Numerical simulation of thermal stratification and air quality in an underfloor air distribution system (UFAD)

Neil Stephen Lopez¹, Selena Kay Galeos¹, Brian Raphael Calderon¹, David Roy Dominguez¹, Bryan Joseph Uy¹ and Rupesh Iyengar²

¹ Mechanical Engineering Department, De La Salle University, Manila, Philippines
² Index Workshop LLP, Singapore, Singapore

*E-mail: neil.lopez@dlsu.edu.ph

Abstract. The penetration of underfloor air distribution systems (UFAD) in residential and commercial air conditioning has been rather slow. The most notable applications would be on data centers, where thermal stratification requirements are more demanding. The present study supports and strengthens recent work in the design and development of UFAD systems, by augmenting literature on proper vent positioning and design. In UFAD systems where thermal stratification is more pronounced, significant energy savings may be achieved through proper positioning of supply and return vents. Using a validated numerical simulation model in ANSYS CFX, four UFAD vent layouts are investigated with regards to their implications on thermal stratification and indoor air quality. Results show that not only ventilation layout, but also vent type selection can significantly affect the performance of a UFAD system. Spreading multiple, smaller supply diffusers is preferable than having large supply diffusers on the perimeter of the rooms, both from a temperature distribution and indoor air quality perspective. Notably, air flow is significantly poor in the perimeter layout, causing warmer temperature at the center of the room.

1. Introduction

A well-designed underfloor air distribution (UFAD) system has great benefits on indoor thermal comfort (ITC), indoor air quality (IAQ) [1], energy efficiency [2], and life cycle costs [3]. A comprehensive review on the benefits and barriers of UFAD technology has been done before [4]. Thermal stratification is key to the performance of UFAD systems. This is because good energy efficiency, ITC and IAQ are largely a consequence of good thermal stratification [5]. However, one of the barriers to UFAD is the deterioration of thermal stratification in actual implementation [6]. Due to this, the detailed performance of UFAD systems requires more investigation and documentation.

The particular aspect this study aims to investigate is the role of the relative positioning of vents. In recent literature, task air conditioning (TAC) is encouraged among UFAD systems [7]. Task air conditioning (TAC), or localized thermal distribution, or personalized air conditioning, is the individual conditioning of the immediate environment within a person’s workstation. On a different note, another study [8] studied thermal comfort as a function of supply diffuser type. Semi-cylindrical wall diffusers provided better comfort results than flat wall and floor swirl diffusers. Based on literature, there is a need to better control thermal stratification in UFAD systems, and to better understand the effects of
vent positioning. Furthermore, simulation studies have recently become a reliable tool for comprehensive analysis of ventilated enclosures.

Table 1. Boundary conditions.

| Supply Vents                  | Inlet with fixed mass flow rate (total for all supply diffusers = 0.1363 kg/s) |
| Return Vent                  | Outlet with fixed mass flow rate (equal to supply, 0.1363 kg/s)               |
| Door Opening (present on validation run only) | Opening at atmospheric pressure                                           |
| Walls (only heat source in the simulated ventilation space) | Fixed Temperature Walls (21 °C)                                           |
| Floor and Ceiling            | Adiabatic Walls                                                              |

The objective of this study is to investigate and report the effects of various UFAD ventilation layouts towards thermal stratification and indoor air quality. Through computational fluid dynamics simulation, four common supply and return vent layouts, discussed in detail in section 3.2., are simulated and their implications on air trajectory, thermal stratification and indoor air quality are analyzed. The paper proceeds with literature review, discussion of the methods, simulation model development using ANSYS CFX, results discussion, and ends with the conclusions.

2. Methods
The numerical simulations are performed on ANSYS CFX 14.5 [9]. The four UFAD ventilation layouts selected are based on the most common general layouts adopted in industry. After the simulation, the results are processed, and the main information extracted pertain to temperature distribution, CO₂ concentration, air velocity, and flow trajectory. The simulation results then are analysed with regards to their implications on thermal stratification and indoor air quality.

