NUMERICAL STUDY OF THE EFFECTS OF EVAPORATIVE COOLER SUPPLY AIR OUTLET HEIGHT ON THERMAL COMFORT

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Abstract: Thermal comfort in a space equipped with a direct evaporative cooler is a function of the height of the cooler's supply air outlet. This article attempts to numerically investigate the impact of hybrid downdraft evaporative cooler (HDEC) supply outlet height on occupant thermal comfort in an office building. DesignBuilder CFD parametric simulations was carried out by varying the height of the HDEC supply outlet from 0.1m to 2.4 m, step 0.1 m above ground level, using Predictive Mean Vote (PMV) as an objective function. The results show that the best PMV of -0.27 was obtained at 0.4m above the floor level.

Keywords: thermal comfort, office building, evaporative cooler, cooler's supply outlet height

1. INTRODUCTION

Building plays a major role in creating a comfortable living environment. An office building is a space where high intellectual concentration is required. Under normal circumstances, people spend about 25% of their daily time in their offices, especially in public service. Therefore, the productivity, concentration, morale, efficiency, and well-being of building occupants are largely a function of their indoor environment [1-3]. In this context, thermal comfort and indoor air quality (IAQ) are the most important indoor environments and therefore achieving thermal comfort in a space is essential [4].

The state of mind that expresses satisfaction with the thermal environment is referred to as thermal comfort. It is therefore fundamental to provide thermal comfort to the occupants of a building. A comfortable building is one whose thermal environment satisfies 80% of its occupants [5]. Occupant comfort and IAQ vary greatly depending on the location of the supply and return of cooling systems [6]. Therefore, understanding the behavior of airflow from HVAC systems in a room is essential for appropriately positioning the diffusers of these systems for optimum comfort of the occupants.

Many studies have been conducted to examine the location of HVAC systems that provide optimal comfort for occupants in a space. To achieve maximum thermal comfort in space, Yongson et al. [7] studied the temperature and velocity distributions for different positions of wall-mounted conventional air conditioners. The results showed that better thermal comfort would be achieved if the air conditioning fan was placed in the corner compared to other locations. Sabtalista et al. [8] studied the effect of floor air conditioning position on thermal comfort. The

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results showed that the floor air conditioner performed better when the air intake vent was far from the occupants due to the minimization of the draft effect. Lee et al. [9] investigated the influence of blade angle and pitch on the ventilation performance of a wall-mounted air conditioner using a Particle Image Velocimetry System and CFD analysis. The findings showed that the airflow rate increased by 19% to 20% when the blade angle was centered. In addition, the effectiveness of the indoor air conditioning was greatly improved when the air conditioner was located in the center of the wall and the blade angle was set to the center. Mutlu and Caliskan [10] studied the effect of thermostat location on particle distribution, energy consumption, and thermal comfort in a room conditioned by cassette air-conditioning system using 3D CFD simulations. They concluded that the location of the thermostat greatly affects particle distribution, energy consumption as well as thermal comfort in the room. Xi et al. [11] evaluated the efficiency of a floor-standing air conditioning system with different installation positions and supply air parameters based on a laboratory. The results revealed that the placement of the floor-standing air conditioner diagonally across from the door provided the optimal comfort. The heights of wall mounted HDEC supply outlets were studied for optimal thermal comfort of a building's occupants. The HDEC system is a direct evaporative cooling system that uses natural ventilation and adiabatically conditions the air through cooling with humidification. Therefore, the windows must be opened to avoid moisture accumulation [12]. Evaporative coolers bring 100% fresh outside air into the room to be air-conditioned and thus improve the quality of the indoor air [13]. The thermal comfort of an occupied building is normally determined by the Fangers thermal comfort model. The two thermal comfort indices in the Fangers model are Predicted Mean Vote (PMV) and Predicted Percent Dissatisfaction (PPD) [14]. The PMV Index predicts the thermal comfort of a space based on the 7-point ASHRAE scale of thermal sensitivity ranging from -3 to +3, with the zero point being thermal neutrality [5]. As shown in Figure 1 [5], PMV and PPD indices are related.

