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## **Numerical Investigation of Thermal Comfort in an Office Room With 4-Way Cassette Air-Conditioner**

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**Abstract:** Buildings account for about 40% of total energy consumption worldwide. This consumed energy is usually as a result of the HVAC systems installed in the building which are delegated with the task of providing thermal comfort or a high quality indoor environment as human spend about 90% of their time in buildings. With energy sources depleting at an unsustainable rate and contributing significantly to climate change, calls are intensifying for greener and more resource efficient systems. To support the drive towards a sustainable society, 4-way cassette air-conditioners are commonly deployed in offices in Eastern China. However, without optimal control of these systems, potential energy saving is lost while high level of indoor comfort is also not achieved. The work in this paper presents a numerical investigation of thermal comfort in an office room with 4-way cassette air-conditioner. In this study, parameters such as supply air temperature and air velocity were varied to observe their effects on the comfort level in the room. The results show that the ability to control these parameters provides promising benefits for use to optimise the control of similar HVAC systems, resulting in building energy efficiency and improved occupant comfort or indoor environment quality.

**Keywords:** thermal comfort, indoor environment, CFD, energy efficiency, 4-way cassette AC.

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## **1. Introduction**

With rising standard of living and deteriorating condition in urban environments, the expectation of occupants in indoor space is becoming very high. This is pushing the need for indoor environment to be more thermally comfortable and provide high living quality to the occupants as humans spend about 90% of their time in buildings [1-3]. In order to achieve these, the installation and use of heating, ventilation and air-conditioning (HVAC) systems alongside complex and sophisticated control systems to provide thermal comfort or high quality indoor environment have been increasing rapidly in recent years, especially in developed and developing countries, contributing to the high total annual energy consumption of buildings worldwide [4]. With energy sources depleting at an unsustainable rate and contributing to climate change, calls are intensifying for greener and more resource efficient systems that can provide or maintain a comfortable indoor environment, while at the same time reduce energy consumption in buildings; stricter energy policies are also being adopted in the European Union and many countries worldwide [5]. To support the drive towards a sustainable society, 4-way cassette air-conditioners are approved by government agencies and are widely deployed in offices in Eastern China [6]. The 4-way cassette air-conditioner (AC) can achieve high airflow efficiency and provide more evenly distribution of supply air through its multi-split outlets when compared with conventional AC with single split as previously studied [7], leading to better indoor comfort.

Numerous studies have been carried out involving thermal comfort in mechanically ventilated rooms, some of which can be found in the literature [8-12]. However, research specifically focused on 4-way cassette AC are limited, and without effective control of these systems, potential energy saving would be lost, while high level of indoor comfort will also not be achieved. Of the researches conducted with the 4-way cassette AC, Noh et al. [13] studied the effect of airflow rate on the ventilation effectiveness in a lecture room. The research concluded that increase in supply airflow rate improves the ventilation effectiveness where the work zone has a pollution (pollutant) source, and mean-age-of-air and residual life are simultaneously considered. In Noh et al. [14], the relationship between supply air angle, supply air volume, ventilation effectiveness, thermal comfort and indoor air quality (IAQ) in a lecture room was investigated. It was found that indoor thermal comfort decreases with the increase of supply air angle, although no significant reduction in IAQ was observed. Air volume however, has no significant influence on thermal comfort and IAQ, but increase in ventilation rate increase thermal comfort.

In this paper, two control parameters (supply air temperature and air velocity) were varied using several operating conditions to investigate their influence on thermal comfort in an office room with two occupants. The investigation is carried out by numerical simulation using three-dimensional computational fluid dynamics (CFD). CFD has been used by many researchers for visualisation of air flow and temperature [15, 16]. It is an efficient tool for predicting indoor environment conditions and thermal comfort.

The effects of the investigated parameters on thermal comfort in this paper will be assessed using the air velocity pattern, temperature distribution and the vertical air temperature.

