Building and Environment 109 (2016) 101–111

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

# Experimental study on air change effectiveness in mixing ventilation

Hideyuki Amai*, Atila Novoselac

*Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, Austin, TX, USA*

ARTICLE INFO

*Article history:*
Received 11 June 2016
Received in revised form
1 September 2016
Accepted 11 September 2016
Available online 12 September 2016

*Keywords:*
Ventilation effectiveness
Mixing ventilation
ADPI
All air heating
Tracer gas

ABSTRACT

Mixing ventilation is the most common air distribution system, and often the same diffusers provide space cooling and heating. Proper diffuser selection affects characteristics of air distribution. Air distribution with all-air-heating is one of the major challenges for mixing ventilation as temperature stratification and corresponding low ventilation effectiveness may appear. The objective of this study is to provide supporting data for air distribution system designs for several of the most common types of ceiling diffusers in the cooling and heating regime. It defines operation range for selecting diffusers with: high ADPI and ventilation and temperature effectiveness. The study is based on experimental measurements in a full-scale test room. Air change effeteness was measured using $CO_2$ tracer gas decay tests with various types of ceiling diffusers and internal loads. Also, the air flow was changed to produce different corresponding throw for the tested diffusers ($T_{0.25}$), which with characteristic space length for the diffuser jet flow ($L$) defined $T_{0.25}/L$ ratio. The results show that under heating conditions the air change effectiveness significantly decreases with decrease of $T_{0.25}/L$. Even for the recommended range of $T_{0.25}/L$, the value of air change effectiveness and temperature effectiveness are low: 0.56 to 0.87 and 0.58 to 0.75, respectively. Under cooling conditions, air change effectiveness and the temperature effectiveness were close to or higher than 1, regardless of diffuser type. The range of $T_{0.25}/L$ value that can achieve good mixing under heating condition was significantly smaller than the one under cooling mode.



## 1. Introduction

Providing occupants comfort and healthy environment with the minimum use of energy is the ultimate purpose of heating, ventilating and air conditioning (HVAC) systems. Building ventilation directly affects indoor air quality, and it influences occupants' heath and productivity. Several types of ventilation methods were investigated by many researchers [1], including mixing system with various inlet and outlet locations, and non-mixing air distribution such as: piston, displacement, stratum, and personalized ventilation. Among various types of ventilation, the most known and used ventilation method is mixing ventilation. The mixing ventilation method has been applied to large variety of room types through the use of diverse types of air diffusers and exhaust vents [2]. With mixing ventilation, locations of air inlet and outlet affect air distribution in the space. Sinha et al. [3] 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 was with inlet near the floor and exhaust near the ceiling because the buoyancy force increased the intensity of recirculation with this combination. When considering position of air supplies in the upper part of the room, Lee et al. [4] experimentally compared high wall jet from grill diffusers with typical ceiling diffusers. Their results showed 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. Unlike the air supply location, impact of the air exhaust location to structure of room air flow is relatively small in most room applications [2]. This is due to lack of jet momentum a rapid decay of velocity with increasing distance from exhaust opening. However, the exhaust location may influence air change effectiveness and contaminant removal effectiveness. In Khan's study [5], the arrangements of wall inlet and outlet greatly influenced contaminant concentration. However, the influence of the outlet location was minimal with ceiling diffuser inlet.

Space partitioning such as cubicles and internal objects such as furniture or occupants may also impact effectiveness of the air distribution [6–8]. However, Shaw et al. [6] showed the partition height up to 1.9 m in a space with total height of 2.9 m, partition has

* Corresponding author. 55W 5TH AVE APT 01A, San Mateo, CA, USA.
*E-mail address:* amai.hideyuki@utexas.edu (H. Amai).

http://dx.doi.org/10.1016/j.buildenv.2016.09.015
0360-1323/

no significant effects on the air distribution patterns. They also found that the layout of a cubicle on the ventilation efficiency is very small. This is confirmed by Lee [7] who showed that internal partition up to 60% of room height had very small impact on the air distribution. This study also showed that when the internal partition is 80% of room height or larger, partition has significantly impacts on the room air flow. When considering occupants, Wu et al. [8] conducted tests on walking humans in a test chamber and analysed impact on $CO_2$ concentration and temperature distributions in the space with three different ventilation method (stratum, displacement, and mixing ventilation). The study showed that short term walking did not change the room temperature or $CO_2$ concentration profiles. However, mixing occurred when occupants walked over a longer period of time.