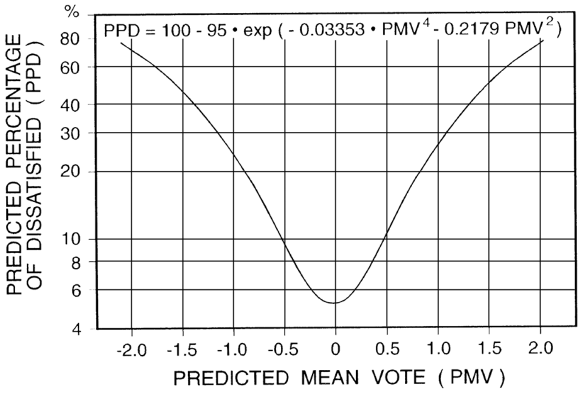


Fig. 1. Predicted percentage of dissatisfaction as a function of the predicted mean vote.

The range of PMV values from -0.5 to +0.5 on the thermal sensitivity scale represents the range in which occupants are thermally comfortable. For this purpose, the influence of the height of the HDEC supply outlet on the thermal comfort of the building users is examined numerically in this work using the PMV index as a performance criterion.

2. METHODOLOGY

2.1. Study area

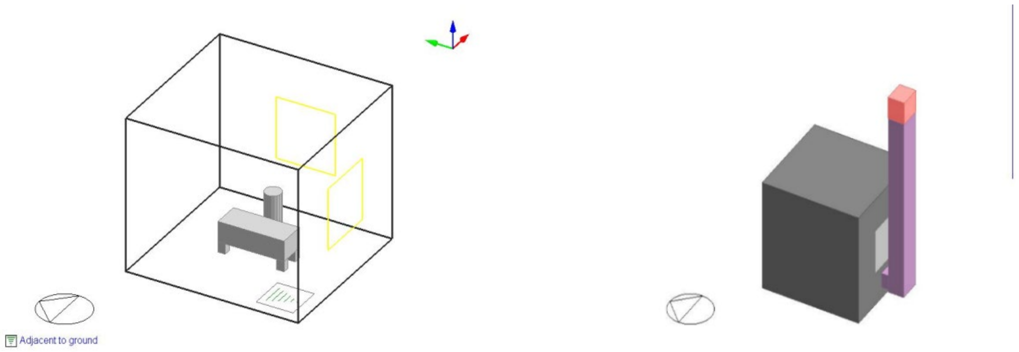
The study area is Bayero University Kano, which is located at latitude 12.05 °N, longitude 8.53 °E and an altitude of 481 m above sea level in the savannah region of North-western Nigeria. The study building is located in the university's excellence center and measures 4 m x 3.7 m x 3 m. The office building is a one-zone building with an occupancy rate of 0.068 people/m^2.

2.2. Numerical study

The numerical investigation was carried out in two stages: (1) Validation of the numerical simulation results with measurement results: The cooled and humidified airflow distributions from the HDEC system inside the office building were simulated with DesignBuilder CFD. The thermal comfort PMV inside the building at a height of 1.1 m above floor level has been determined for HDEC outlet heights from 0.1 m to 2.4 m, step 0.1 m. (2) Using DesignBuilder CFD simulation, the validated CFD was used to calculate the PMV at various HDEC outlet heights.

2.2.1. Creation of model of the office building

The architectural information of the office space was used to create the building model using DesigBuilder software. The architectural information of the site office room was obtained from the physical planning unit of Bayero University Kano. The office room is a single zone and its zone level model is shown in Figure 2(a), while its integration with the HDEC system is represented by the 3D model shown in Figure 2(b).



