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Effect of Local Floor Heating System on Occupants' Thermal Comfort and Energy Consumption Using Computational Fluid Dynamics (CFD)

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Abstract: In this article, the influence of splitting a local underfloor air distribution system (UFAD) on indoor thermal comfort for three occupants was studied numerically. A validated computational fluid dynamics (CFD) model was employed in this investigation. The proposed heating system was evaluated and analyzed for different values of air temperature and supply velocity. Providing suitable thermal comfort and saving energy are considered the main evaluation indexes for this study. Three cases, cases 2, 3, and 4, of the proposed local UFAD system were compared with a traditional heating system case, case 1. The supplying air velocity and air temperature in the reference case were 0.5 m/s and 29 °C, while in cases 2, 3, and 4, they were 0.4 m/s and 29 °C, 28 °C, and 27 °C, respectively. The results show that acceptable indoor human thermal comfort and energy demand reduction were achieved by using the splitting UFAD concept.

Keywords: underfloor air distribution; local heating; CFD; energy saving; thermal comfort

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1. Introduction

The energy consumed by Heating, Ventilation, and Air Conditioning (HVAC) systems indoors represents about 40 percent of the total energy demand in the construction sector. These processes are significant in maintaining comfortable indoor air conditions [1]. High energy demand is required to satisfy occupants' requirements as recommended by numerous standards [2]. HVAC systems provide indoor occupants with thermal comfort requirements in summer or winter [3]. Most HVAC systems are designed to provide occupants with good thermal comfort and adequate air quality with reduced energy demand. A significant proportion of demand energy is consumed for the purpose of heating buildings. Consequently, a slight improvement in the energy consumption of a heating system will enhance energy savings and reduce global warming [4]. Subsequently, to reduce the energy consumption resulting from heating systems, modern buildings have employed many energy-efficient construction technologies such as improved thermal insulation and air tightness. However, sometimes, these technologies may reduce the supply of outdoor fresh air and cause poor air quality. To avoid this problem, floor heating systems are used in mechanical ventilation systems, which supply fresh air indoors from the floor level [5]. In recent years, floor heating (FH) systems have drawn growing interest and applications and have dramatically risen in their use worldwide compared to traditional heating systems. Numerous advantages of FH systems include their noiselessness, efficient use of space, uniform temperature control, and relatively low energy consumption [6].

Many detailed studies of the energy-saving potential of the proper use of heating/cooling have already been carried out [7–13]. The standards of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the International

Organization for Standardization (ISO), and the Japanese standard are employed to construct radiant heated floors with defined air temperature limitations. Cultural factors such as sitting on the floor or sitting on seats, wearing shoes, and bare feet were illustrated by Shin et al. [14]. They determined the relationship between generated heat, floor temperature, and significant design points. Design charts were developed to estimate heat generation, the largest surface temperatures, and the disparity between the maximum and minimum temperatures of the surface. The charts help researchers' analyses of various choices for radiant surface floors.

A precast lightweight radiant floor plate, which was an engineered sheet including an insulating board at the base, thick aluminum foil, a plastic heating hose, and a surface path, was studied by Yu et al. [15]. The distance length between the pipes that were used for heating had a direct impact on the corresponding resistance. However, the thickness of the aluminum foil had no noticeable impact on the heating panel's thermal efficiency. Through their capillary systems, radiant surface floors use capillary copper tubes, in combination with solar panels, for better efficiency of such devices. Li et al. [16] have provided an empirical method for heat transfer in the multilayer floor structure of a radiant floor device. Experiments were used to check the solution, and it can be used to predict floor surface temperature distribution. Enhanced overhead convection for radiant surface floor heating systems was given and tested by Li et al. [16] by inserting holes into the radiant floor. Wang et al. [17] found that convective heating systems in the form of intermittent heating could raise the indoor temperature faster than radiant floor heating. In their results, the thermal efficiency, especially during the preheating phase, improved significantly. Atienza Márquez et al. [18] have investigated the incorporation of radiant surface floors and fan coil units in the same area. The results show that the combined device demonstrated the strongest relationship between energy usage and level of comfort. Ma et al. [19] examined the efficiency of a solar groundwater heat pump incorporated with radiant surface floor heating and compared it with a traditional central heating system. The findings revealed that the current machine saved 30.55% of electricity.

In particular, the surface floor heating system can save up to 18.96 percent of energy compared with the standard radiator. Sebarchievici et al. [20] measured the efficiency of an office's ground-coupled heat pump fitted with a radiator only or a radiant surface floor heating system. The energy usage and CO_2 emissions of the radiator heating system were 10% higher than the heating floor surface system under different operating conditions. An innovative method of optimum control, i.e., model predictive control (MPC), has been improved for FH systems by Maomao Hu et al. [6], which can concurrently understand all powerful variables like temperature, occupied area, and volatile electricity.

Given the efficiency of online computation, a control-oriented thermal dynamic model was built and described in a stochastic state-space form for a room combined with the FH method. An economical MPC controller was enhanced for FH, which was formulated as a mixed-integer linear programming problem. The findings show that the MPC controller was able to utilize the thermal mass of the building relative to the traditional on–off controller to optimally transfer energy usage to low-price times, increase comfort at the beginning of occupancy, minimize energy consumption at high cycles and reduce electricity costs for occupants and users. In an office building operated by the UFAD scheme, the thermal comfort of occupants was measured by Alajmi et al. [21], utilizing various methods such as a field study and subjective and physical observations, and analyzed using computational fluid dynamics (CFD). The results were more representative of the relative degree of the thermal comfort of the occupants in the room, according to the Air Distribution Efficiency Index (ADPI). In addition, the quest for using CFD to obtain optimal working conditions and optimize the thermal comfort for people culminated in an increase of 90 percent in the ADPI relative to the current conditions. In another analysis by Chao and Wan [22], the airflow behavior in an area ventilated by the UFAD system was coupled with the temperature distribution. In the investigation, the findings revealed an undesirably elevated velocity of air close to the outlet terminal, resulting in high draft risk and comfort deterioration. Another significant research study was carried out by Rabanillo-Herrero et al. [23] to determine the effectiveness of climate change and thermal comfort in winter conditions with many conditioning systems such as heating floor radiators, radiant ceilings, and underfloor heating at different locations in the interior area. An experimental study was created in the experiment chamber to validate several CFD results. The findings revealed that with the occupant thermal comfort obtained, the average efficiency of air change differed between all instances by just 2.40%, making this factor unimportant. Even then, because of the convective effect, the direction of the airflow in the premises will be influenced by the thermal activity, giving a great variation due to the position of the thermal systems. Thus, as it reaches the room or rises toward the ceiling, the air trajectory can falter, producing areas with lower temperatures in the middle. An underground distribution system of air with an independent flow and exhaust outlet has been examined by Heidarinejad et al. [24]. In their study, the suitable angle of the swirl diffuser was chosen by contrasting the general conditions of comfort achieved from three investigated angles of entry.

The impacts of the height of the return outlet on thermal comfort requirements, indoor air quality (IAQ), and energy demand are studied at this proper inlet angle. It is observed that choosing the return outlet position at the height of 1.3 m from the floor would result in a 15.3 percent saving in energy and retain the defined range of IAQ and internal thermal comfort. Alajmi and El-Amer [25] examined the energy efficiency of the UFAD system for different air supply temperatures in commercial buildings. The results showed that the energy savings would be greater when using UFAD compared with mixing ventilation (MV) systems. Kim et al. [26] tested the internal thermal comfort of the occupants via a UFAD in a broad indoor setting. Based on their study, the UFAD system could produce a smaller vertical profile of air temperature differences, and a more stable climate than traditional overhead air distribution (OHAD) systems was achieved. Cheng [27] studied the internal thermal comfort and energy conservation of a small office combined with an UFAD device numerically. They observed that a downward construction height of the return vent would maximize energy savings while adversely affecting thermal comfort. The return vents were proposed to be positioned for seating occupants at the upper level of the inhabited zone, which is 1.3 m.

