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# CFD investigation of airflow pattern, temperature distribution and thermal comfort of UFAD system for theater buildings applications

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ABSTRACT

A 3D-CFD investigation of airflow, temperature distribution and thermal comfort in high rise ceiling theaters air conditioned with underfloor air distribution (UFAD) system is presented for different operating and geometric conditions. Numerical simulations are implemented, using a commercial CFD package (Fluent 6.3), to understand the effects of supply air temperature, supply air velocity, space height and number of supply air diffusers on the performance of the air conditioning system and thermal comfort. For UFAD system evaluation, the traditional overhead mixing air distribution (OHAD) system are also modelled and compared with the UFAD system. The results showed that (i) the used numerical technique could accurately predict the airflow and temperature distribution in the high rise conditioned space, (ii) UFAD system is capable of creating smaller vertical variations of air temperature and a more comfortable environment and energy saving than OHAD system, (iii) the supply air velocity and temperature, number of diffusers and height of the space have a significant impact on thermal comfort, (iv) the optimum system performance and thermal comfort obtained at 18 °C supply air temperature, 0.8 m/s supply air velocity and proper numbers and distributions of supply diffusers, (v) the percentage of energy saving due to using UFAD system increases with increasing the theater height. The simulation results are validated with the available experimental data and good agreement are obtained.



## 1. Introduction

The importance of reducing building energy consumption has increased ever since global warming became a serious issue. For space heating and cooling, air distribution strategies in HVAC have a strong influence not only on indoor environmental thermal comfort but also on energy costs. Air distribution system also has a direct impact on space organization, floor height planning, interior layout and construction cost [1]. A relatively new approach of air distribution, the underfloor air distribution (UFAD) system, has been widely used in new commercial buildings. UFAD systems are mechanical air distribution systems that delivers conditioned air through grilles mounted in the floor. The air is directly supplied to the occupants' area causing occupants' plumes and zone heat load to stratify to the upper layer of the zone and then is typically exhausted from the ceiling. The space is divided into two zones, occupied zone where cold air and unoccupied zone in the upper layer where air is warm. The floor-mounted grilles are positioned so that each occupant receives his own flow of air which causes temperature stratification from the lower to the upper layer of the zone.

UFAD system is more effective when the zone height increases as in the case of theaters, hotel lobbies, showrooms, worship buildings, etc. Rapid economic growth the desire of a higher quality life has currently led a boom in construction of gymnasiums, concert halls, and theaters. Since most of these cultural facilities are composed of large spaces, they generally require a high level of dependency on mechanical ventilation with conditioned air. Furthermore, since these large cultural facilities have high ceilings, a great amount of energy could be required by traditional air distribution to maintain the optimal indoor temperature for a comfortable environment. For such facilities with high ceilings, an UFAD system would be more appropriate to enhance thermal comfort with energy saving, and would also allow both individual control of ventilation volume and distribution of air only to occupied zones. Using computational fluid dynamics (CFD) is capable for analyzing the flow pattern, temperature distribution and thermal comfort of the air conditioning system in short span of time, which was previously impossible from experimental and theoretical methods [2]. Moreover, CFD gives virtual distribution of airflow, temperature, etc. in entire domain which is highly difficult to get from experiments because of time and cost involved. Unfortunately, there is no universal flow model to represent the entire flow pattern for the air conditioning system [3].

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**Nomenclature**

| | |
|---|---|
| UFAD | Underfloor air distribution system |
| 3D | Three dimensional |
| CFD | Computational fluid dynamics |
| OHAD | Overhead air distribution system |
| PMV | Predicted mean vote |
| PPD | percent persons dissatisfied |
| μ | Dynamic viscosity (kg.m/s) |
| $\mu_t$ | Eddy viscosity (turbulence viscosity) |
| p | Pressure (Pa) |
| T | Air temperature (°C) |
| ρ | Air density (kg/m$^3$) |
| u | Velocity vector in x-direction |
| V | Velocity vector in y-direction |
| W | Velocity vector in z-direction |
| ΔT | Temperature ratio, $\Delta T=(T-T_s)/(T_{Exhaust}-T_s)$ |
| Φ | phase function |