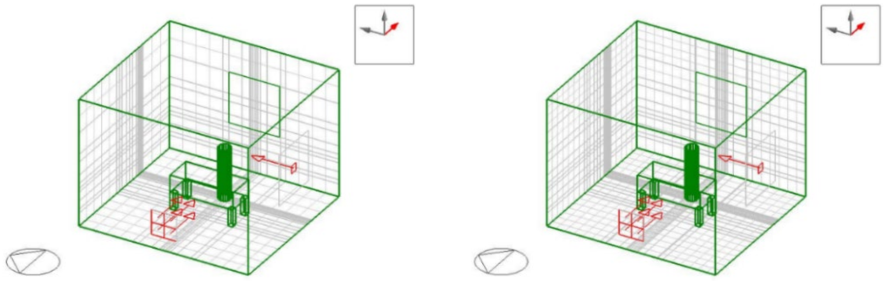
a) b)

Fig. 2. a) 3D Zone Level; b) 3D Integrated HDEC-Office Building Model.

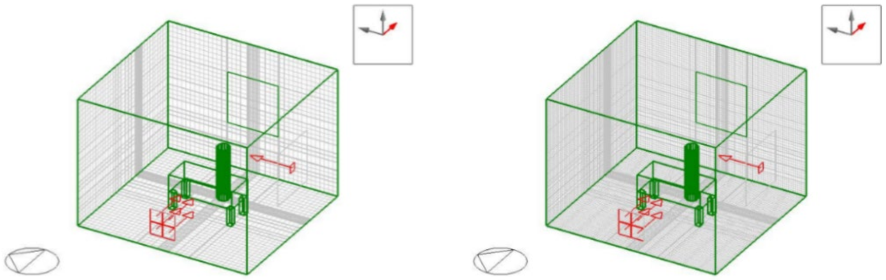
2.2.2. Grid generation and independence test

Grid generation and independence test with a good computational mesh are essential for a successful and accurate solution [15]. A study has shown that if the overall grid is too coarse, the resulting solution would be inaccurate, but if the overall grid is too fine, the resulting solution would be inaccurate, the computation time and cost can be prohibitive. In essence, solution cost and accuracy are functions of power quality. Uniform rectilinear coordinate grids used by the DesignBuilder software were used to generate the building model's grid.

A grid was generated using default DesignBuilder parameters for a coarse grid containing the minimum number of elements required to represent the geometry of the single zone model and satisfy the default grid rules. As shown in Figure 3(a), the default grid spacing of 0.300, gridline merge tolerance of 0.0300, and 4800 elements were used. To ensure grid independence, three more refined grids with 10,920, 47,385 and 344,250 elements were generated by using the "Max. X size", "Max. Y Size" and "Max. Z Size" have been set. These refined grids are shown in Figure 3 (b, c and d).



a) Coarse grid b) Refined grid 1



c) Refined grid 2 d) Refined grid 3

Fig. 3. Coarse and refined grids of the geometrical model.

In each grid (coarse and fine), the temperature distribution was measured at a height of 1.1 m above the floor, which corresponds to the shoulder of a seated occupant, as recommended by [5]. The coarse grid with 4800 elements differs from the finest grid with 344,250 elements by about 13%, while the refined grids 1 and 2 differ from the finest grid by 8.3% and 2.1%, respectively. Therefore, the refined grid 2 with 47385 elements is considered sufficient for the purposes of the numerical simulation.

2.2.3. Assigning the boundary conditions

In this study, the boundary conditions employed for the DesignBuilder CFD analysis are summarized in Table 1.

Table 1. Boundary conditions for DesignBuilder internal and external CFD simulations.

Internal CFD Analysis		External Analysis	
HDEC outlet	Airflow rate: 396 L/s Temperature: 24°C	Wind analysis	Grid spacing (m): 2.0000 Grid line merge
South window	Airflow rate: 84 L/s Temperature: 28.2°C		Tolerance (m): 0.2000 Velocity (m/s): 3.24
Eastern wall Southern wall	Fixed heat flux: 0.341 kW Fixed heat flux: 0.201 kW		Direction : South Exposure: Suburban
Other walls, ceilng and floor	Isenthalpic	Site domain factors	Length (m): 3.00 Width (m): 3.00
Occupants	One occupant, fixed heat flux: 8.11W/m^2		Height (m); 1.40
Equipment	1 laptop, fixed heat flux: 3.37 W/m^2	-	
Metabolic rate	1.0 met (58.2 W/m^2)		
Clothing level	0.5 clo (0.08 °C. m^2/W)		
Zone air temperature	31.3°C		
Zone relative humidity	65%		
Number of sphere segments in mean radiant temperature calculation	24		

2.2.4. The governing equations

The numerical method used by DesignBuilder CFD is known as a primitive variable method, which involves the solution of a set of equations that describe the conservation of heat, mass, and momentum.

