the temperature of the cooled wall connected to a dedicated chiller, which together mimicked exterior wall or window in winter condition. Although particle image velocimetry (PIV) measurement [15] can be used to better visualizing the airflow fields, velocity and temperature at sixty locations in the occupied zone at four different heights above the floor (0.1 m, 0.6 m, 1.1 m, and 1.7 m) were measured with twelve hot-sphere anemometers (HT-400, SENSOR, Poland, accuracy: ±0.03 m/s + -3%, temperature: ±0.2 °C). The measurements were repeated five times for each experiment to obtain sixty locations with the twelve available sensors. At the same time, the vertical temperature (0.1 m, 0.6 m, 1.1 m, 1.4 m, 1.8 m, 2.2 m) was measured at five different locations by thermistors (Model 44033, OMEGA, Accuracy: ±0.1 °C). Furthermore, supply and exhaust air temperatures were monitored during the experiments to ensure the stability of the chamber conditions.

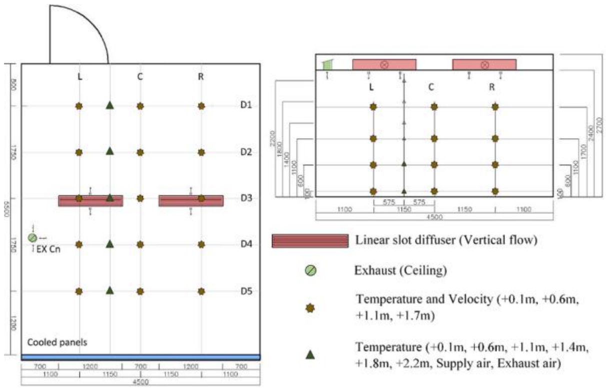

Fig. 2. Experimental setup of a test room for ADPI measurements. (Chamber geometry, temperature and velocity measurement locations).

Fig. 3 illustrates experimental setup for E and ƐT measurements. The experimental setup allowed adjustable blade diffusers with high side wall position, and 2 slots and 4 slots linear slot diffusers with vertical flow. Dimensions of the plenum box for adjustable blade diffuser is also described in Fig. 3. Furthermore, Fig. 3 shows the five specific exhaust locations to evaluate the impact of the exhaust locations. There were three locations for ceiling mounted positions: EX Cd, EX Cn, and EX Cw, and the two locations near floor: EX Fd and EX Fw.

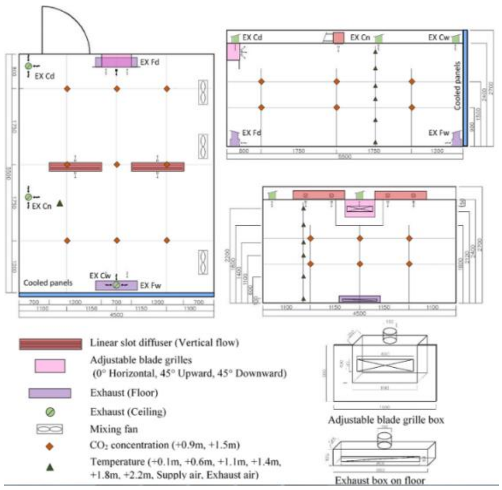

Fig. 3. Experimental setup of a test room for E and ƐT measurements (Chamber, adjustable blade grille box and exhaust box geometry, temperature and CO2 concentration measurement locations).

3. Results And Discussion

This section is divided into two parts, presenting results from two series of experiments: 1) experiments with linear slot diffusers with vertical flow, and 2) experiments with adjustable blade diffusers with different deflector angles and exhaust locations.

Fig.4 shows the results of ADPI,E and ƐT with ΔT = -5 °C. Fig. 4 displays the results of 2 slots diffusers (Fig. 4a and b) slots diffusers (Fig. 4c and d). The solid marks indicate that supply air temperatures (TSA) is less than 8 °C above average occupied space temperature (<T>0). Marks without fill indicate that TSA is 8 °C or more than <T>0.

