The Effect of Ceiling Height on Thermal Comfort for Ceiling-Based Air Distribution Systems Vs Underfloor Air Distribution Systems in an Office Space

Meshal AlOtaibi
Architectural Engineer, and PhD candidate
University of Kansas
Lawrence, KS 66045, USA
m.al_otaibi@hotmail.com

Abstract

The aim of this research is to evaluate the operation of ceiling-based distribution (CBAD) systems and underfloor air-distribution (UFAD) systems and determine their effect on thermal comfort based on ceiling height. This research will help in understanding how the type of air conditioning system affects thermal comfort. The data, which are thermal comfort values, collected using a simulation program called FloVENT. Other tools such as predicted mean vote PMV tool and predicted percentage of dissatisfied PPD tool are used to collect the data. The main expected result of this research is that CBAD and UFAD systems improve thermal comfort of a building and lower its energy consumption. The findings from this research can be used by designers, engineers, manufacturers, contractors and home owners to design, develop and select the most appropriate heating and air-conditioning system to satisfy occupants throughout a building's lifecycle. This not only benefits home developers, owners, and occupants but also contributes positively to the environment by saving energy and reducing the carbon footprint of housing.

Keywords
Thermal comfort, PMV, PPD, FloVent, Comfort standards

1. Introduction

1.1 Ceiling Based Air-Distribution Systems

Ceiling based air-distribution systems are a type of air conditioning system that supplies air into the building space through the ceiling and exits through return grilles or vents, as shown in Figure (1) below. It is the traditional system of air conditioning that with which many designers, contractors, and people are familiar with. This system conditions the entire building space (both occupied space-floor-to-head-height level, and unoccupied space -–head height-to-ceiling level It requires relatively higher cooling load; hence it is most suitable for conditioning spaces with low heating loads.

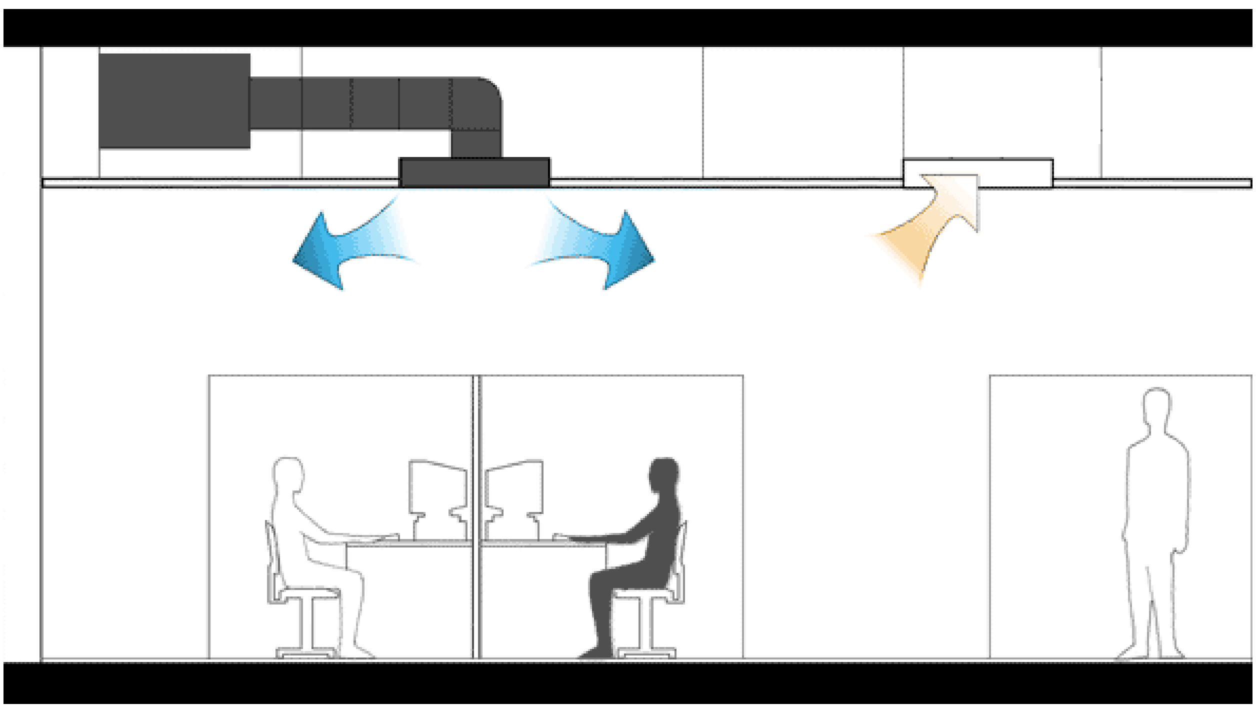

Figure (1): Ceiling based Air-conditioning Systems are type of air conditioning system that supplies air into the building space through the ceiling and exits air through return grilles or vents