The studies that have been reviewed indicate a requirement for further detailed information regarding the influence of the splitting or local UFAD system within equipped office rooms on both internal thermal comfort and energy consumption. This study holds significance as it fills a gap in existing research by examining the impact of using local UFAD systems on thermal comfort and energy consumption in office rooms. The study adopts a distinct approach involving using a heated floor system in a specific area of the office room, aiming to achieve cost-effective high efficiency while ensuring safe and reliable operation. The findings of this investigation will contribute to the advancement of office buildings that are more energy-efficient and provide acceptable thermal comfort.

2. Description of the Simulated Room

In this investigation, a typical office room with dimensions of 4 m in length, 3 m in width, and 3 m in height was examined numerically to investigate the influence of utilizing the proposed local UFAD system on both internal thermal comfort for the occupants and enhancing energy demand. As to limited computational resources and computing time, only four simulation cases were examined in this investigation. In order to decrease the energy demand and provide a suitable internal environment, the simulated room was divided into three zones depending on the occupants' seating position. The reference case, case 1, was equipped with only the main supply opening (0.2 m $\times$ 0.7 m $\times$ 1.0 m) as a traditional installation (see Figure 1). The ASHRAE Standard 55 (2017) [28] suggests a suitable floor temperature range for individuals wearing regular footwear during cooling, which should be at or above 19 °C. Similarly, during heating, the recommended floor temperature range should be below 29 °C for those wearing normal footwear. Depending on these suggestions, the local UFAD system with a 1 m × 0.25 m dimension was installed under each person's seat (see Figure 1). The supply air velocity was 0.4 m/s, and supply temperatures were 27 °C, 28 °C, and 29 °C for cases 2, 3, and 4, respectively. For case 1, the reference case, the supply condition of velocity and temperature was 0.5 m/s and 29 °C, respectively. In addition, the air exhaust with a dimension of 0.35 m × 0.35 m was positioned at the ceiling level. Also, the bounded walls were assumed to be adiabatic walls. This study employed five different temperatures and velocities to evaluate the proposed air distribution system, as listed in Table 1.

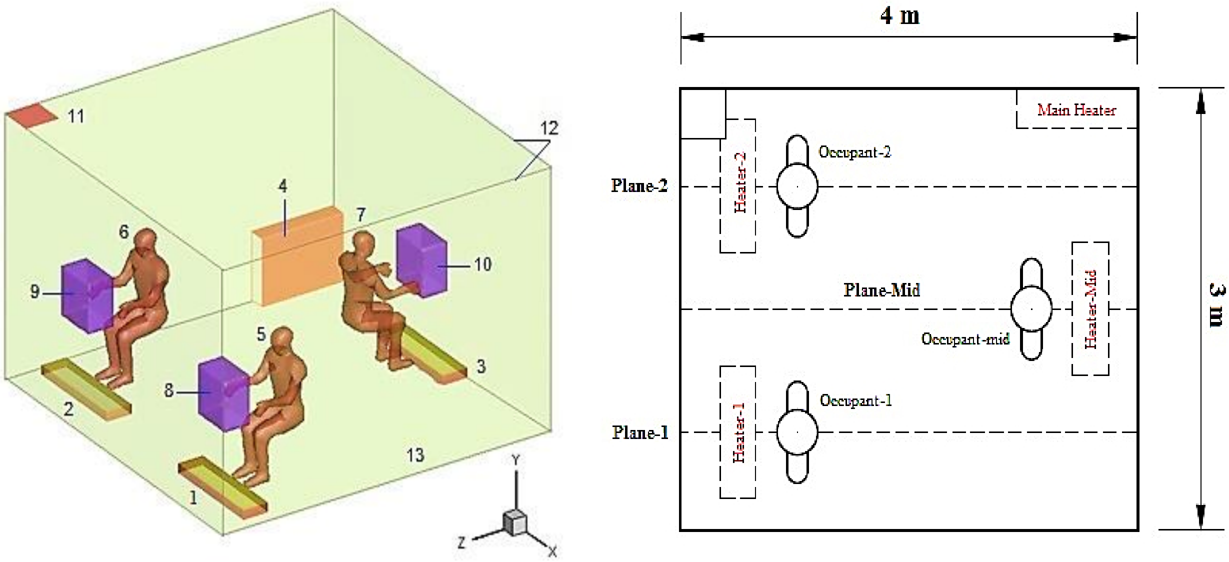

Figure 1. Simulated room description: (1) Heater, (2) Heater, (3) Heater-mid, (4) Main heater, (5) Occupant-1, (6) Occupant-2, (7) Occupant-mid, (8) Computer-1, (9) Computer-2, (10) Computer-mid, (11) Exit, (12) Bounded walls, and (13) Floor.

Table 1. Cases under study.

Cases	Supply Air Temperature °C	Supply Air Velocity m/s
Case-1 (reference case)	29	0.5
Case-2	29	0.4
Case-3	28	0.4
Case-4	27	0.4

3. Methods

3.1. Grid Design and Grid-Independent Test

ANSYS ICEM CFD was used in this examination to create the mesh system. A tetrahedral unstructured grid is highly recommended for such a complex case study. A suitable mesh density distribution was taken carefully, especially in an important region inside the investigated room, such as heat sources and outlets (see Figure 2). Also, a suitable value of y+, 3.5 < y+ < 11, was employed to obtain good solution stability and accurate simulation results. The heat flux generated by the internal heat sources affects the velocity distribution indoors. For this reason, an enhanced wall treatment was employed in this investigation to predict an accurate simulation results in regions near the wall. In order to achieve this, the proper y+ value was employed. In the current study, the quality of mesh was rated at 0.7 on a scale from 0 to 1. This value, 0.7, represents the mesh effectiveness in discretizing the domain for numerical solution. A higher mesh quality provides more accurate simulation results. For the current simulation, the mesh quality of 0.7 is considered reasonably acceptable and is expected to give accurate results. A mesh-independent test was conducted in this examination to ensure mesh validity and to improve the simulation results' accuracy and simulation cost. For this particular investigation, the grid size was determined by comparing simulation results for the three different grid sizes listed in Table 2. In order to perform the mesh-independent test, the temperature and velocity profile were calculated at the center of the simulated room using different mesh sizes, as listed in Table 2, to determine the best grid size. The results, presented in Figure 3a,b, indicate that there were no significant variations in velocity and temperature distribution when increasing the grid cells from mesh B to mesh C. Consequently, mesh B was selected as the grid size for the remaining analysis. Based on this test, about 1,700,000 elements were chosen as the best mesh size for all case studies.

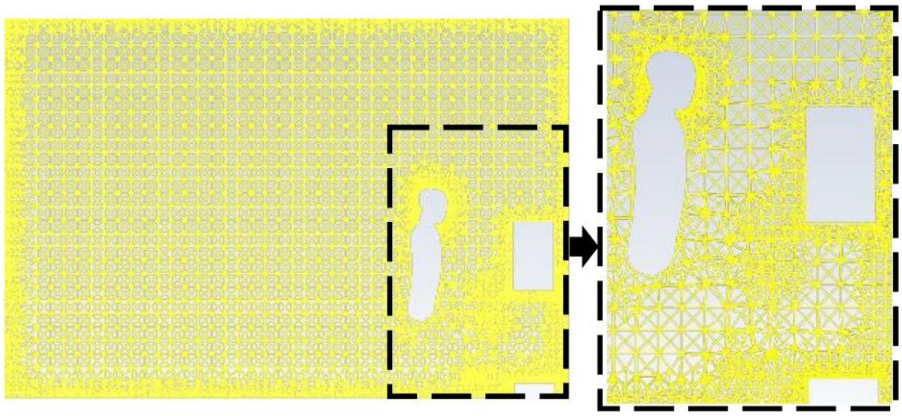

Figure 2. Mesh distribution in room domain.