3. Model development

3.1. CFD model development and pre-validation
The CFD model utilized in the study was experimentally pre-validated using an overhead system ventilated room. The total volume of the room was 54.57 cu.m. For wall temperature measurement, the 4 walls (2 x 4.18 m by 2.72 m; 2 x 4.80 m by 2.72 m) were each divided into 15 equal sections. Temperature was measured at the center of each section using an infrared thermometer. For space temperature measurement, the floor area was divided into 9 equal sections. Temperature was measured at the center of each section, at 5 different elevations of 0.5 m intervals using a digital thermometer. Supply and return air temperature were also measured using the same instrument. Air flow from supply and return, as well as air exfiltration through the door gap were measured using a handheld anemometer. Space carbon dioxide concentration was measured in 45 locations using a CO₂ analyser. Three cycles of measurement were taken and the final measurement for each location was taken as the average. The average prediction errors were 13% and 6% for temperature and carbon dioxide concentration, respectively. For temperature prediction, the error range was 0-31%, with the highest errors occurring directly underneath the vents, and near the door. For carbon dioxide concentration prediction, the error range was 0-13%, with the highest errors occurring near the door.

3.2. Ventilation layouts
Small swirl diffusers are utilized when multiple supply vents are desired to be distributed within the ventilated room. On the other hand, linear or rectangular grille-type supply diffusers are utilized when the vents are located near the end or sides of the room [10]. Specific details on the ventilation layouts
are provided below, while the actual rooms are illustrated in Figure 1 and the boundary conditions provided in Table 1.

3.2.1. **Surrounded layout: Multiple supply (swirl type) / Center return.** This layout represents a room utilizing multiple small supply diffusers evenly spread out within the room, for localized air conditioning. The return vent is located at the center of the room (ceiling level) to achieve a symmetrical layout.

3.2.2. **Distributed layout: Multiple supply (swirl type) / Side return.** Similar to the surrounded layout, this utilizes multiple small supply diffusers spread out within the room. However, the return vent is located at the end of the room (ceiling level). This location for the return vent is common when it is desired for adjacent rooms to share the same main duct.

3.2.3. **Lengthwise layout: Side supply (rectangular grille) / Side return.** When localized air conditioning is not necessary, a lengthwise layout may be adopted wherein the supply vents in the form of rectangular grille diffusers are located on one end of the room, opposite to the return vent (ceiling, other end). With this layout, the conditioned air is forced to travel the whole length of the room.

3.2.4. **Perimeter layout: Perimeter supply (rectangular grille) / Center return.** A variation of the lengthwise layout is the perimeter layout, wherein rectangular grille supply diffusers are placed on both ends (perimeter) of the room, while the return vent is located at the center of the room (ceiling level).

![Figure 1. Ventilation layouts. A) surrounded layout; B) distributed layout; C) lengthwise layout; D) perimeter layout.](image)

4. **Results discussion**

4.1. **Thermal stratification**

Conditioned air is supplied at the same mass flow rate and temperature for all cases, to be able to attribute good air distribution to efficient use of energy. The temperature gradient obtained for UFAD layouts was on the average 7 °C. For UFAD layouts with supply vents on the sides, it is observed that there is a 2 to 4 °C temperature difference from the floor to a height of 0.5 m. In comparison, the layouts with multiple, spread-out supply vents display a much desirable thermal stratification, wherein the
temperature from floor to 0.5 m is almost constant. Negligible difference is seen between the surrounded and distributed layouts. For the perimeter layout, it is observed that the center of the room is 3 to 5 °C warmer than the sides where the supply vents are located. The same is observed but subtler on the lengthwise layout, which is using the same rectangular grille supply diffuser. This can be explained further by the supply air trajectory of such layouts, which is discussed more in section 4.2.

Notably, the zone right below the return vent is significantly warmer in the perimeter layout (i.e. center of the room). As shown in Figure 2, the center zone is 14 °C warmer than the front and back zones of the room. In a lesser degree, this is also observed in the surrounded layout (8 °C temperature difference between center and front zone). This difference in temperature distribution across front to back is not seen on the other layouts, suggesting that this is only common to layouts having the return vent at the center. On the other layouts, the difference in temperature distribution is only observed from side to side, primarily due to vent positioning. However, reducing to the occupied zone only, this difference reduces to half a degree for the perimeter layout, and becomes negligible for the surrounded layout.

Figure 2. Thermal stratification contour plots. All contour plots are taken from center of the room.

Figure 3. Airflow trajectory of various vent layouts.