1.2 Underfloor Air-Distribution Systems

The underfloor air distribution system, conditions space by that supplying fresh air from below, using a so-called “upside mechanism” (Geortner, 2005), Figure (2). The system introduces conditioned air through floor diffusers and exhausts air from the building via return grilles or vents in the ceiling (Tsai Liou and Lin, 2014). The only space conditioned is the occupied space, which requires almost half the cooling load of the CBAD system, hence it is suitable for conditioning spaces with high heat loads such as laboratories where there is a lot of equipment and people. The system also has greater flexibility because it can be rearranged to fit into any building layout, thus lowering reconfiguration costs.

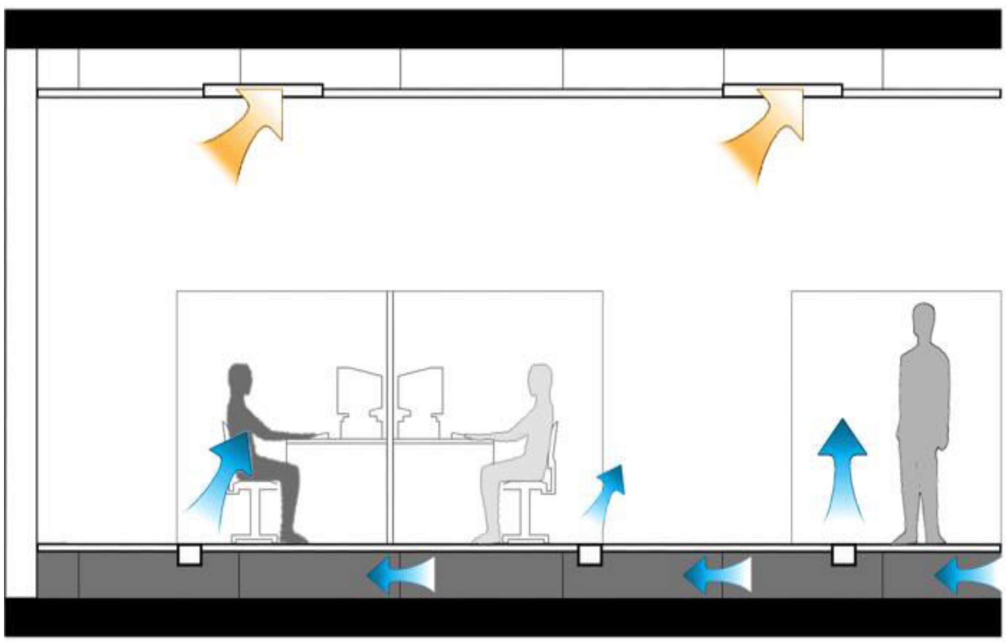

Figure (2): Underfloor Air Distribution systems introduce conditioned air through floor diffusers and exhausts air from the building via return grilles or vents in the ceiling

These systems increase energy efficiency of the building (by saving energy used by fans in heating, ventilation and air conditioning systems,), and by increasing the flexibility, comfort, and productivity of occupants, thus lowering the building costs throughout its lifecycle and improving the occupants' thermal comfort. By increasing thermal comfort, the system also significantly increases overall productivity, well-being and satisfaction of staffs when used in office spaces (Hoof, 2008).

In general, conducting this study will help in understanding how CBAD and UFAD systems work, how they improve thermal comfort, how they reduce energy consumption by buildings, and, therefore, how they mitigate air pollution, global warming, and climate change. Thus, the main motivation of the study is to establish how CBAD and UFAD systems can be used to solve some of the problems affecting human life by improving thermal comfort and enhancing human health and well-being.