Table 2. Mesh test.

Mesh	Number of Cells
Mesh A	1,300,000
Mesh B	1,700,000
Mesh C	2,100,000

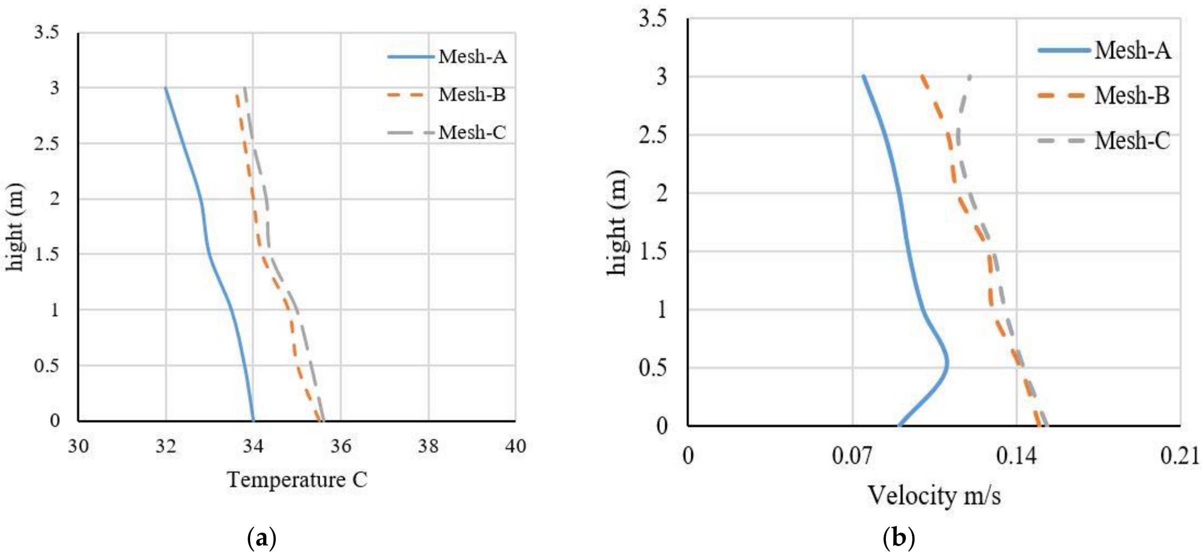

Figure 3. Mesh independent test: (**a**) temperature profile; (**b**) velocity profile.

3.2. Air Flow Modeling

This study chose a suitable turbulence model to simulate the accuracy of the air temperature distribution and indoor air movement. This turbulence model is based on the instantaneous Navier–Stokes equations and was developed using a mathematical approach known as the "renormalization group" (RNG) method. The renormalized group (RNG) k-ε turbulence model equations were utilized to calculate the internal air velocity and temperature. This model was adopted in many recent studies for the same purpose, and its importance for obtaining accurate simulation results in a short time. This model can accurately calculate the velocity in close regions of the wall [29,30]. This model is presented as follows [31]:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + \rho\varepsilon \quad (1)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k + C^*_{2\varepsilon}\,\rho\frac{\varepsilon^2}{k} \quad (2)$$

where

$$C^*_{2\varepsilon} = C_{2\varepsilon} + \left(C_\mu \eta^3\left(1 - \frac{\eta}{\eta_o}\right)\right)/1 + \beta\eta^3 \text{ with } \eta = (Sk/\varepsilon) \text{ and } S = \sqrt{2S_{ij}}S_{ij}$$

The constants used in this study are given by the following:

C_μ, σ_k, and σ_ε are 0.0845, 0.7194, and 0.7194, respectively. $C_{1\varepsilon}$ = 1.42, $C_{2\varepsilon}$ = 1.68, η_o = 4.38, β = 0.012.

The indoor airflow behavior was examined using ANSYS Fluent for all cases. The wall boundary layers were evaluated according to the enhanced wall treatment concept. The concept of Boussinesq was used in this examination. The semi-implicit method for the pressure-linked equations SIMPLE algorithm was also utilized to deal with the coupling of pressure and velocity. In addition, a second order was adopted in this investigation. The validity and reliability of any numerical computations and iterative processes are mainly based on convergence criteria, which are essential for providing accurate predictions. The convergence criteria of the numerical solutions were determined when the residuals for continuity and the RANS equations were lower than 10^{-4} and those for the energy equation were lower than 10^{-6}. Furthermore, the errors for the overall mass flow rate and internal heat flux balances were less than 0.035% and 0.4%, respectively. In this study, the duration of each simulation case was about 13 hours. These convergence criteria ensure that the computations are accurate and yield trustworthy results. Table 3 presents all the details of boundary conditions and the model used in this study.

Table 3. Detailed information for the investigated room.

Turbulence flow model	Renormalized group RNG k–ε
Radiation	Discrete ordinates (DO)
Numerical schemes	Pressure, staggered of third order PRESTO for the other terms, upwind second order and SIMPLE algorithm
Boundary conditions for the simulated room	
Walls	Adiabatic wall
Air supply (main)	Inlet velocity (0.5 m/s, 29 °C)
Supply air (local)	Inlet velocity (0.4 m/s, 27 °C, 28 °C, and 29 °C)
Exhaust	Pressure outlet
Occupants (seated and writing)	Heat generation 60 W/m^2 × 3
PC case	Heat generation 60 W × 2
PC monitor	Heat generation 70 W × 2
Lamps	Heat generation 24 W × 2

4. Results and Discussion

4.1. Validation of Utilized Model

Depending on the experimental results performed previously [32], the utilized turbulence model was validated in this study. The validation process involved measuring the temperature distribution at three different locations, namely L1, L2, and L3. These columns were located at the center of the room in the case study. The selected model's boundary conditions specification and matching are essential elements affecting the precise simulation of internal air movement and air temperature distribution in a room. As shown in Figure 4, the compared results between the previous experimental results of Khaleel et al. [32] and the present numerical results show that most of the compared data were very close and acceptable. In order to guarantee the accuracy of the validation results, the level of imprecision was evaluated for temperature and velocity The point-wise error percentage was calculated using Equation (3). The analysis revealed that the error percentage for temperature did not surpass 9%. To obtain more comprehensive details regarding the validation of boundary conditions and geometry, refer to the study conducted by Khaleel et al. [32].

$$\text{Percentage error} = \frac{Value_{num} - Value_{exp.}}{Value_{exp.}} \times 100\% \tag{3}$$

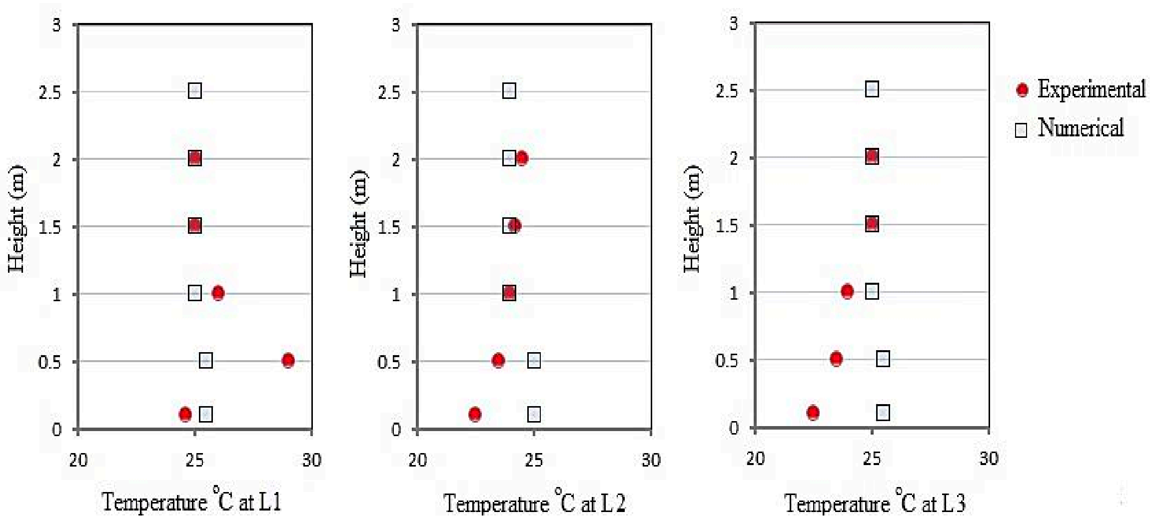

Figure 4. The comparison between the experimental and numerical results.