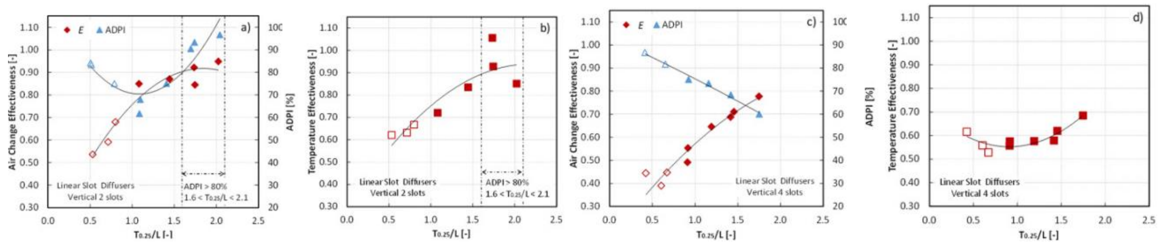

Fig. 4. Linear slot diffusers with vertical flow under ΔT = -5 °C (Case A.1-6 Case A.7-12, Case B.1-8 and Case B.9-17), a) and c): T0.25/L vs. E (left side y-axis) and ADPI (right side y-axis), b) and d): T0.25/L vs. ε_T.

With 2 slots linear slot diffusers (Fig. 4a), higher ADPI found in lower and higher T0.25/L. Although ADPI is high in lower T0.25/L, E and ƐT are low. The range of T0.25/L that can achieve ADPI higher than 80% with TSA less than 8 °C above <T>0 (herein after recommended range) is 1.6–2.1. E and ƐT are approximately 0.9 within recommended range. The small momentum of supply air at low T0.25/L cannot provide enough mixing in the space and causes high thermal stratification and low ADPI. Conversely, a strong vertical momentum increases overall mixing performance of the space, resulting in higher ADPI, E and ƐT; however the excessive air speed may resuts in discomfort asociated with a draft in the area below the diffuser.

Different from the results of 2 slots, ADPI is decreased as T0.25/L is increased with 4 slots diffusers (Fig. 4c). ADPI higher than 80% is found only in lower T0.25/L at which high thermal stratification causes lower E and ƐT. However, higher T0.25/L improves both Eand ƐT due to an increased mixing effect. 4 slot diffusers performs quite different from 2 slot diffusers regarding ADPI. This will be further discuss in the later results section with descriptions of room air velocity and temperature fileds.

Fig.5 shows the results of ADPI, E and ƐT measurements with ΔT = -2. ADPI is higher than 80% for both 2 slots and 4 shots diffusers within the tested ranges of T0.25/L, implying that small ΔT enhances ADPI significantly. The highest E is greater with 2 slots diffusers than with 4 slots diffusers: E is 1.1 with 2 slots diffusers, 0.8 with 4 slots diffusers respectively. The highest ƐT is also greater with 2 slots diffusers than with 4 slots diffusers: 1.05 with 2 slots diffusers, 0.9 with 4 slots diffusers respectively.

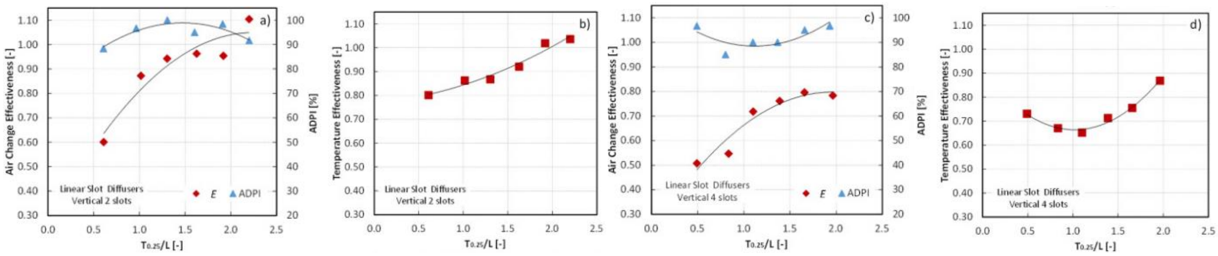

Fig. 5. Linear slot diffusers with vertical flow under ΔT = -2±2 °C (Case A.13-18, Case A.24-29, Case B.18-23 and Case B.24-29), a) and c): T0.25/L vs. E (left side y-axis) and ADPI (right side y-axis), b) and d): T0.25/L vs. ƐT.