2. Research Questions

This research explores the design and operation of CBAD and UFAD systems and how to measure thermal comfort of each of these systems. The research also examines the role played by CBAD and UFAD systems in enhancing the occupants' thermal comfort, and reducing energy consumption. So, the general question of the research is: What are the relative benefits of CBAD or UFAD systems in supplying the air- conditioning needs of building users efficiently?

3. Scope and Methodology

The main data collected in this study is the thermal comfort values of the rooms be selected for this study. The overall thermal comfort values are determined by measuring environmental and personal factors of the room, which includes air temperature, surface temperature, air velocity, relative humidity, clothing thermal insulation, and metabolic rates of the occupants. This will be accomplished by analyzing how the rooms are air-conditioned using CBAD and UFAD systems and movement of air and heat in the rooms using FloVent simulation program. Basically, FloVent is used to explore how conditioned air flows into the room, circulates through it, and flows out. From this analysis, two specific tools, predicted-mean-vote (PMV) and predicted percentage of dissatisfied (PPD), will be used to determine the thermal comfort of the room. PMV will be used to determine the number of occupants who are comfortable at a particular thermal comfort condition whereas PPD will be used to determine the number of occupants who are not satisfied with particular comfort conditions. By determining these values, it will be possible to establish the effect of CBAD and UFAD on thermal comfort in a building or room.

4. Probable Findings

Airflow in buildings is influenced by several factors including size, shape and orientation of the rooms; type, shape and configuration of the roof; height of the building; air conditioning system and environmental conditions. In general, it is expected that CBAD and UFAD systems reduce air temperature and surface temperature, and increase air velocity, relative humidity, metabolic rate and clothing thermal insulation. A combination of this results to reduced energy consumption by mechanical heating and cooling systems, improved indoor air quality and ventilation efficiency, reduced building costs in its entire lifecycle, reduce floor-to-floor height of new buildings, improved thermal comfort of the building's occupants, and improved productivity and satisfaction of occupants. Therefore, it is expected that CBAD and UFAD systems improve thermal comfort in buildings.

5. Research Methods and Process

As stated before, this research will be performed by collecting data using FloVENT software, PMV and PPD methods. Some of the details of these methods are as follows:

5.1 FloVENT Software

FloVENT is a software used for computational fluid dynamics (CFD) analysis (Sapian,2009). The software is able to predict airflow, contamination distribution, heat transfer and comfort values and/or indices especially in buildings using mathematical equations of the fluid flow. The software simulates airflow distribution in 3D. In this research, FloVENT will be used to simulate, model and analyze airflow and comfort levels in the selected rooms (Lim et al., 2013). By modelling the rooms, it will be easier to collect various data sets such as heat transfer and airflow. This data will be used to determine comfort indices of the rooms. Thermal comfort values of the rooms in this research will also be collected using other two related tools namely predictive mean vote (PMV) model and predicted percentage of dissatisfied (PPD) model

5.2 Predicted Mean Vote (PMV)

PMV is a variable obtained using American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) 55 thermal tool. This method will be used to determine six variables, including ambient air temperature (T_a), mean radiant or surface temperature (T_r), air velocity (V_a), relative humidity (RH), activity level or metabolic rate (M), and clothing level or clothing thermal insulation (I_{cl}), which influence thermal comfort of occupants and generate one variable known as PMV. The first four variables are environmental factors while the last two variables are personal factors (Gauthier and Shipworth, 2012). The value of PMV is dependent on the independent variables ($PMV = PMV\ (T_a, T_r, V_a, RH, M, I_{cl})$) and it is determined using equation (1) below. The PMV variable is able to predict the percentage of occupants in the room who will be comfortable at a particular thermal condition. Thus, the method will be used to measure the value of each of the six variables after which they will be used as inputs in the PMV equation.

$$PMV = [0.303e^{-0.036M} + 0.028][(M\text{-}W)\text{-}3.96E^{-8}f_{cl}[(t_{cl} + 237)^4\text{-} (t_r + 237)^4]\text{-}f_{cl}h(t_{cl}\text{-}t_a)\text{-}3.05\,[5.73 - 0.007(M\text{-}W)\text{-}p_a]\text{-}\,0.42\,[(M\text{-}W)\text{-}58.15]\text{-}\,0.0173M(5.87 - p_a)\text{-}0.0014M(34 - t_a)] \quad \text{..... (1)}$$

Where $e =$ Euler's number (2.718), $h_c =$ coefficient of convective heat transfer, $f_d =$ clothing factor, $I_d =$ clothing insulation, M = metabolic rate (W/m^2), $R_{cl} =$ clothing thermal insulation, $v =$ air velocity, $t_{cl} =$ surface temperature of clothing ($°C$), $p_a =$ air vapor pressure (kPa), $t_a =$ air temperature ($°C$). $t_r =$ mean radiant temperature ($°C$), and W = external work (0).