4.2. Temperature Distribution Indoor

The internal healthy zone and comfortable thermal conditions are essential elements to create an acceptable and productive indoor environment. Subsequently, indoor temperature distribution has become necessary to provide suitable thermal comfort for occupants. In this examination, the internal environment was predicted under three different locations of occupants sitting, as shown in Figure 5. The investigation of the thermal comfort conditions inside a room is presented in Figures 4–7. The local UFAD system was used to enhance the thermal environment for the occupant as well as reduce energy consumption.

Figures 6–9 show the temperature distribution in suggested locations inside the room for cases 1, 2, 3, and 4, respectively. Also, the presented results of air distribution and thermal comfort for cases 2, 3, and 4 that use the local UFAD system will be compared with the reference case in addition to the energy consumption when using such systems. Figure 6 represents the temperature distribution of the reference case (case 1). In this case, a conventional heating system was used to supply the test room with an air temperature of 29 °C and an air velocity of 0.5 m/s. In this case, the temperature distribution is not uniform, and a high amount of energy is wasted by extracting the supplied air directly from the exhaust opening before reaching the room domain.

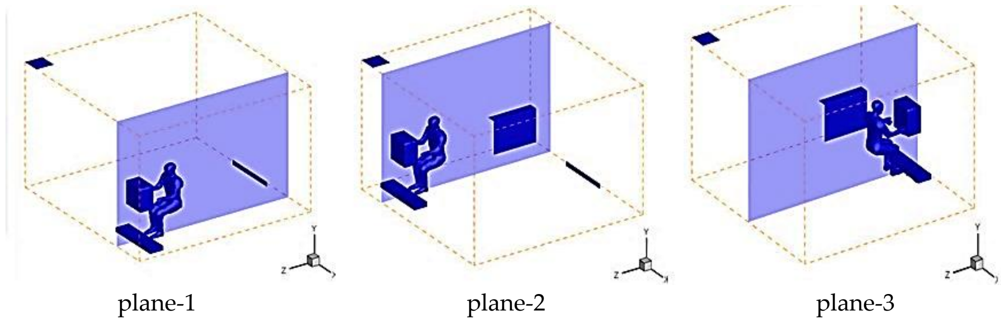

Figure 5. Occupants and cross-section plane locations.

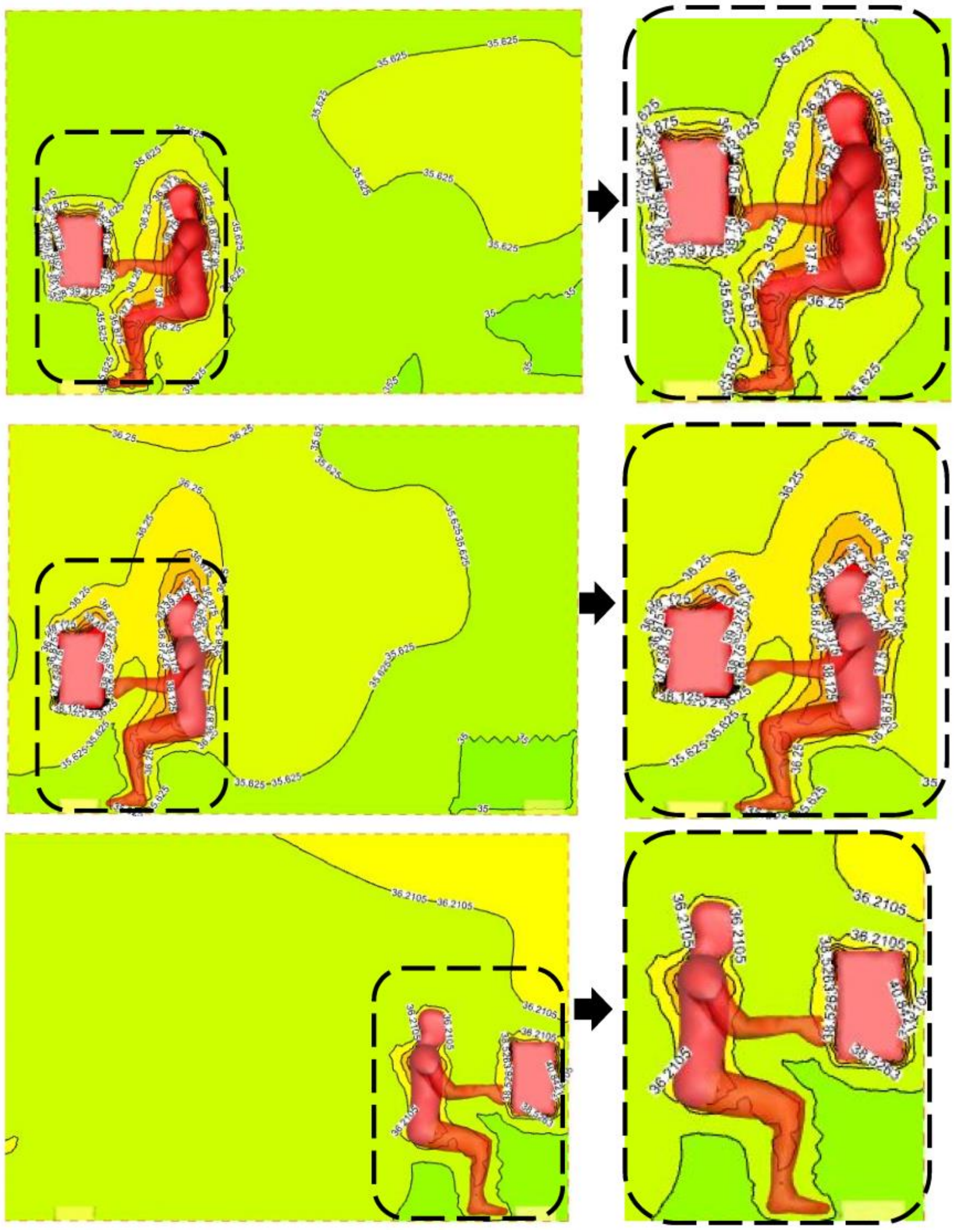

Figure 6. Air temperature distribution—case 1 (reference case) for each plane.