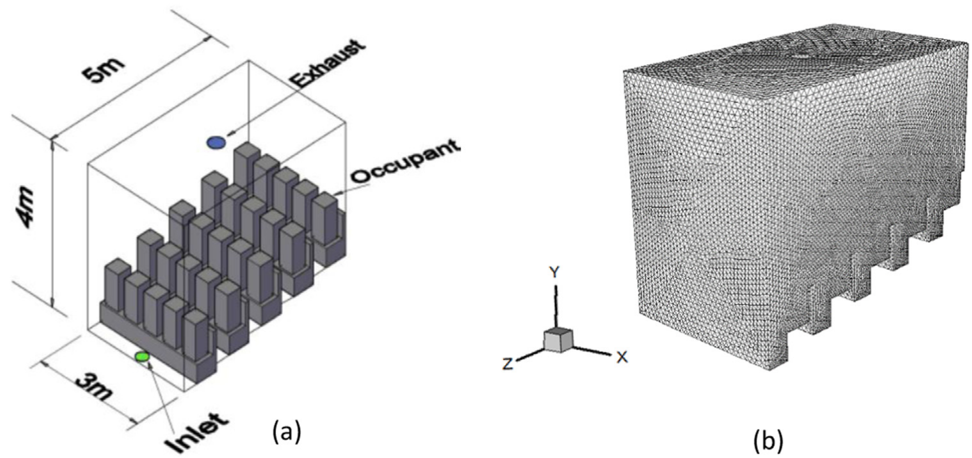


**Fig. 1.** (a) Computational domain, (b) Mesh with boundary conditions.

**Table 1**
Studied parameters and their ranges.

| Studied parameter | Studied ranges |
|---|---|
| Supply air temperature, $t_s$ | 16,18, 20, 22 °C |
| Supply air velocity, $V_s$ | 0.4, 0.8, 1.2, 1.6 m/s |
| Space height, *H* | 4, 7, 10 m. |
| Number of supply air diffuser, $N_d$ | 1, 2, 3. |

On introducing the UFAD systems, Bauman [4] presented discussion about several advantages shown by the UFAD system; Halza [5] compared the advantages of UFAD system and overhead ductless system; Webster [6] presented an overview of the principles, features, benefits, and limitations of the underfloor air distribution system. Woods [7] did a review by literature searching and field investigations to assess the actual performance of UFAD system in real world, showing that there are gaps in available data, and remarked on evaluation and selection approach. Webster et al. [8] presented a study about a building that operated with a UFAD system. They showed little troubleshooting with the system operation, pointing out the positive aspects of using well-designed UFAD systems. Alajmi and El-Amer [9] investigated the effectiveness of UFAD systems in commercial buildings for various types of application and different air supply temperatures in a hot climate (The State of Kuwait). The results showed that the saving of energy in using UFAD was not prejudicing on occupant comfort. It was found that the UFAD system can save up to 30% energy compared to OHAD. Xu and Niu [10] proposed a numerical procedure, based on coupling two types of modeling, CFD simulation and dynamic cooling load simulation, to predict annual energy consumption for UFAD systems. It was found that the dimensionless temperature coefficient was almost a constant, when the locations of heat sources were fixed. As compared with the mixing system, it was found that the UFAD system derives its energy saving potential from the following three factors: an extended free cooling time, a reduced ventilation load, and increased coefficients of performance (COP) for chillers. Chung et al. [11] clarified details of the thermal stratification due to UFAD, which is crucial to system design, energy efficient operation, and comfort performance, with an aim of examining the impact of mean radiant temperature (MRT) on thermal comfort.

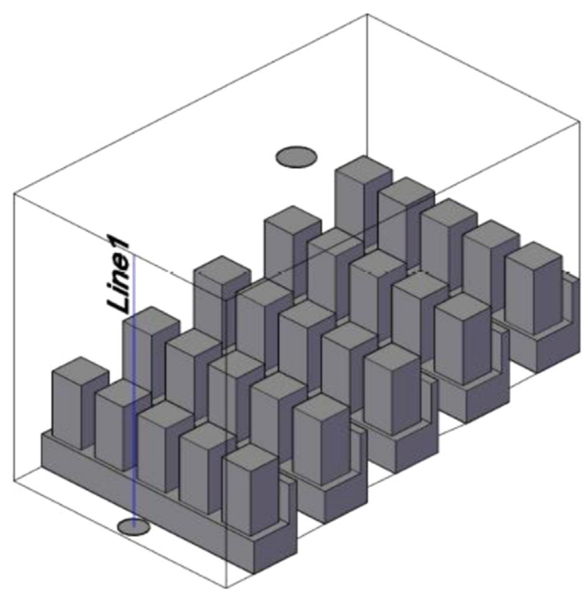


**Fig. 2.** Line1 location for grid dependency study.