In this research, PMV method will be used to determine the thermal comfort of the room occupants. The process will start by selecting the ranges for the six independent variables mentioned above by following the procedure in BS ISO 7730. This BS will be followed by selecting the input values for the independent variables, considering the precision in ISO 7726, then selecting the distribution of the variables. In this case, the variables will be distributed evenly. The next step will be to select a sample randomly from the chosen distributions of the variables. Each input value in the sample selected will be assigned a specific weighting Thereafter, the chosen sample inputs will be supplied to the PMV model to generate a sequence or density distribution of output PMV values (Gauthier and Shipworth, 2012)

5.3 Predicted Percentage of Dissatisfied (PPD)

PPD measures thermal comfort by predicting the number or percentage of occupants who will not be satisfied with the thermal conditions of the room. Therefore, PPD is a function of PMV and is directly calculated from PMV (Carlucci and Pagliano, 2013). The procedure for determining PPD is similar to that of PMV. It is summarized as follows: selecting the ranges of each independent variable; choosing input values for each independent variable, selecting the distribution of the independent variables, selecting a sample for the chosen distributions, and inputting the values of independent variables into the PMV model. This is the procedure that will be followed when carrying out the research. After determining the PMV value, PPD will be calculated using equation (2) below.

$$PDD = 100 - 95e^{[-(0.3353PMV4+0.2179PMV^2)} \quad \text{........ (2)}$$

It is worth noting that these tools have sensors that measure the different variables in the room. The values recorded by the sensors are used by the models to simulate the needed thermal comfort values.

5.4 Computer Simulation Setup

The aim of this project is to inspect the effect of an underfloor air distribution system versus ceiling air distribution system on thermal comfort in an office environment. This will be accomplished by comparing the thermal comfort performance of the two systems. The ultimate goal is to examine the influence of supply air volume, supply air temperature, and the ceiling height on thermal comfort of an underfloor air distribution system, and ceiling air distribution system under 2 different cases for each system illustrated by “table 1” below. The personal factors in the room are consistent for all the cases, which includes clothing thermal insulation metabolic rate of the occupants in a typical office activity, and the partial pressure of water vapor is shown in “table 2”. These factors values are used to calculate the predicted mean vote (PMV) as well as predicted percentage of dissatisfied (PPD) in the simulation. The input values for the heat sources in FloVENT in the office room are in “table 3”

Variables	Conditions
Supply air volume	80 CFM (UFAD), 121 CFM (CBAD)
Supply air temperature	65°F (UFAD), 68°F(CBAD)
Ceiling height	At 8ft, and 10ft for both systems

Table (1): The Variables Tested for Thermal Comfort

Personal factors	Value
Clothing thermal insulation “Trousers, short-sleeve shirt”	(0.57 Clo)
Metabolic rate “Typing”	(1.1 Met Units) = (65 W/m^2)
Partial pressure of water vapor	500 Pa

Table (2): Personal Factors

Heat sources	Value
Two monitors	30 W each
Two computers	256 W each
Three lighting fixtures	48 W each
Two occupants	100 W each

Table (3): Heat Sources in the Office Room

Table 1: ASHRAE Thermal Sensation Scale

Value	**Sensation**
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table (4): ASHRAE Thermal Sensation Scale

The flowchart shown below Figure (3) describe the process I employed in presenting the FloVent modeling and simulating the thermal comfort conditions in the office space.