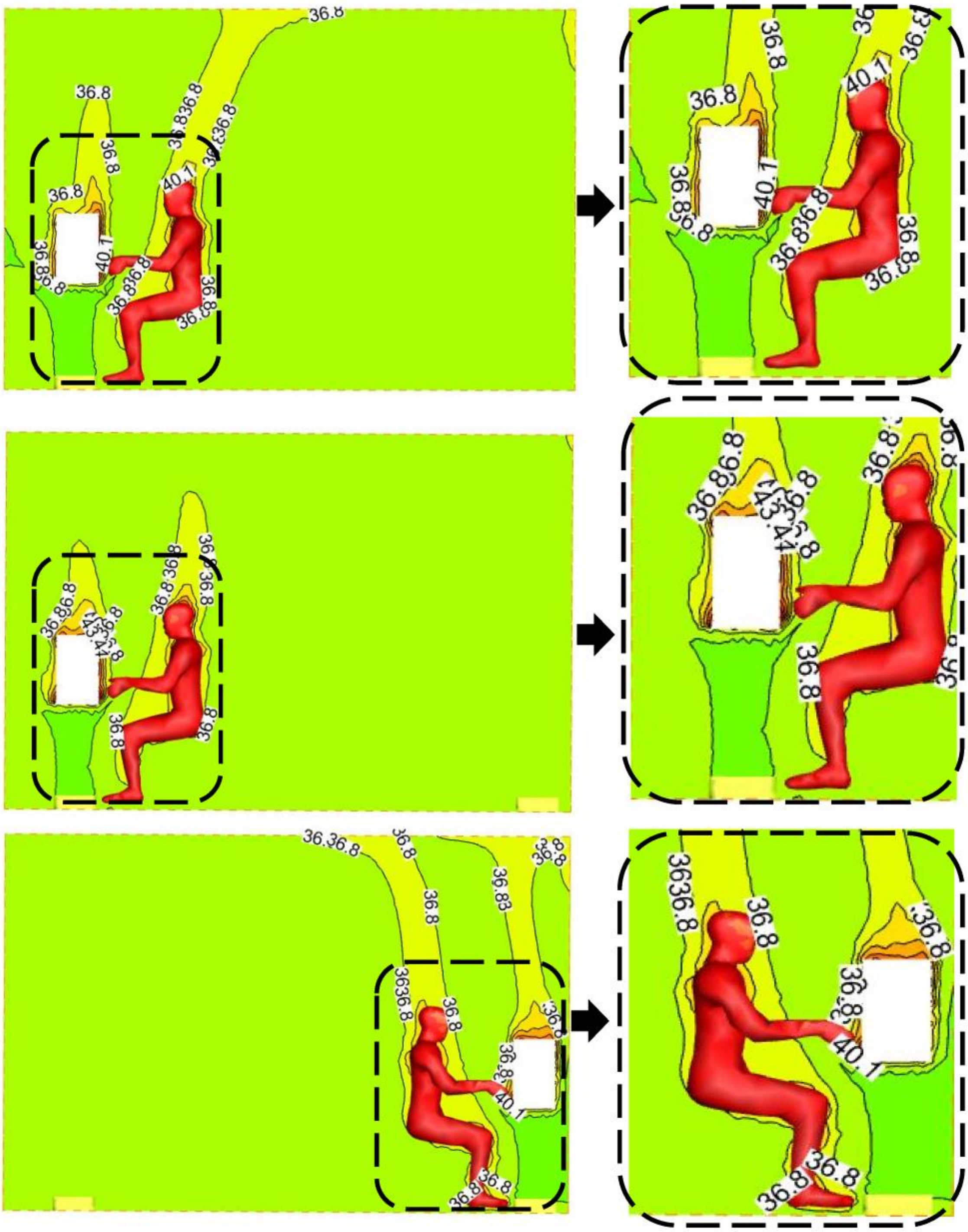

Figure 7. Distribution of air temperature—case 2.

In Figure 7, it is easy to see the air distribution for case 2. The local UFDA systems under seats were used as a proposed local heating system room. These systems supplied the room with airflow velocity and temperature of 0.4 m/s and 29 °C, respectively. Also, it was observed through this case that the temperature distribution and thermal comfort were stable compared with the reference case. To reduce energy consumption, considering the preservation of the internal environment of the space, the supplying air temperature was reduced to 28 °C with a constant air velocity of 0.4 m/s, as shown in Figure 8. A slight decrease in temperature with a homogeneous temperature distribution was found in some areas around the occupants without significantly affecting human thermal comfort. Therefore, in this case, the conditions are considered acceptable to a large extent in terms of preserving the internal environment and energy consumption compared to the rest of the cases. In case 4 shown in Figure 9, the supplying air temperature was lowered again to 27 °C with a constant air velocity. It is observed that the air temperatures around occupants remarkably decreased but without affecting thermal comfort. This is because the temperatures, in this case, fall within the acceptable range to provide indoor thermal comfort.

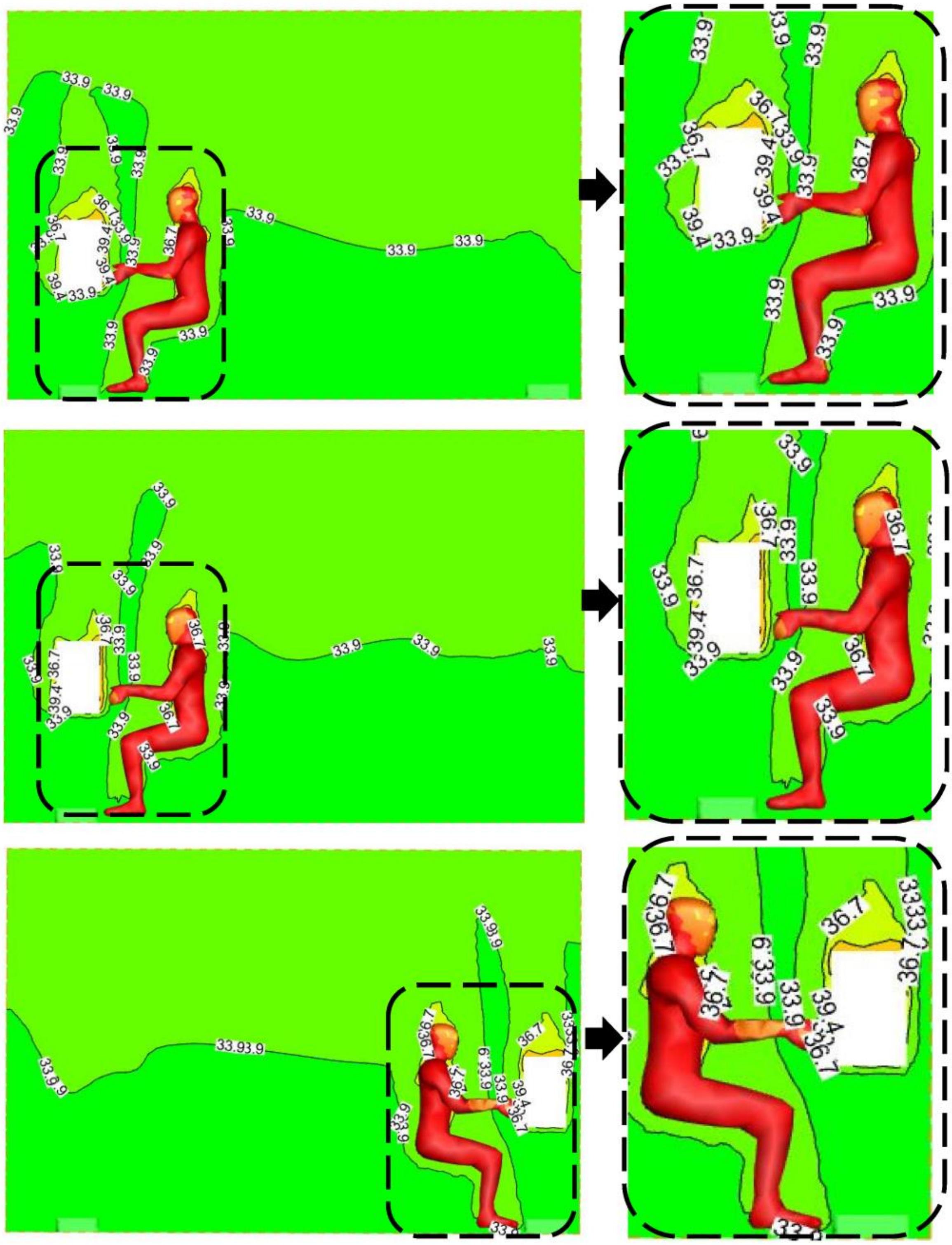

Figure 8. Distribution of air temperature—case 3.