Fig. 6 shows the results of velocity and temperature fields with ADPI measurements (Case A.1, A.3, A.5, and A.12). Temperature fields show with temperature differences between supply air and point of measurements (ΔTSA-i = TSA-Ti). For Case A.1 (2 slots, T0.25/L: 0.5 (2.1 h−1)), air velocity below 1.7 m is less than 0.25 m/s. Temperature stratification (maximum temperature difference within occupied space) is less than 2 °C. For Case A.3 (2 slots, T0.25/L: 1.1 (4.5 h−1)), jet from the diffuser (velocity higher than 0.25 m/s) reaches to 1.7 m. Temperature stratification is 4 C° between 0.1 m and 1.7 m.

Fig. 7 shows the results of ADPI, E and ƐT measurements with different blade angles: 0° Horizontal, 45° Downward, and 45°. ADPI shown in Fig. 7a, c and 7e with right side of y-axis extracted from a previous study [3]. The solid marks indicate that TSA, is within 8 °C above <T>0. Marks without fill indicate that TSA is 8 °C or higher than <T>0.

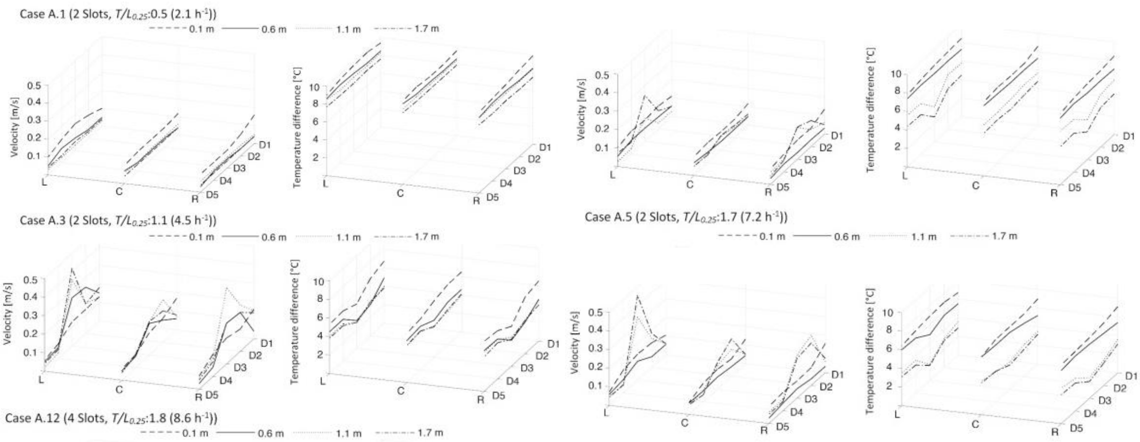

Fig. 6. Velocity and temperature fields in ADPI measurements (Case A.1, A.3, A.5, and A.12).