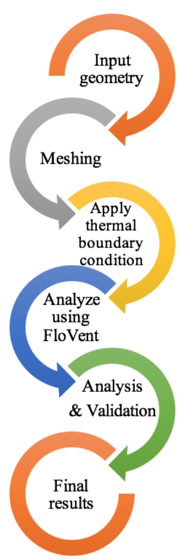

Figure (3): Flowchart of the research process

6. Thermal Comfort Study of an Office Space

Figures (5), and (1, 2 & 3), show a virtual model of the interior space of an office area I used as case study developed using Revit Autodesk, and FloVent computational fluid dynamics (CFD) software respectively. The use of FloVent method to model and simulate the thermal comfort conditions in the office space by investigating different possible solutions. The current condition of the office space equipped with conventional ceiling air distribution system, however I replaced it with underfloor air distribution system. I used 2 cases for each of the systems (CBAD & UFAD) by setting the ceiling height at 8ft, and 10ft. My goal is to identify the temperature distribution at multiple points of the space, the thermal comfort conditions for each case of the systems based on the Predicted Mean Vote (PMV), and the Predicted Percentage of Dissatisfied (PPD). I used ASHRAE standard 55-2013, and ASHRAE thermal sensation scale table (4) as reference to validate the FloVent modeling and simulation procedure. When validated, I used the models to examine if the thermal comfort conditions fall within the recommended range specified by ASHRAE standard 55- 2013. The following figure (4) show the type of underfloor supply grille used in this project.

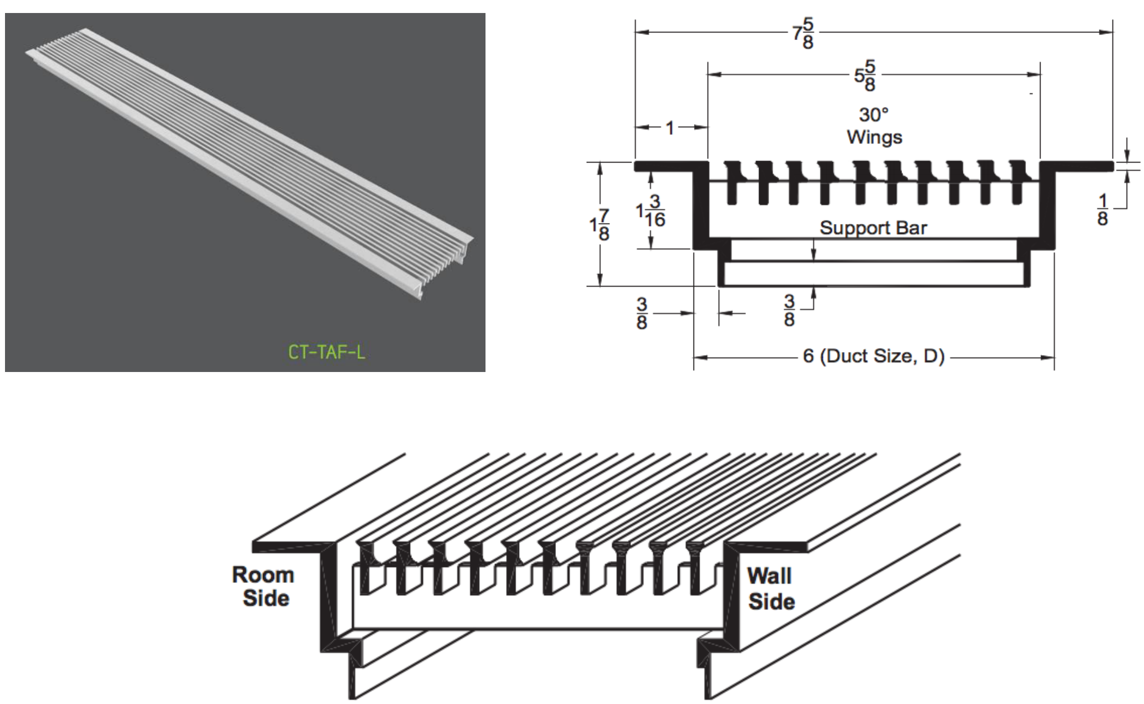

Figure (4): Underfloor Supply Grille Specification (Source: Titus)