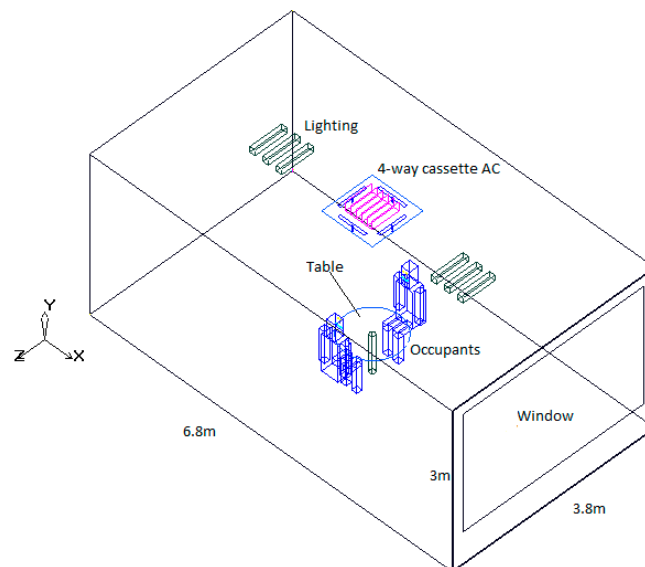
## 2. Methods

### 2.1. Model description

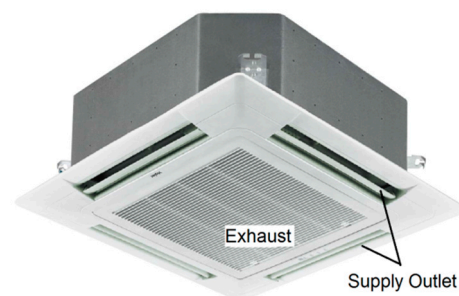
The room model used in this case study is shown in figure 1a below. The room is modelled based on the condition in an actual office located within the Science and Engineering Building of The University of Nottingham Ningbo Campus. The conditions of the office room are similar to that of a typical office in Eastern China and as such, the results obtained are expected to be applicable to a wide range of similar applications.

**Figure 1. (a)** CFD model of office room with 4-way cassette air-conditioner. **(b)** 4-way cassette air-conditioner.

**(a)**



**(b)**



The room under consideration here has a dimension of 6.8 x 3.8 x 3m and is setup as a two-occupant office. The room has a window of 3.4 x 2.4 located at the upper portion of an exterior east-wall. Warm air is supplied into the room through outlets of a ceiling recessed 4-way cassette air-conditioner, while cool air from the room is evacuated at the centre of the air-conditioner for reconditioning, see figure 1b.

To simulate a working environment under winter conditions, two thermal mannequins (104W) and fluorescent lamps (6 x 14W) were located in the room. The temperature of the window is set to 18°C while the walls, floor and ceiling are assumed to be adiabatic non-slip. The conditions for the air-conditioner and considered cases are contained in section 2.3.

### 2.1. Governing equations

It is assumed that the airflow in the room is three-dimensional, steady-state, incompressible and turbulent which can be described by the conservation laws of mass, momentum and energy. The governing equations are thereby time-averaged Navier-Stokes and continuity equations given as:

Mass conservation

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

where  $U_i$  is the mean turbulent velocity component in  $x_i$ -direction.

Momentum (Navier-Stokes) equation

$$\frac{\partial}{\partial x_j} (\rho U_i U_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} (-\rho \overline{u_i u_j}) + g_i (\rho - \rho_o) \quad (2)$$

where  $P$  is the pressure,  $g_i$  is the gravitational acceleration,  $\rho$  is the air density and  $\rho_o$  is the density at a reference temperature.