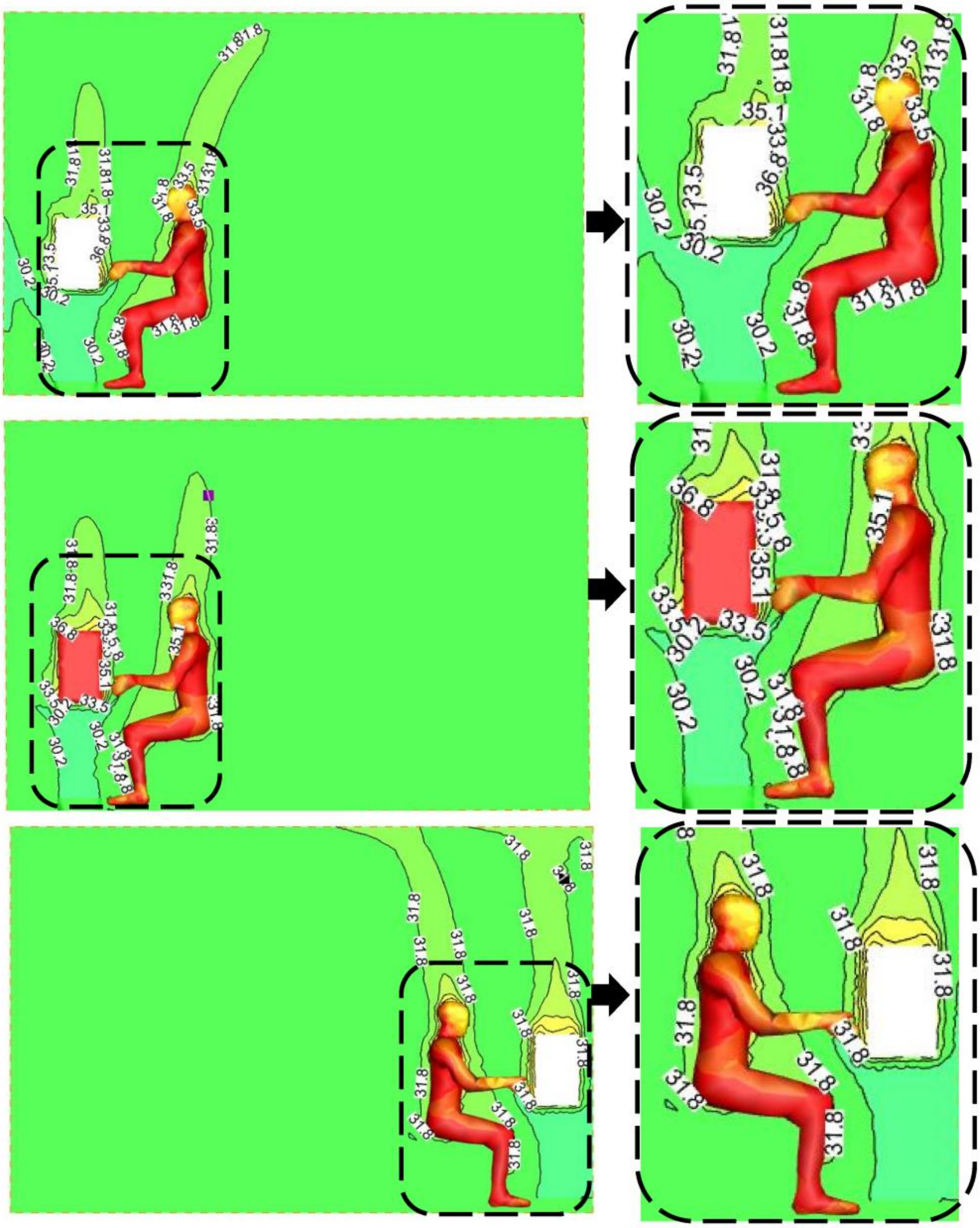

Figure 9. Distribution of air temperature—case 4.

4.3. Indoor Air Movement

Internal thermal comfort is an important factor to consider when designing buildings. One crucial aspect of this is the indoor air movement around occupants. In this regard, it is important to evaluate and compare the indoor air movement distribution in different cases to determine the suitable design conditions. This paper focuses on comparing the air movement distribution in cases 2, 3, and 4 with the reference case (case 1) to determine their suitability for internal human thermal comfort. Figures 10–13 show the comparison of the air movement distribution in cases 1, 2, 3, and 4. The figure shows there are similar results based on the indoor air distribution in cases 2, 3, and 4 with case 1. It is due to the use of 0.4 m/s of supplying air velocity as the same value for all investigated cases. Therefore, it is not easy to find a noticeable difference in the air movement distribution.

As a result, the internal thermal comfort has no significant change among these cases. In summary, internal thermal comfort is highly required to be considered for designing a building. Air movement in a zone has a significant effect on the internal thermal comfort around occupants. The air movement is also required to be evaluated and compared for different cases to find the optimum design. In this study, the air movement distribution of case 1 is compared with cases 2, 3 and 4, which have the same results because the supplying air velocity is 0.4 m/s for all cases. Therefore, it is essential to consider other factors that affect air movement, such as temperature and pressure differences, to enhance the internal thermal comfort in buildings.