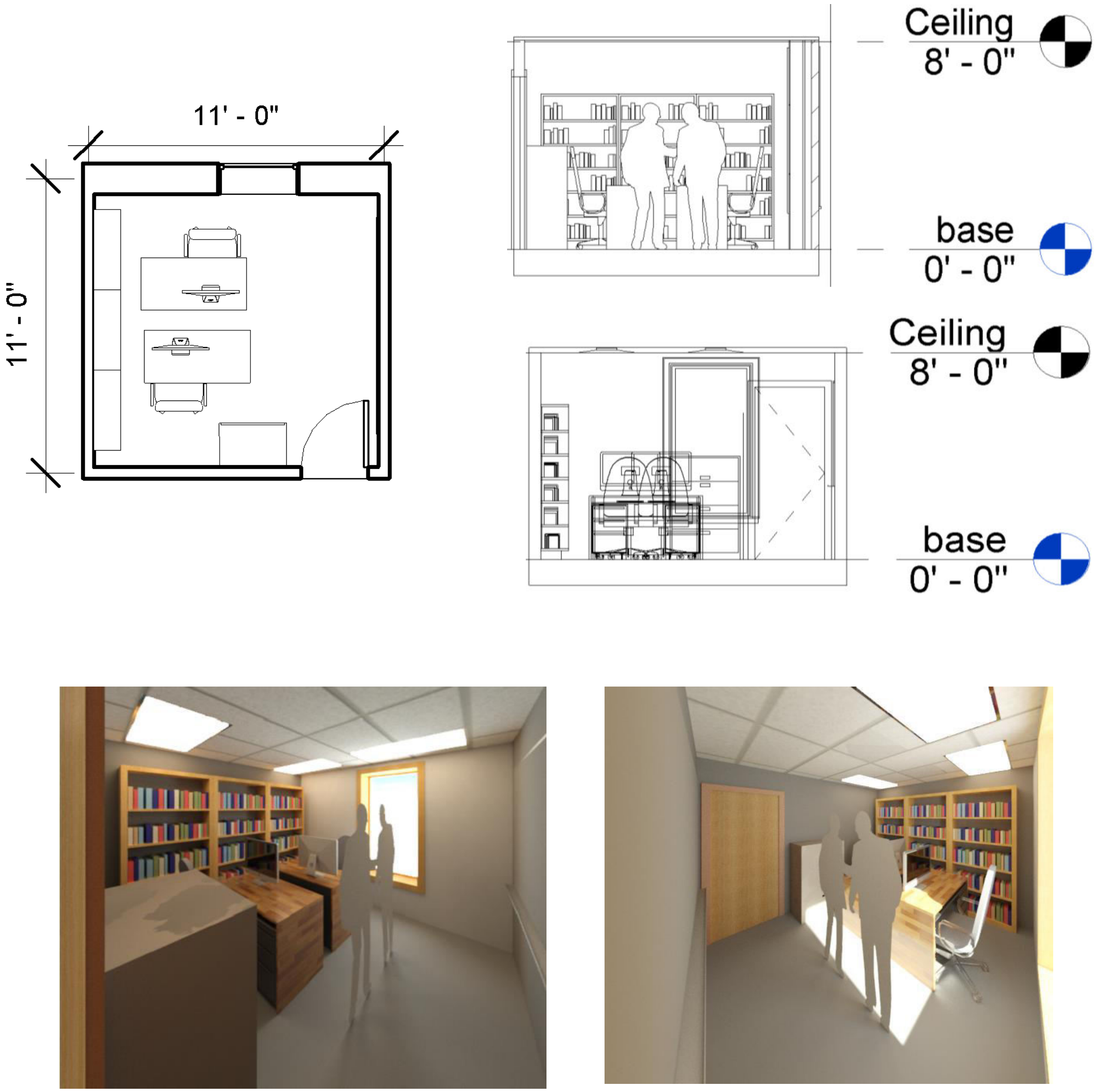

Figure (5): virtual model of the interior space of an office area

6.1 *Comfort condition with Underfloor Air Distribution System at (8ft) Ceiling Height*

Figure (6) shows difference of the average air temperature, and air speed in various points of the office space, when the air is supplied from an underfloor air distribution system and the ceiling height is at (8ft.). The air temperature (71-72°F) falls within the acceptable level of thermal comfort, as specified by the ASHRAE standard 55-2013 which is between 70°F and 80°F. It can be clearly seen that in figure (6) at any given point within the (6ft.) occupied space, the air temperature is within the acceptable limit of the thermal comfort according to ASHRAE 55-2013. Figure (7) shows the predicted mean vote (PMV) value between (0.4 & -0.5) falls within the recommended range between (+0.5) and (-0.5) according to ASHRAE thermal sensation scale Table (4). PMV variable can predict the percentage of occupants in the room who will be comfortable at a thermal condition. Figure (7) also shows the predicted percentage of dissatisfied (PPD) value is (5-10%) meets the recommended acceptable PPD range for thermal comfort from ASHRAE 55 which is less than 10% occupants dissatisfied for an interior thermal space condition.