The Reynolds stress  $-\rho \overline{u_i u_j}$  in equation (2) above is estimated by Boussinesq hypothesis and represented as:

$$-\rho \overline{u_i u_j} = \mu_t \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (3)$$

where  $\mu_t$  is the eddy viscosity computed as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \quad (4)$$

$k$  is the turbulence kinetic energy given as:

$$k = \frac{1}{2} \overline{u_i u_i}, \quad (5)$$

and  $\delta_{ij}$  is the Kronecker delta.

Energy conservation

$$\frac{\partial}{\partial x_j} (\rho U_j T) = \frac{\partial}{\partial x_i} (-\rho \overline{u_i T'}) \quad (6)$$

Transport equation

In the  $k - \varepsilon$  model, the transport equations for kinetic energy  $k$  and dissipation rate  $\varepsilon$  are given as:

$$\frac{\partial}{\partial x_i} (\rho U_i k) = \frac{\partial}{\partial x_i} \left( \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + \rho (S_k + S_B) - C_D \rho \varepsilon \quad (7)$$

$$\frac{\partial}{\partial x_i} (\rho U_i \varepsilon) = \frac{\partial}{\partial x_i} \left( \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right) + C_1 \rho \frac{\varepsilon}{k} (S_k + S_B) - C_2 \rho \frac{\varepsilon^2}{k} \quad (8)$$

$S_k$  represents the source term for turbulent kinetic energy, while  $S_B$  represents the buoyancy and can both be expressed with the following equations:

$$S_k = \frac{\mu_t}{\rho} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} \quad (9)$$

$$S_B = -\beta g \frac{\mu_t}{\rho \sigma_t} \frac{\partial T}{\partial x_j} \quad (10)$$

### 2.3. Case studies

In this study, a total of 7 cases were investigated; to test the effect of supply temperature and velocity conditions on thermal comfort in the office room, the supply temperature was varied between 24 ~ 30°C, while the supply velocity was varied between 0.71 ~ 1.208m/s for each outlet of the 4-way cassette air-conditioner. The relative humidity is set to 50% while other boundary conditions for the room were kept constant for all the test cases. Table 1 below shows all simulated test cases.

**Table 1.** Supply condition for simulated cases.

Case	Supply velocity (m/s)	Supply temperature (°C)	Supply outlet angle (°)
1	1.055	30	30
2	0.71	30	30
3	0.958	30	30
4	1.208	30	30
5	1.055	24	30
6	1.055	25	30
7	1.055	27	30

### 2.4. CFD simulation

Construction of the CFD model geometry was done with Airpak 3.0.16 as well as the mesh generation. Airpak is a subset of the commercial ANSYS CFD package specially designed for HVAC, it uses ANSYS Fluent numerical simulation engine to perform simulations [17]. ANSYS Fluent 14.5 was used as the finite-volume solver to numerically simulate the airflow and temperature field base on the RNG  $K - \epsilon$  model [18]. Convergence criterion was set to be less than  $10^{-3}$  tolerance, while the energy conversion criterion was set to normalise residual below  $10^{-6}$ , these were obeyed in all cells to make sure that the solution no longer changes with further iterations. The simulations were carried out on an Intel i7 processor computer with 16GB of internal memory.

To adequately predict the situation in the room, several grid options were considered and a grid independence test was performed to make sure that the accuracy of the simulation is not influenced by the grid choice (i.e. no further significant changes were noticed in the result). Finer grids were also set for the air-conditioner outlets and inlet (exhaust) as well as heated surfaces.

## 3. Results and Discussion

The numerical results obtained from the cases simulated are analysed and presented as follows.