4.2. Airflow trajectory
Ideal air distribution is seen on layouts using multiple swirl diffusers (surrounded and distributed). By spreading out the vents throughout the room, the space is well ventilated. Without significant
recirculation or stagnation in the flow, conditioned air in these layouts get a good residence time. On the other hand, it is observed that in cases where the supply vents are on the sides (Lengthwise and Perimeter), air in a significant portion of the room stagnates, and flow is trapped on one side of the room. For example, with the lengthwise layout, air stagnates at the zone below the return vent for a significant amount of time. This behavior for both the lengthwise and perimeter layouts could be attributed to the use of the rectangular grille supply diffuser. Because of the significantly larger supply vent orifice compared to the smaller swirl diffuser, the same air flow rate is supplied at a low velocity, and this results to a very low throw height for the supply air. With very little momentum, the supplied air is forced to reside longer in the room until enough pressure is built to exit through the return vent on ceiling level. This creates a 3-degree temperature gradient from about foot to knee area, which could be uncomfortable for some occupants.

4.3. Indoor air quality
Carbon dioxide concentration as affected by ventilation layout is illustrated using volume rendering in Figure 6. It is observed that the distribution of carbon dioxide is similar to the thermal stratification of the same layout. This highlights one of the key advantages of UFAD, wherein the contaminated air is accumulated at the exhaust zone with the help of buoyancy effects and the characteristic unidirectional flow of air from floor to ceiling. Old or contaminated air effectively is flushed out to the exhaust zone in UFAD systems, whereas it is only diluted in OH systems.

![Figure 4. CO2 concentration of various vent layouts.](image)

5. Conclusion
Using numerical simulation, the effect of various UFAD ventilation layouts to thermal stratification, air flow trajectory and indoor air quality were presented in this study. In UFAD systems where thermal stratification is more pronounced, significant energy savings can be achieved by spreading out multiple swirl-type diffusers instead of using rectangular grille-type vents. Spreading out multiple, smaller-type supply vents provides better temperature distribution than large supply diffusers located on the perimeter of the room. The smaller diffusers also result to greater supply velocity which in turn provide healthier air circulation and residence time inside the ventilated space. Notably, air flow is significantly poor in the perimeter layout, causing warmer temperature at the center of the room right below the return vent.
It must be noted that all observations, especially the air flow trajectories, are subject to furniture and other obstacles which could be present in an actual room.

Acknowledgement
The authors would like to acknowledge the guidance provided by Engr. Efren Dela Cruz of De La Salle University, Manila, Philippines, Engr. Hans Felix Bosshard and Dr. Manuel Belino of Far Eastern University Institute of Technology, Manila, Philippines.

References
[1] Li R, Sekhar SC and Melikov AK 2010 Thermal comfort and IAQ assessment of under-floor air distribution system integrated with personalized ventilation in hot and humid climate Building and Environment 45 1906–13
[2] Inatomi TAH Abe V and Leite BC 2006 Energy consumption of underfloor air distribution systems: a literature overview Proc. 23rd Conf. on Passive and Low Energy Architecture (Geneva)
Lehrer D and Bauman F 2003 Hype vs. reality: new research findings on underfloor air distribution systems Proc. of Green Build (Pittsburgh)
Lian Z and Ma R 2006 The principle and design of underfloor air-conditioning system (Shanghai: Shanghai Jiaotong University Press)
[3] Webster T 2005 Alternative air conditioning technologies: underfloor air distribution (UFAD) Energy Engineering 102 58–77
Webster T, Benedek C and Bauman F 2008 CBE UFAD Cost Analysis Tool: Life Cycle Cost Model, Issues and Assumptions (Berkeley: University of California, Berkeley)
[4] Zhang K, Zhang X, Li S and Jin X 2014 Experimental study on the characteristics of supply air for UFAD system with perforated tiles Energy and Buildings 80 1–6
[5] Bauman F and Webster T 2001 Outlook for underfloor air distribution ASHRAE Journal 43 18-27
Webster T and Bauman F 2006 Design guidelines for stratification in UFAD systems – guidance for sizing interior and perimeter zones of underfloor-air-distribution systems. HPAC Engineering 78 6–27
[6] Yin P 2010 Identification of air conditioning energy conservation technologies and measures: Some uncertain points in UFAD system design HVAC 40 64–73
[7] Bauman F, Carter T, Baughman A and Arens EA 1998 Field study of the impact of a desktop task/ambient conditioning system in office buildings ASHRAE Transactions 104 1–19
[8] Almesri IF and Awbi HB 2011 Predictions of thermal comfort in stratified room environment Build Simul 4 169-80
[9] ANSYS® Academic Research Release 14.5
[10] "UFAD Diffusers." UFAD Diffusers., University of California, Berkeley, n.d. Web. 27 Nov. 2016. <http://www.cbe.berkeley.edu/underfloorair/diffusers.htm>.