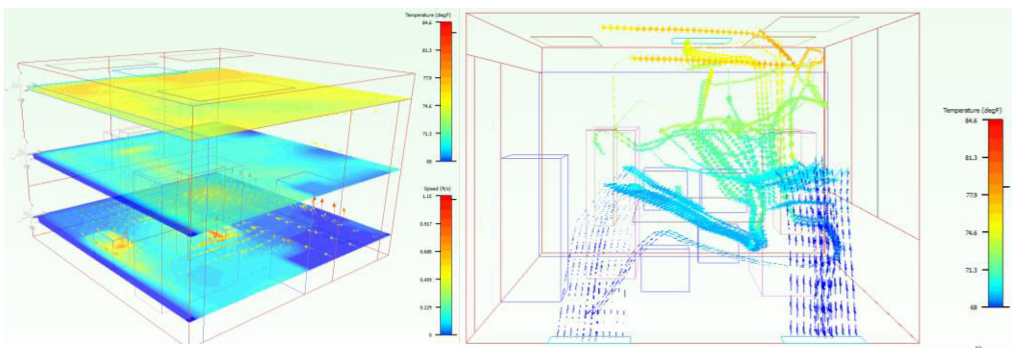

Figure (6): The difference of the air temperature, and air speed in various points of the office space, when the air is suppling from an Underfloor Air Distribution System.

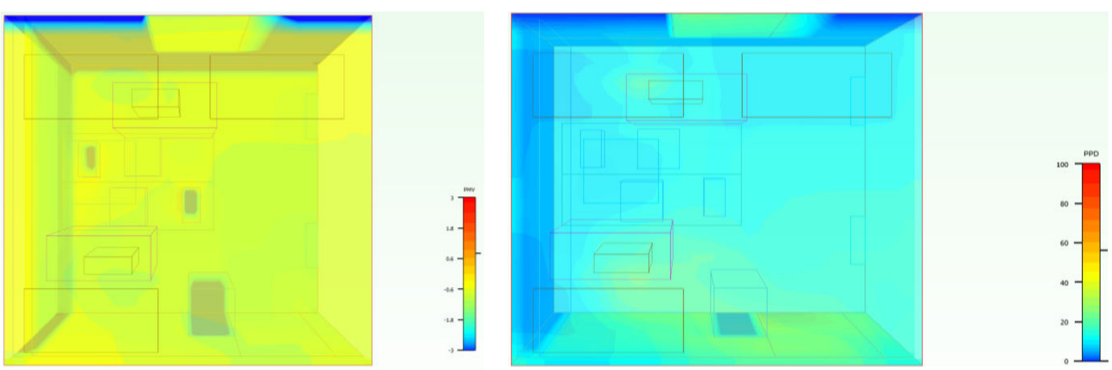

Figure (7): PMV predict the percentage of occupants in the room who will be comfortable at a thermal condition, and PDD variable predicting the number or percentage of occupants who will not be satisfied with the thermal conditions of the room

6.2 *Comfort condition with Ceiling Air Distribution System at (8ft) Ceiling Height*

The model shows the air temperature (68-69°F) is not within the acceptable level of thermal comfort, as specified by the ASHRAE standard 55-2013 which is between 70°F and 80°F. It can be clearly seen that at any given point, the air temperature is well outside the acceptable limit of the thermal comfort according to ASHRAE 55-2013. The Predicted Mean Vote (PMV), the PMV value is between (-1.8 & -3) which is outside the recommended range between (+0.5) and (-0.5) according to ASHRAE thermal sensation scale Table (4). PMV variable can predict the percentage of occupants in the room who will be comfortable at a thermal condition. The Predicted Percentage of Dissatisfied (PPD) value is (30-40%) which is well outside the recommended acceptable PPD range for thermal comfort from ASHRAE 55 which is less than 10% occupants dissatisfied for an interior thermal space condition