### 3.1. Velocity pattern

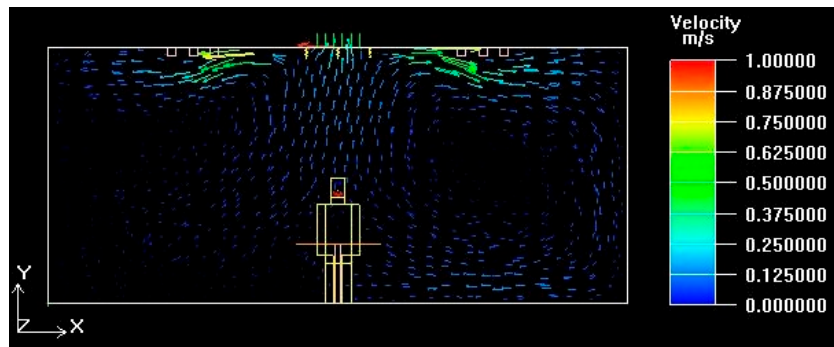
Air velocity is an important thermal comfort parameter as it helps in evaporating sweat thereby giving a cooling sensation. However, when it is supplied in excessive quantity, it can cause draught sensation. Normally, an average air velocity below 0.15m/s is desired. From the velocity contours of the simulated cases shown in figure 2, it is observed that the air velocity in all cases towards the top of the room at above 2 metres is significantly higher than 0.15m/s. This is however expected as the air supply inlet is

located in that region. The patterns show that the thrown air from the air-conditioner is sent in the direction of the walls while approaching the occupied zone and is returned back at the middle of the room. On approaching the occupied zone, the air velocity is reduced considerably and is within the desired range.

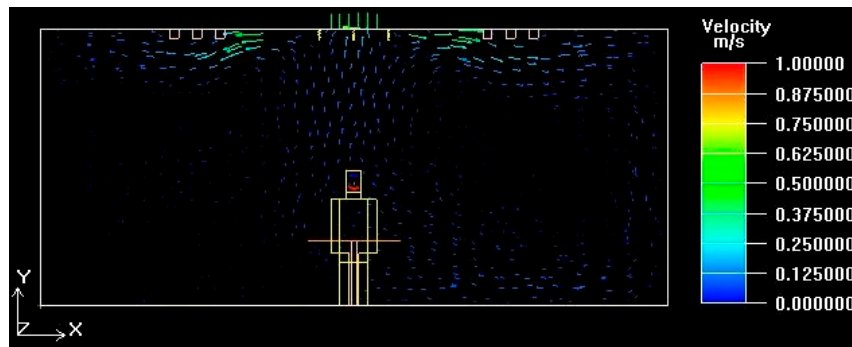
Following up on the above observation, the supply inlet air velocity has minimal influence on thermal comfort in this environmental setting and thus could be considered for energy reduction for example through reduced fan speed, although the effect of such decision on air quality might need to be considered.

**Figure 2.** Velocity contour on centre plane at Z=1.9m. **(a)** Case 1, **(b)** Case 2, **(c)** Case 3, **(d)** Case 4, **(e)** Case 5, **(f)** Case 6, **(g)** Case 7.