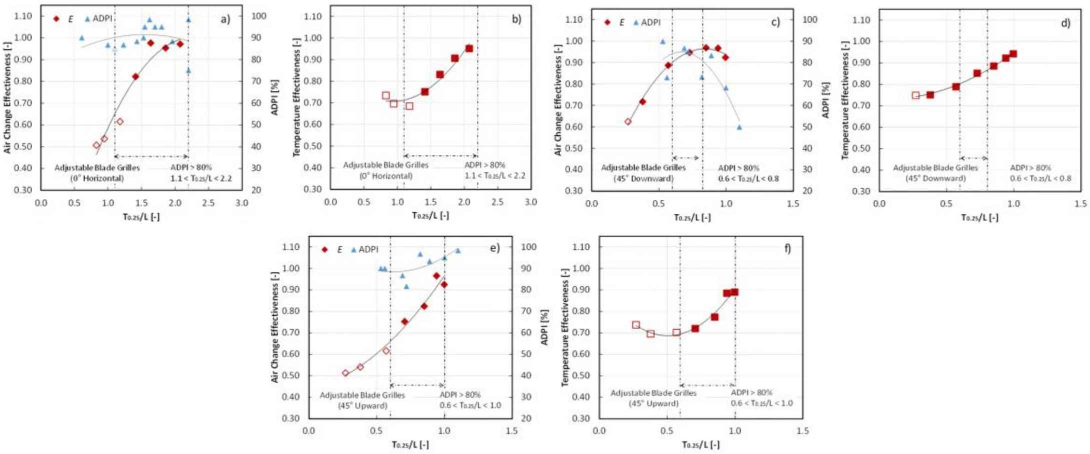

Fig. 7. Adjustable blade grill with different blade angles (Case B.30-36, Case B.37-43 and Case B.44-50, and ADPI results from a previous study [3]), a), c) and e): T0.25/L vs. E (left side y-axis) and ADPI (right side y-axis), b), d) and f): T0.25/L vs. ƐT.

With 0° Horizontal adjustments in Fig. 7a and b, the ranges of E and ƐT within recommended ranges are 0.65–0.98, and 0.71–0.95 respectively. E is significantly decreased when T0.25/L is small. Even within recommended range, E and ƐT are approximately 0.6 and 0.7 respectively. The thermal stratification for such conditions is quite high since TSA is 8 °C or higher than <T>0.

Fig. 8 shows the results of E and ƐT with different exhaust locations with the 0° Horizontal adjustments. Fig. 8a shows E, and Fig. 8b shows ƐT. The vertical dash lines display the recommended range with EX Cn.

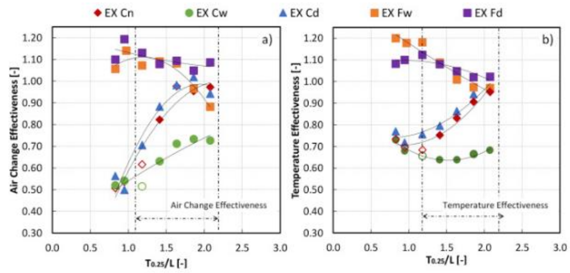

Fig. 8. Adjustable blade grill (0° Horizontal adjustment) with different exhaust locations (Case B.30-36, Case B.51-57, Case B.58-63, Case B.64-71 and Case B.72-78), a): T0.25/L vs. E, b): T0.25/L vs. ƐT.

Results shows that similar to EX Cn, E and ƐT are almost equivalent to those for EX Cd. The location of EX Cw yield lower E and ƐT than EX Cn. The maximum E and ƐT are 0.7 because short circuit occurs when the exhaust is located at the opposite side of the diffuser. With near floor exhaust (EX Fw and EX Fd), E and ƐT are significantly higher than the ceiling mounted exhaust especially with low T0.25/L. With EX Fw, E and ƐT are greater than 1.0 when T0.25/L is lower than 1.7. E and ƐT slightly decrease as T0.25/Lincrease. As exhaust located opposite side of the diffuser, short circuit flow may increase once jet from the diffuser reaches to the opposite side of the wall. With Ex Fd, E and ƐTare higher than 1.0 and they are not sensitive to T0.25/L. The results suggest that near floor exhaust significantly improves ventilation effectiveness and air distribution performance compared to ceiling mounted exhaust. A higher supply airflow rate (higher T/L0.25) may not be helpful for effective air distribution for the floor mounted exhaust.

Fig. 9 compares vertical and horizontal flow adjustments of linear slot diffusers under ΔT = -5 °C. Results of E and ƐT with the horizontal flow adjustments are extracted from a previous study [11]. Fig. 9 also shows the recommended ranges with dash lines. The ranges indicate with air change rate to compare different T0.25/L.

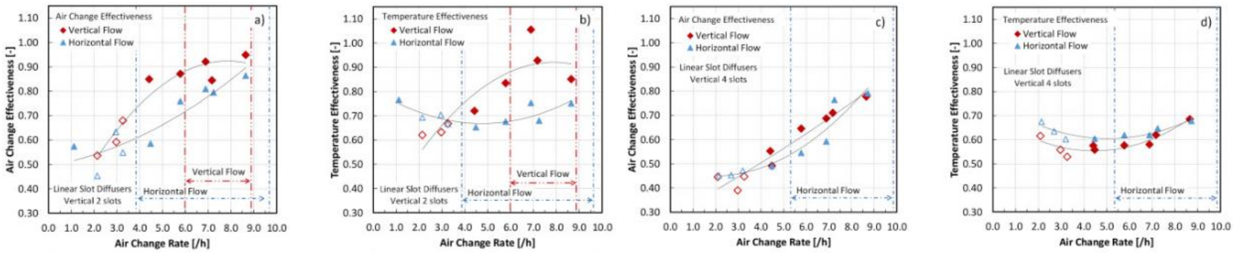

Fig. 9. Linear slot diffusers with vertical and horizontal flow (Case B.1-8, Case B.9-17 for vertical flow and results from a previous study [20] for horizontal flow), a) Air change rate vs. E, b): Air change rate vs. ƐT.