6.3 *Comfort condition with Underfloor Air Distribution System at (10ft) Ceiling Height*

The variation of air temperature within the office space, when the air is supplied from an underfloor air distribution system is little above the limit. The acceptable level of thermal comfort, as specified by the ASHRAE standard 55-2013 is between 70°F and 80°F. It is seen here that the air temperature in the space is little above the limit of thermal comfort close to the ceiling and lighting fixtures, whereas the air temperature in the occupied space is (68-68.8°F) which appear to be below the comfort level limit. The PMV value results between (-0.6 & -1.8), also the model shows that the office space is outside the recommended acceptable level specified by the ASHRAE thermal sensation scale table (4). The PPD result is between (20-30%) show that more than 10% of the occupants are dissatisfied with the interior thermal space condition, which is doesn't comply with the ASHRAE standards 55-2103.

6.4 *Comfort condition with Ceiling Air Distribution System at (10ft) Ceiling Height*

The variation of air temperature within the office space, when the air is supplied form an underfloor air distribution system is shown in figure (28). The acceptable level of thermal comfort, as specified by the ASHRAE standard 55-2013 is between 70°F and 80°F. It is seen here that the air temperature in the space is (69°F) outside the boundary of thermal comfort. The air temperature in the occupied space is below the comfort level boundary. The PMV value is between (-0.7& -3), and that the office space is outside the recommended satisfactory level specified by the ASHRAE thermal sensation scale table (4). The PPD result is between (35-45%) also that more 10% of the occupants are dissatisfied with the interior thermal space condition, which is doesn't comply with the ASHRAE standards 55-2103.

7. Conclusion and Future Directions

A thermal comfort study in an office space was presented, by conducting FloVent computational fluid dynamics (CFD) software method to model and simulate the thermal comfort conditions in the office space. In order to investigate the temperature distribution at each point across the room, air flow behavior, PMV and PPD values. Furthermore, thermal condition cases within the office space when it was underfloor air distribution system or when it was ceiling air distribution system. The thermal conditions (6.2), (6.3), and (6.4) is well outside the recommended limits that is specified by the ASHRAE 55-2013, and ASHRAE thermal sensation scale table (4). Nevertheless, in thermal condition (6.1) the temperature distribution is more uniform virtually throughout the office space, the level of thermal comfort falls within the acceptable recommended range according to ASHRAE standard. Moreover, the FloVent analysis show that altering ceiling height (lower ceiling 8ft) has significant impact when it comes to temperature distribution, and the level of thermal comfort in an office space by utilizing underfloor air distribution system. The table (5) below show the summary of the final results.

However, these methods have some limitations. The major limitation is that the methods do not consider the unique designs and types of buildings. It is obvious that each type of building design influences thermal comfort conditions differently. This means that disregarding design parameters of the building reduces the accuracy of these methods. The methods were developed based on laboratory studies, which assumed a single type of building. Also, the methods do not consider whether the building being analyzed is naturally ventilated (free-running), complete air-conditioned, and hybrid or mixed mode. These two limitations affect the accuracy of results obtained when determining the effect of CBAD and UFAD systems on thermal comfort of a building. Therefore, when conducting this research, it will be important to clarify the assumption that the type of building or building parameters are neglected, although that is not sufficient. Neglecting these parameters simply means accepting the error in all the calculations. The best way is to find ways of improving the FloVENT, PMV, and PPD models methods. These methods should incorporate building types and design parameters, and the type of ventilation being used in the building.

Condition	Air Vol.	Air Temp.	Air Speed	Ceiling Height	Met. (W/m)	Clo	PMV	PPD%
#	CFM	°F	ft./s	ft.				
1 (UFAD)	80	71-72°F	0.39	8	1.1 (65)	0.57	(0.4 & -0.5)	(5-10%)
2 (CBAD)	121	68-69 °F	0.408	8	1.1 (65)	0.57	(-1.8 & -3)	(30-40%)
3 (UFAD)	80	68-68.8 °F	0.42	10	1.1 (65)	0.57	(-0.6 & -1.8)	(20-30%)
4 (CBAD)	121	69 °F	0.45	10	1.1 (65)	0.57	(-0.7& -3)	(35-45%)

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