**(a)**



**(b)**



**(c)**

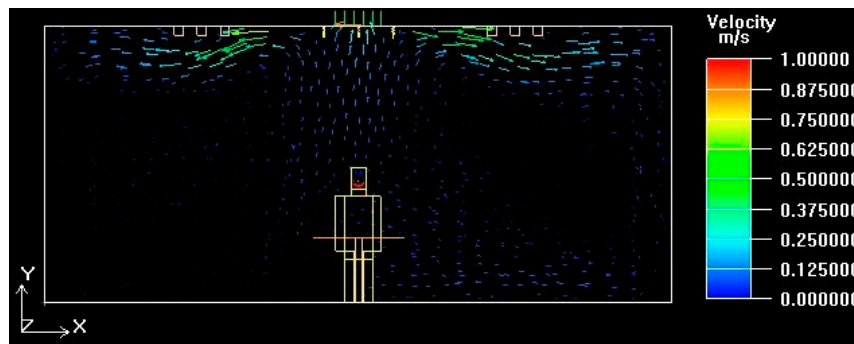
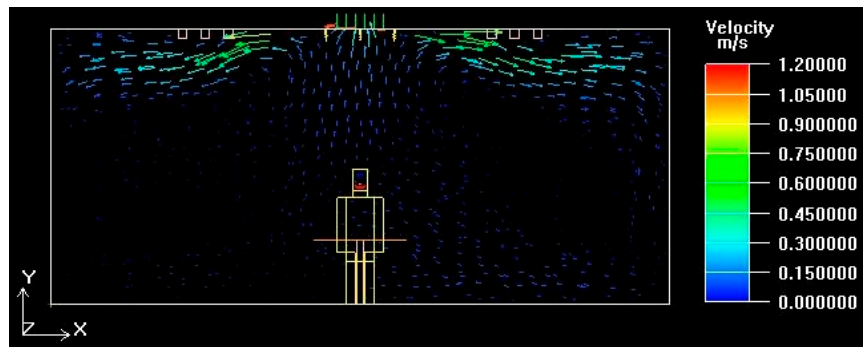
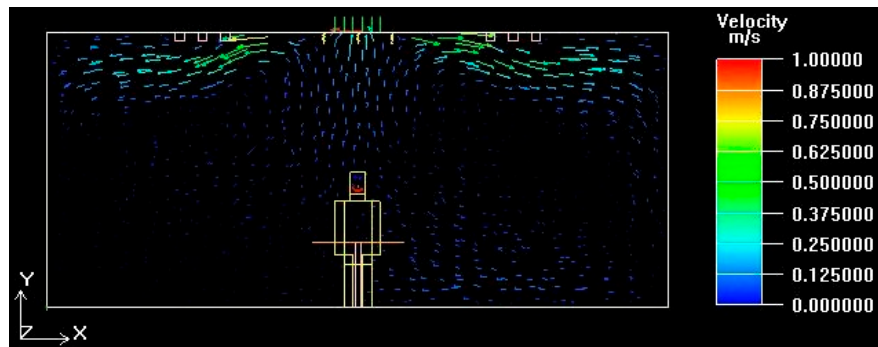


Figure 2. Cont.

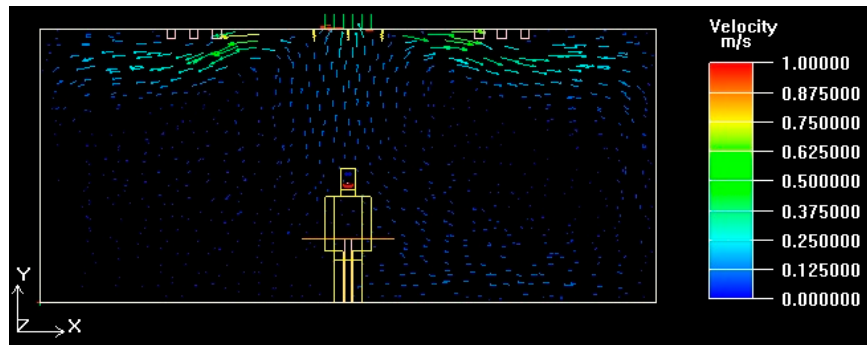
(d)



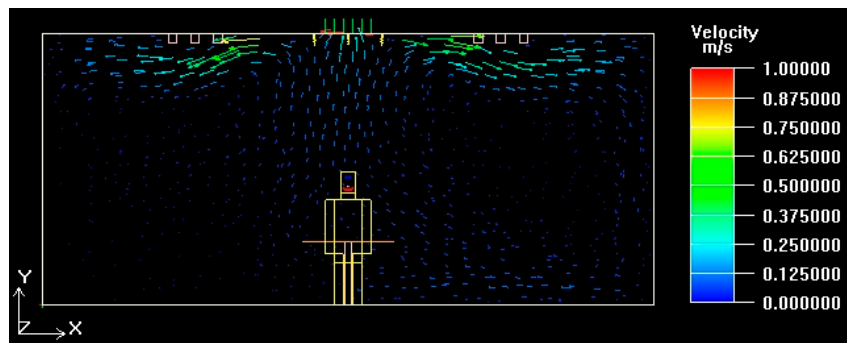
(e)