The equation of mass conservation, known as the continuity equation, is given by equation (1) [16].

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

The equation for momentum conservation is given in equation (2).

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i \tag{2}$$

The equation for total energy conservation is given in equation (3).

$$\frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + u_i\frac{\partial P}{\partial x_i} + \tau_{ij}\frac{\partial u_i}{\partial x_j} \tag{3}$$

where u_i are velocity component in the i direction; P is pressure; τ_{ij} is tensor; x_i is coordinate; g_i is acceleration in the I - direction; h is enthalpy; k is conductivity.

The CFD numerical method used by DesignBuilder software, which relates to the set of those equations above, particularly describes the main environmental factors, including the conservation of heat, temperature, mass, momentum, and where a turbulence model is used. The equations comprise a set of coupled non-linear secondorder partial differential equations having the following general form, in which the dependent variable is given by equation (4):

$$\frac{\partial}{\partial t}(\rho\emptyset) + \mathrm{div}(\rho u\emptyset) = \mathrm{div}(\tau\ \mathrm{grad}\ \emptyset) + \mathrm{S} \tag{4}$$

The rate of change and convection are represented by the first and second terms on the left, respectively, while the diffusion and source terms are represented by the first and second terms on the right, respectively. The turbulence model is regarded as critical in numerical modeling for describing the flow behavior of the indoor thermal environment [17].Therefore, in this study, the standard k-e turbulence model was used since it is a well-established method in research on natural ventilation [18]. The Upwind scheme was also employed for the discretization of the transport equations.

2.2.5. Model validation

After the grid independence, the accuracy of the model was determined through a validation process. The model was validated by comparing the measured values of the door temperature of the Bayero University Kano office building equipped with the HDEC system with the simulated interior temperature from the CFD model. Figure 4 shows the comparison between experimental and simulated internal temperatures.

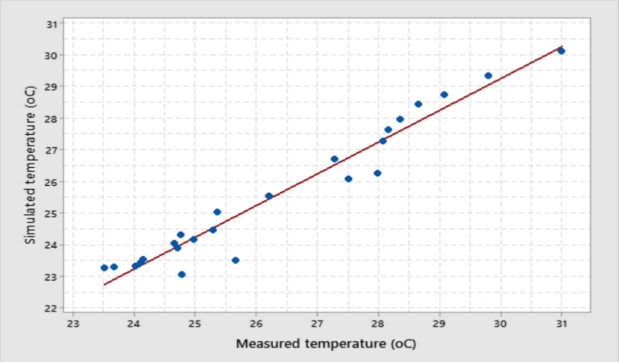


Fig. 4. Comparison between Measured and Simulated Indoor Temperature.

The coefficient of correlation between the measured and the simulated temperature at a 95% confidence level using Minitab 19 software is 0.974. The high correlation between the measured and simulated temperatures indicates the high accuracy of the building model used for this study.

2.3. Determination of thermal comfort of the building model

Measurement data from a Bayero University Kano office building equipped with the HDEC system was used as input for the DesignBuilder CFD simulation to determine thermal comfort. The HDEC system integrated into an office building in the Centre of Excellence of Bayero University Kano is shown in Figure 5.