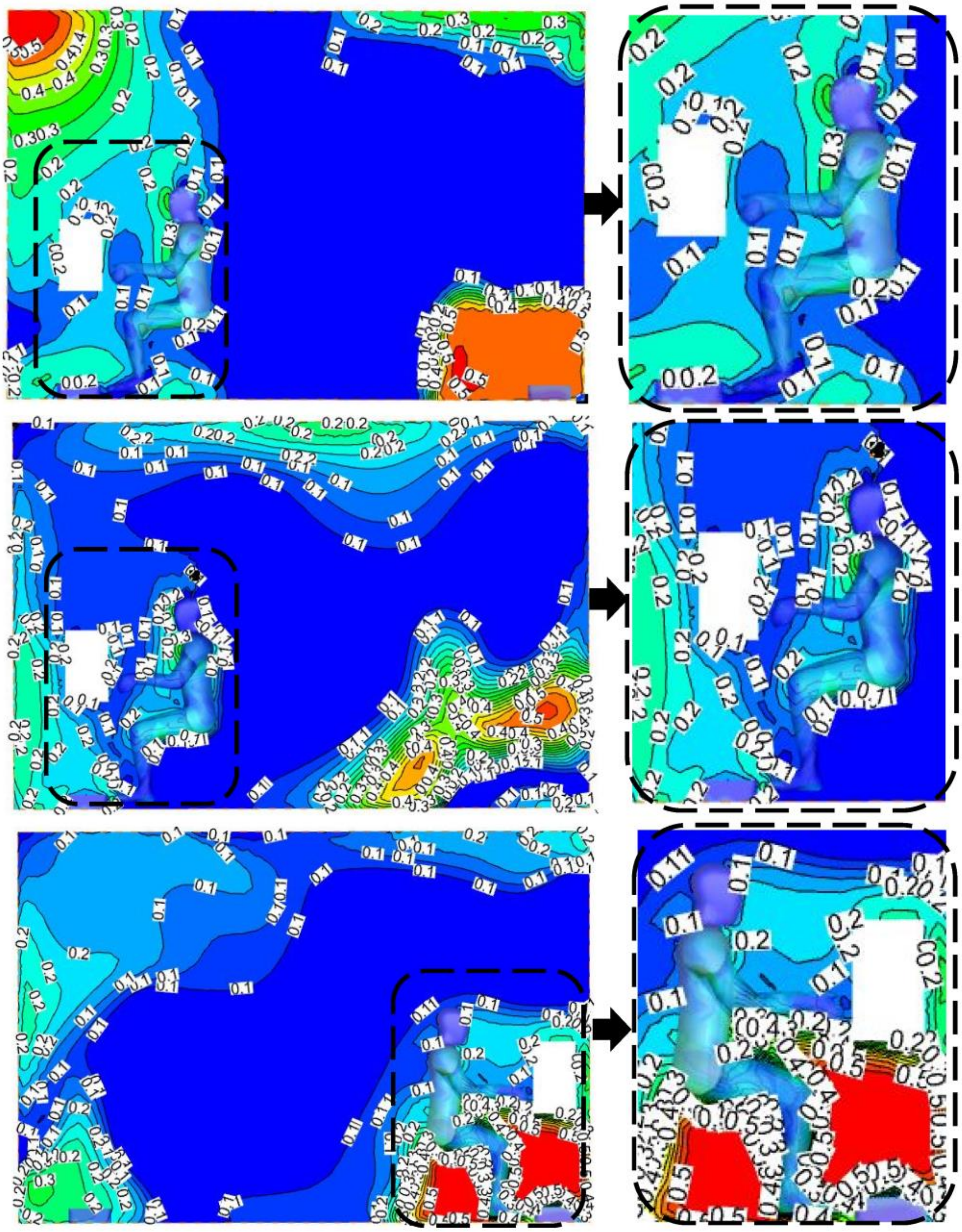

Figure 10. Velocity contour for case 1 (reference case).

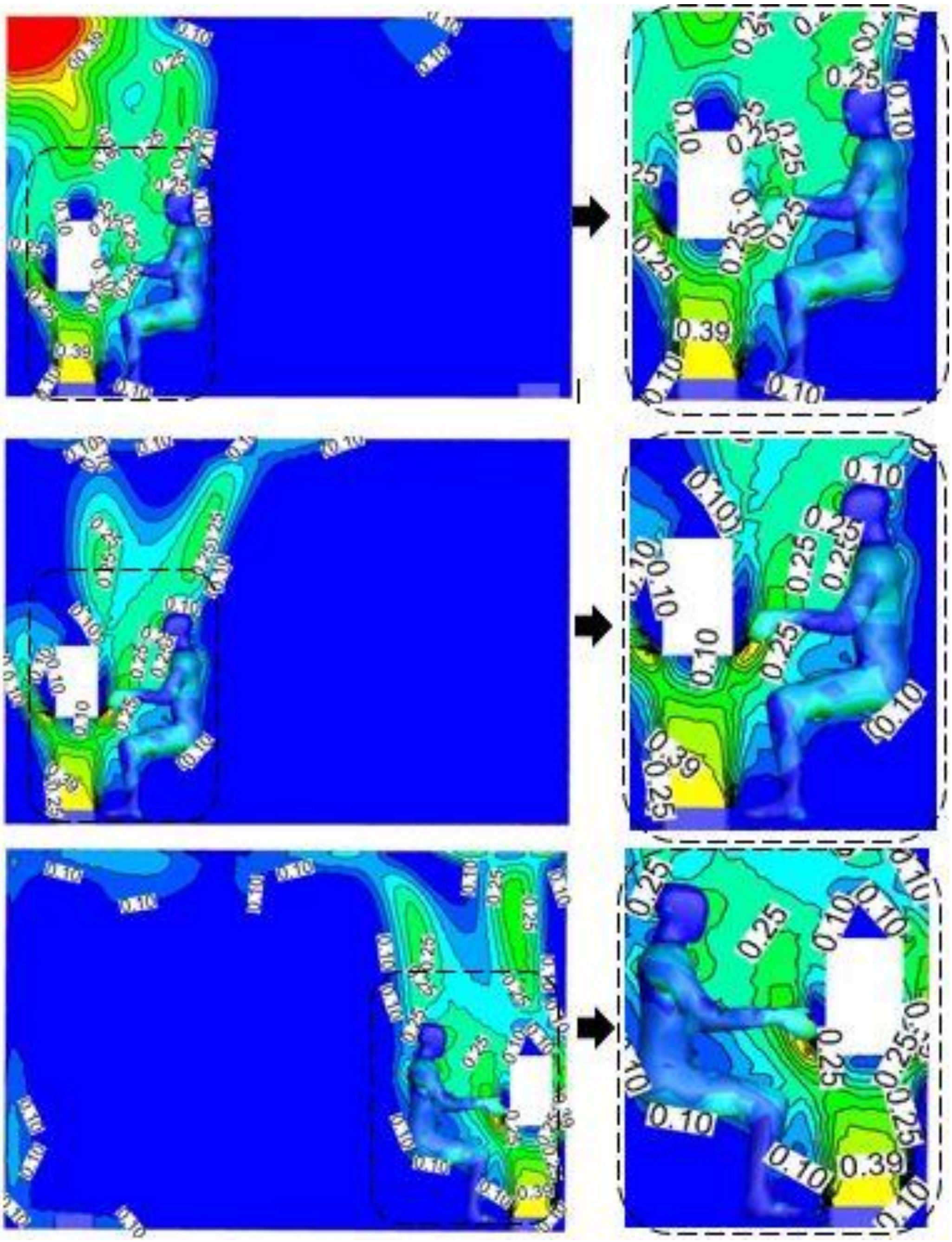

Figure 11. Velocity contour—case 2.

4.4. Thermal Comfort Evaluation

Heating systems are essential to any building, as they ensure thermal comfort and maintain a healthy indoor environment. The effectiveness of any heating system depends on its ability to distribute heat evenly throughout the building and maintain a comfortable temperature for its occupants. In this study, we evaluate the effectiveness of a proposed heating system for a building by assessing the temperature distribution in the vertical direction. In order to evaluate the effectiveness of the suggested heating system for a building, the temperature distribution profile in the vertical direction was used as the primary evaluation criterion. The ASHRAE standard mandates that the temperature difference between the occupant's head and feet should not exceed 3 °C to ensure thermal comfort. This evaluation criterion is important in expressing the thermal comfort of individuals under any HVAC system. Figure 14a–c present the computed temperature differences for each occupant in each case study for the proposed heating system. These figures show that in all scenarios, the temperature differences between the occupant's head and feet do not exceed 3 °C. The investigation assessed how uncomfortable individuals felt in all of the situations being studied. Figure 14d illustrates the locations of the four observation points with two located in each occupant's space. Point 1 measures the air temperature at foot level, 0.1 m from the floor, while point 2 measures the temperature at head level, 1.1 m from the floor. The difference between these points is used to evaluate indoor thermal comfort. Therefore, the results of our study indicate that the proposed heating system is effective in maintaining a comfortable indoor temperature for its occupants. The temperature distribution profile in the vertical direction is uniform, and the temperature difference between the occupant's head and feet is within the ASHRAE standard. Therefore, we can conclude that the proposed heating system is effective in ensuring thermal comfort in the building.