(f)



(g)



3.2. Temperature pattern

The temperature distribution patterns of the simulated cases are shown in figure 3. From the patterns, the higher temperature air is located at the top of the room above the occupied zone, while the lower temperature air is located below. This is more pronounced for the cases with higher supply temperature. Since thermal stratifications result in poor thermal comfort, reducing the supply temperature of the 4-way cassette air-conditioner will lead to better thermal comfort. In addition, reduction in supply temperature will also result in better energy efficiency and potential energy savings.

**Figure 3.** Temperature distribution on centre plane at Z=1.9m. (a)Case 1, (b)Case 2, (c)Case 3, (d)Case 4, (e)Case 5, (f)Case 6, (g)Case 7.

(a)



(b)



(c)

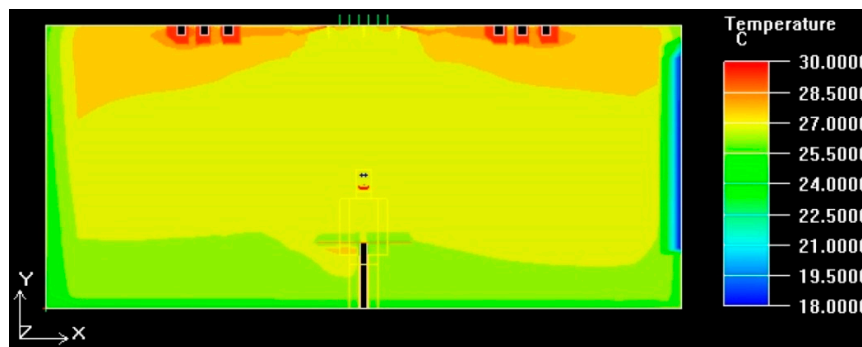




Figure 3. Cont.

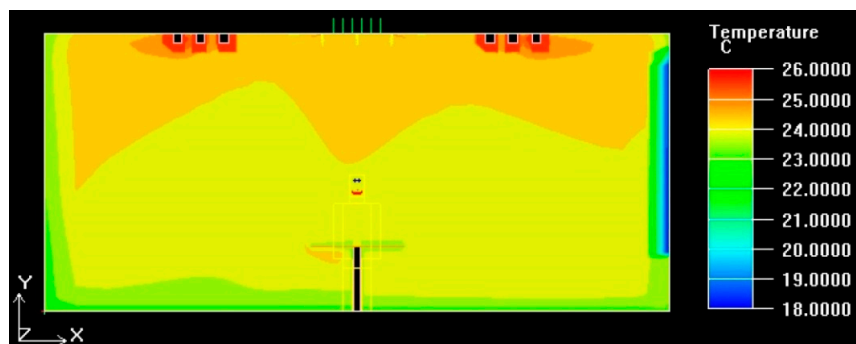
(d)



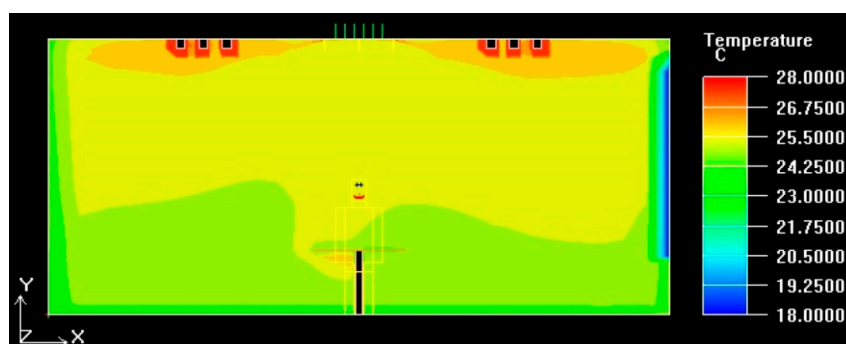
(e)