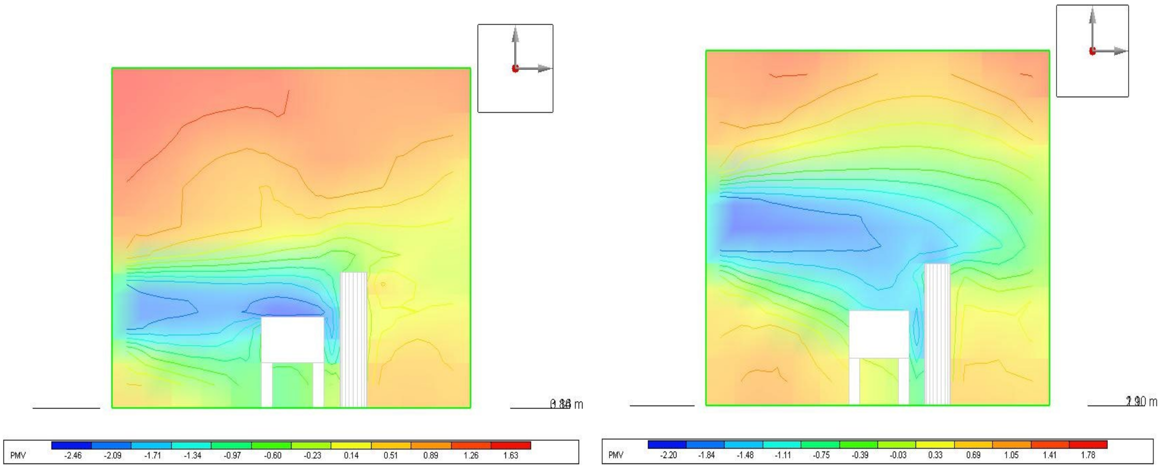
Fig. 5. HDEC integrated to office building.

2.4. Parametric Analysis of the CFD Model

A DesignBuilder parametric analysis was employed by keeping the boundary conditions constant while varying the HDEC supply outlet from 0.1m to 2.4m, step 0.1m above the floor level. A DesignBuilder CFD simulation was then carried out to determine the effect of the height of the HDEC supply outlet on the thermal comfort of the space using PMV as a performance criterion.

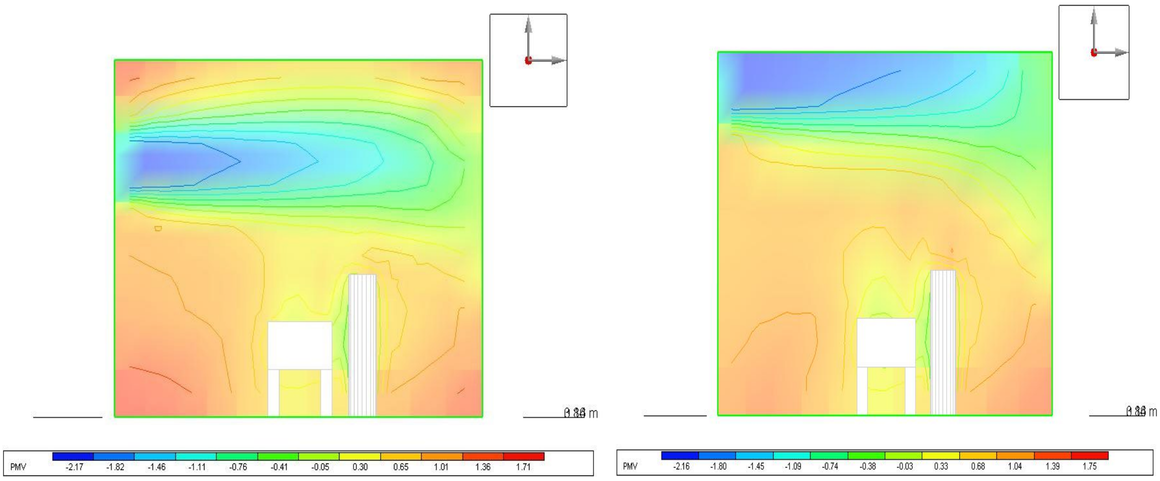
3. RESULTS AND DISCUSSION

The HDEC supply outlet height determines how the cooled and humidified air supplied by the HDEC system reaches the occupants as shown on the 2D PMV contour plots at a representative height of 0.6 m, 1.2 m, 1.8 m, and 2.4 m above the floor level in Figure 6. This implies that the variation in the HDEC supply outlet influences the characteristics of the thermal comfort zone of the office building.



a) h = 0.6m

b) h = 1.2m



c) h = 1.8m

d) h = 2.4m

Fig. 6. 2D Contour Plot of PMV at representative HDEC supply outlet heights.