Fig. 10 compares E and ƐT of different angles adjustments for adjustable blade diffusers under ΔT = -5 °C. The dash lines display the recommended ranges with air flow rate. The recommended range is narrower with 45° Downward than with 0° Horizontal and 45° Upward. 45° Downward is able to increase E and ƐT about 30% and 15% at the maximum, compared to the 0° Horizontal condition, respectively. Similar to the adjustment of the linear slot diffuser, downward blades can direct air flow to the occupied space to improve E and ƐT under heating conditions. However, air flow rate needs to be properly controlled to avoid significant decrease in ADPI.

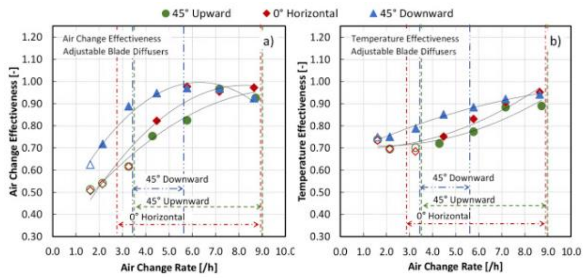

Fig. 10. Adjustable blade grills with different deflector adjustments (Case B.30-36, Case B.37-43 and Case B.44-50), a): Air change rate vs. E, b) Air change rate vs. ƐT.

Fig. 11 compares ΔT = -2 °C and ΔT = -5 °C under the same heating load for linear slot diffusers with vertical flow. The figure examines how ΔT effects ventilation performance. Lower ΔT may significantly increase E and ƐT. Compared to the Cases with ΔT = -5 °C, Cases with ΔT = -2 °C increase E about 75% on average (100% at the maximum) and also increase ƐT about 45% on average (65% at the maximum), respectively. This analysis provides supportive data for HVAC designers to determine optimal design ΔT. A lower ΔT may require less fresh air (ventilation rate) to satisfy required ventilation rate in occupied zone and less heating energy as it improves both E and ƐT.

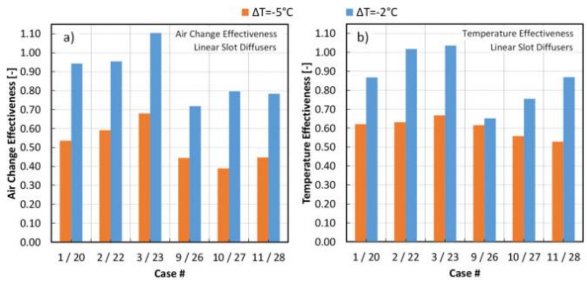

Fig. 11. Linear slot diffusers with vertical flow under same heating load (ΔT = -5 °C and ΔT = -2 °C). a): E, b): ƐT.

4. Conclution

This study conducted experimental measurements of ADPI, E and ƐT in a full-scale test room. Combined with previous studies [3][11][12][13], the results provide supportive data for optimal diffuser selections in mixing ventilation, with an emphasis on the improvement of E and ƐT in heating applications. Proper applications of each tested strategy: diffuser adjustment, lower ΔT and exhaust location may significantly improve Eand ƐT. This study shows that the proper adjustment of diffuser, lower ΔT and different exhaust location may improve E about 25–30% at the maximum, 75% in average and 70% at the maximum, respectively. However, designer also have to consider other aspects of those strategies such as narrower range of recommended T0.25/L with vertical flow and trade off of fan power with lower ΔT.

Acknowledgements

This work is supported by the National Natural Science Foundation of China（No. 11602066） and the National Science Foundation of Heilongjiang Province of China (QC2015058 and 42400621-1-15047), the Fundamental Research Funds for the Central Universities.

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