(f)



(g)

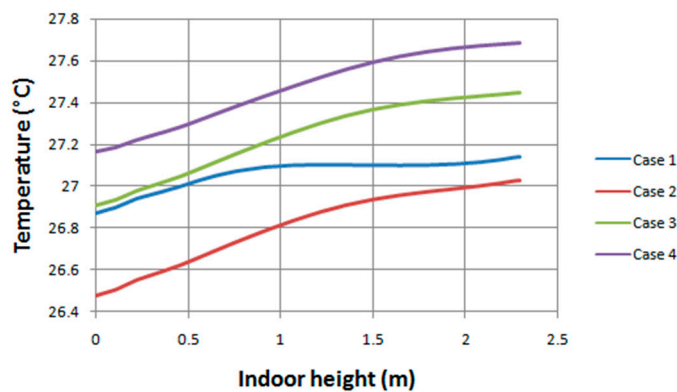


### 3.3. Vertical air temperature

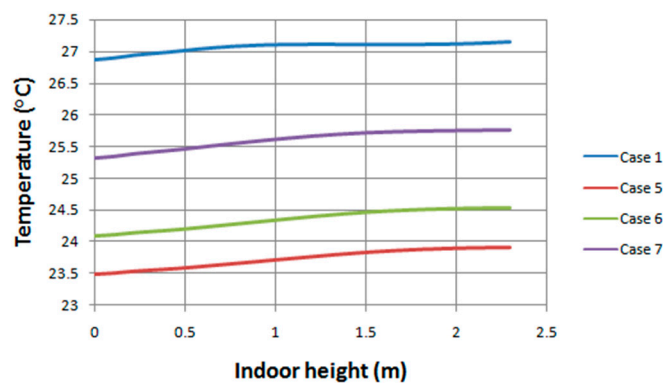
By using the vertical air distribution shown in figure 4, more detailed information about the air temperature and velocity can be obtained. Important information that can be acquired from the vertical air distribution is the vertical air distribution difference (VATD), which is the difference of air temperature between the location of the head and ankle of an occupant. These locations for a person in seating position (which would most commonly be the case in an office) are at height 1.1 metres (for the head) and 0.1 metres (for the ankle). Based in the ASHRAE 55 standard guide [19], the VATD between these 2 points should be less than 3 °C. The VATD for all the simulated cases in this study are within the recommended requirement, which is obvious as VATD is not concerned with the unoccupied zone. Going by the guide, a lower temperature setting is desirable for use in the 4-way system to reduce energy consumption and also noted earlier, to improve thermal comfort.

**Figure 4.** Vertical air temperature profile at centre of room at X=3.4m, Z=1.9m. **(a)**Supply velocity variation, **(b)**Supply temperature variation.

**(a)**



**(b)**



## 4. Conclusions

A numerical investigation has been carried out using CFD on an office room equipped with a 4-way cassette air-conditioner system. Temperature ranging between 24 and 30 °C, and inlet supply velocity ranging between 0.71 and 1.208m/s per outlet of the 4-way air-conditioner were considered to better

understand the effects of the parameters on the system and potential energy saving. A detailed energy study will however need to be carried out to quantify the potential energy reduction.

In summary, the following observations were made in this study:

Variations in supply air velocity within the tested range and under these conditions have no significant influence on thermal comfort, as such reduced supply air velocity can be considered for energy efficiency.

All considered cases in the stud satisfy the less than 3 °C vertical air temperature difference, despite the presence of significant temperature stratification at the top non occupied zone of the room especially for cases with higher temperature.

Reducing inlet supply temperature can reduce the temperature stratification in the room; improve thermal comfort and help in reducing energy consumption.

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