The aforementioned studies show that many factors influence the supply air distribution when mixing ventilation diffusers supply cold air jets (cooling mode). In this cooling mode operation the overall effectiveness of the air distribution is slightly better or worse than the one with perfect mixing. However, fewer studies focused on ventilation effectiveness with mixing diffusers used for space heating. Air distribution with all-air-heating is one of the major challenges for mixing air distribution. Although, all-air-heating ventilation is widely used, researchers found low ventilation effectiveness under heating condition [9–13]. Fisk et al. [9] 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. [10] measured ventilation effectiveness and ADPI under heating conditions with recommended minimum ventilation rate while considering different supply and return positions. 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. This value was even lower, 0.66, when the room-supply temperature difference was 13 °C. Short-circuit flow from the supply to exhaust was apparent for each configuration. This low ventilation effectiveness under the heating condition was implemented into the ASHRAE standard 62.1 [14]. The standard defines zone air distribution effectiveness as 1.0 when the supply-room temperature different is less than 8 °C and the supply air jet throw of 0.8 m/s ($T_{0.8}$) reaches lower part of the room (area that is 1.4 m above the floor level). When the 0.8 m/s jet throw does not reach the lower part of the room, or when the supply-room temperature difference is larger than 8 °C, the nominal ventilation effectiveness is 0.8.

Thermal discomfort and impact of draft and temperature non-uniformity is defined by the Air Distribution Performance Index (ADPI) [15,16]. This widely accepted index for diffusers selection and position (diffuser design) shows the performance of diffusers when considering spatial temperature and velocity field and is well established in the diffuser selection guideline. 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 [17,18]. ADPI incorporates the throw and the characteristic length, and it provides design variables for selecting diffusers. The current ADPI diffuser selection method is only valid for overhead air distribution systems under cooling operation [19]. However, it is a common practice to use the same mixing ventilation diffusers to provide space heating in addition to cooling [20–22]. This practice causes many issues during the heating period. Recently, Liu et al. [23] expanded the ADPI concept in heating mode and obtained ADPI values with recommended design criteria for various types of diffusers under both cooling and heating mode.

Even this new updated cooling and heating ADPI concept considers only temperature uniformity and drafts caused by high velocity. The impact of stratification and low ventilation effectives with all-air heating systems is taken into account by just one correction factor in the ASHRAE Standard 62.1 [14]. Combining the ADPI with this correction factor does not always result in the proper diffuser selection that considers both thermal comfort and ventilation effectiveness. For example, when the throw is too short, it is possible that the jet detaches from ceiling and increases draft risk under cooling condition. Also, short throw length may cause inadequate mixing, resulting in high temperature gradient and low air quality under heating condition. It is necessary to have some momentum of flow to obtain an adequate mixing in the occupied zone. However, too large of a supply jet momentum may generate a draft when the flow rate is above a certain level. The temperature difference between return and supply should also be restricted, as a high-temperature difference may cause either a draft and/or a large vertical temperature stratification that ends in inefficient energy use. Few studies have focused on ventilation effectiveness with mixing diffusers used for space heating, although all-air-heating ventilation is widely used [2]. A comprehensive design process for diffuser selection and positioning that considers both thermal comfort and ventilation effectiveness at the same time is needed.

Therefore, the objective of this study is to provide data for guiding design of air distribution system designs for several of the most common types of ceiling diffusers when used for both (1) cooling and (2) heating regime. The studied diffuser types are: linear slot diffuser, round ceiling diffuser, louvered face diffuser with no lip and perforated diffuser directional pattern (4way). The study defines operation range for diffuser selection when considering high ADPI, ventilation effectiveness, and temperature effectiveness. The presented results build upon the recently finished project to expand the ADPI based diffuser selection guideline [24], and add an air quality component (ventilation effectives) in the current diffuser selection guide that consider only thermal comfort parameters.

## 2. Theoretical background and indices

This section explains the theoretical background and indexes implemented in this study. Among several indices, $T_{0.25}/L$ and *ADPI*, air change effectiveness, and temperature effectiveness were utilized to evaluate the performance of the diffusers regarding thermal comfort, ventilation effectiveness, and heat removal efficiency. The chosen indices are well researched and widely used in the industry and by many researchers.

### 2.1. $T_{0.25}/L$ and ADPI

Diffuser selection, location, supply air volume, discharge velocity, and air temperature differential result in air motion in the occupied zone. Three methods for selecting diffusers for mixing ventilation are used in practice: (1) by appearance, flow rate, and sound data, (2) by isovels (lines of constant velocity), and (3) by comfort criteria [25]. The last method, comfort criteria, involves use of ADPI and $T_{0.25}/L$ ratio. It utilizes manufactures' catalogue data for jet throw $T_{0.25}$ (distance from the diffuser at which velocity decrease to 0.25 m/s) and the characteristic length ($L$) space dimensions available for the throw. $T_{0.25}/L$ ratio is a dimensionless index that categorizes the performance of diffusers in the targeted space. Calculating $T_{0.25}/L$ can predict ADPI, which indicates uniformity of temperature and acceptability of the velocity in the space. For example, ADPI of 90 means that 90% of occupied space have acceptable temperature and velocity. Designers should select and