The parametric simulated PMV values of the HDEC outlet height of 0.1m to 2.4m step 0.1m above the floor level are shown in Figure 7.

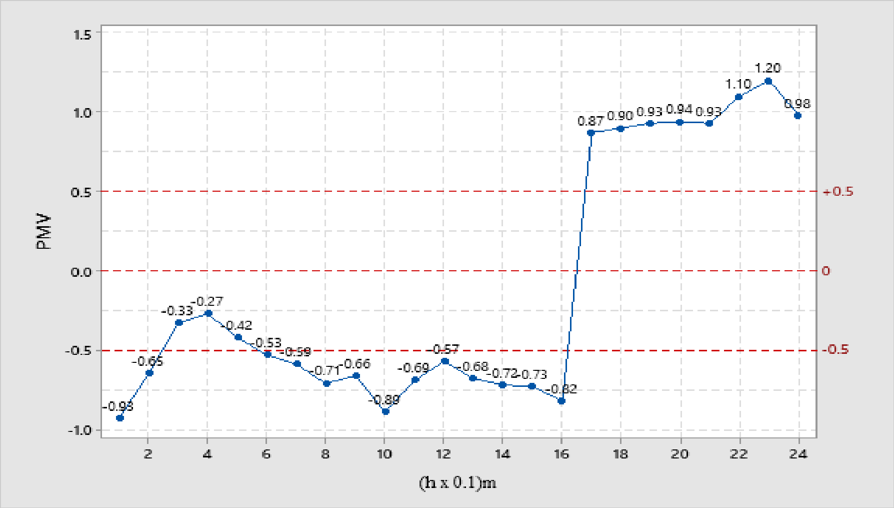


Fig. 7. Plot of PMV vs height of HDEC supply outlets.

The results of the selected 2D contour plots of the parametric simulations of the office building with the height of the HDEC supply outlets of 0.6m, 1.2m, 1.8m, and 2.4m from the floor level are shown in Figure 6 while for the supply outlet heights of 0.1m to 2.4m, step 0.1m are shown in Figure 7. Based on the recommendations of [5], it can be seen that the values of PMV when the level of HDEC supply outlets ranges from 0.3 m to 0.5 m fall within the thermal comfort band of -0.5 to +0.5. This implies that better thermal comfort would be achieved in the occupied space when the HDEC supply outlet height ranges from 0.3m to 0.5m, with the best result obtained at a height of 0.4m.

Better results were obtained at the relatively lower height of the HDEC supply outlets. This could be attributed to the HDEC system's behaving as a displacement ventilation system since the supply airflow rate is small and is supplied at lower heights. Under this scenario, the cool and humidified air supply at the lower heights displaces the warmer indoor air due to buoyancy. The thermal plume of the occupants also enhances the buoyancy effect. Hence, only cooler air surrounds the occupants while the warmer air is displaced upward and eventually exhausted out of the occupied space. This agreed with the work of Shan et al. [19], who stated that the lower the height of diffusers, the more stale and warmer air is displaced upward closer to the ceiling. On the other hand, the higher the height of the HDEC supply air diffuser, the more the HDEC system behaves like a mixed ventilation system. From the 2D contour plots it can be seen that the indoor air of the occupied space is relatively mixed and therefore feels warmer/hotter in the space with higher HDEC supply air discharge heights. This can be seen from the PMV values falling outside the comfort band on the hotter side of the thermal sensation scale shown in Figure 7.

4. CONCLUSIONS

The influence of the height of the HDEC supply outlet on the thermal comfort of an office building at Bayero University Kano was investigated numerically. The lower heights of the HDEC supply outlets gave better results, with PMV values of -0.33, -0.27, and -0.42 obtained at 0.3 m, 0.4 m and 0.5 m respectively, with the best PMV of -0.27 obtained at 0.4 m. Therefore, using lower heights of the HDEC system would improve the thermal comfort of occupants in an office building or other similar building integrated with the HDEC equipment.

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