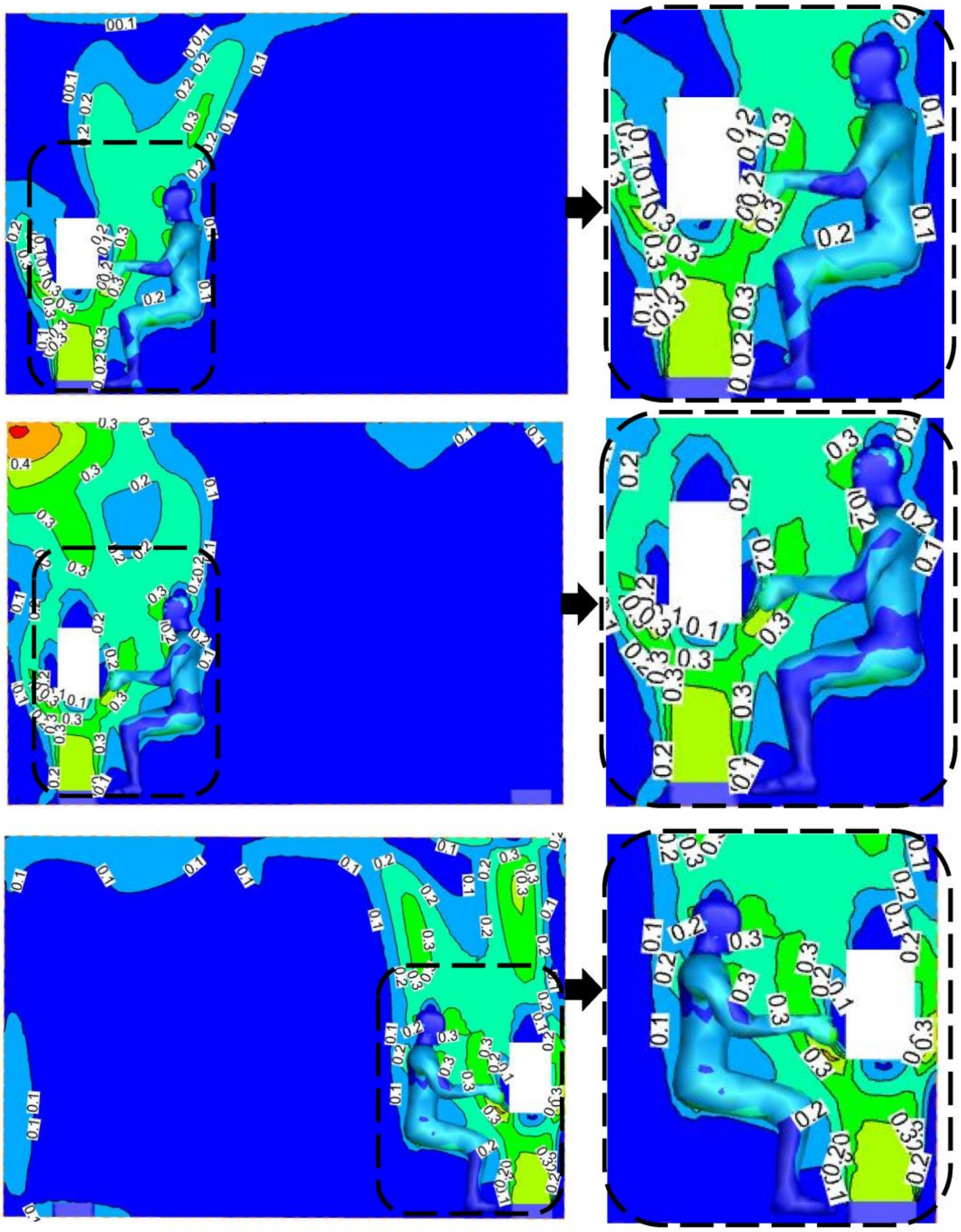

Figure 12. Velocity contour—case 3.

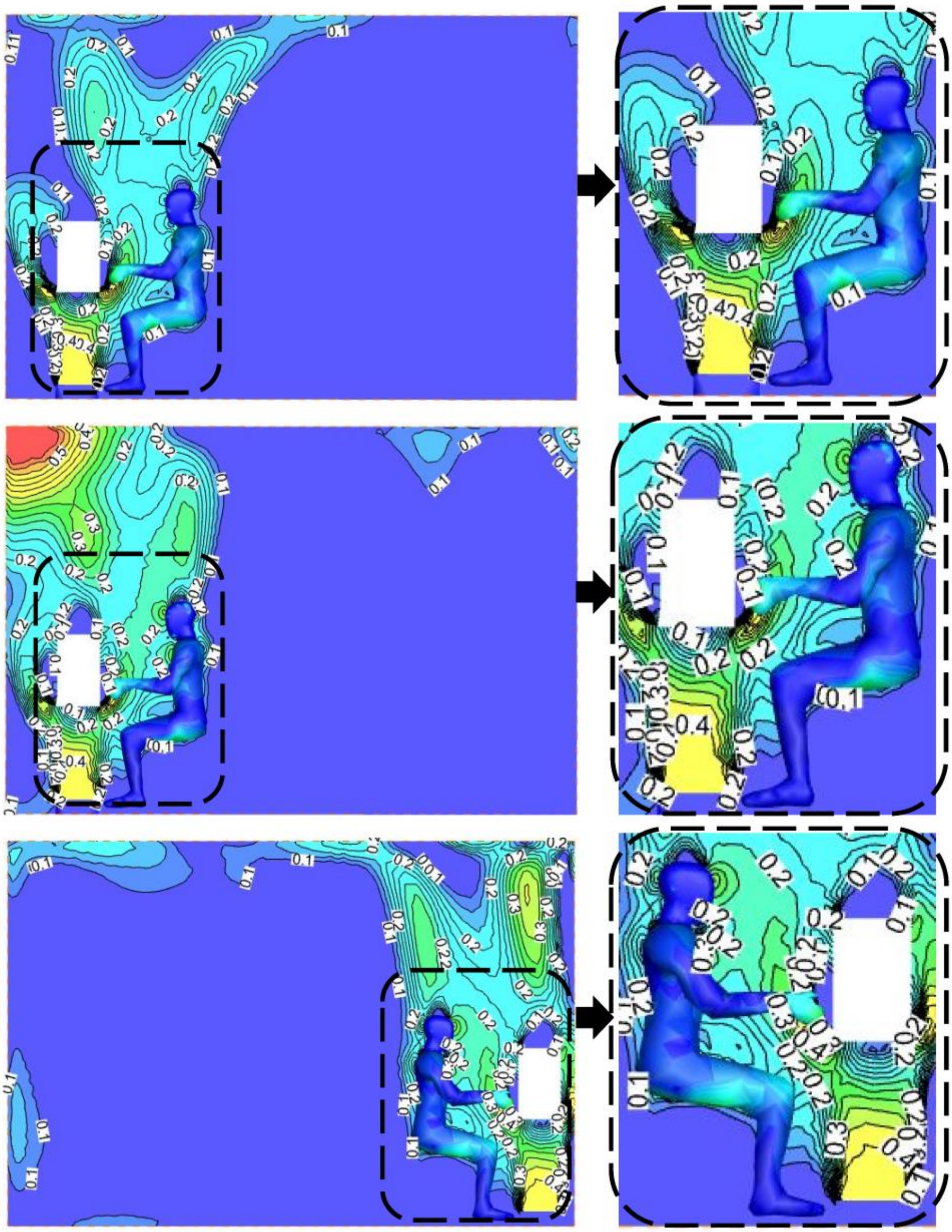

Figure 13. Velocity contour—case 4.

4.5. Energy Enhancement Evaluation

The energy efficiency is a crucial factor to consider when evaluating an HVAC system. The investigation focuses on reducing the supply air temperature while maintaining an excellent, comfortable indoor environment to improve energy efficiency. Additionally, a thermostat was used to control the heating mode and achieve the desired indoor temperature. When there is good air distribution in the room, the load on the heating coil decreases, resulting in improved energy consumption, as seen in cases 2, 3, and 4. The results show that the proposed heating system achieves a uniform indoor temperature distribution and meets the thermal comfort requirements in all case studies. Also, case 4 is identified as the most energy-efficient option, with the lowest energy consumption while still providing comfort. In conclusion, this study confirms that reducing the supply air temperature can lead to significant energy savings without compromising indoor comfort.

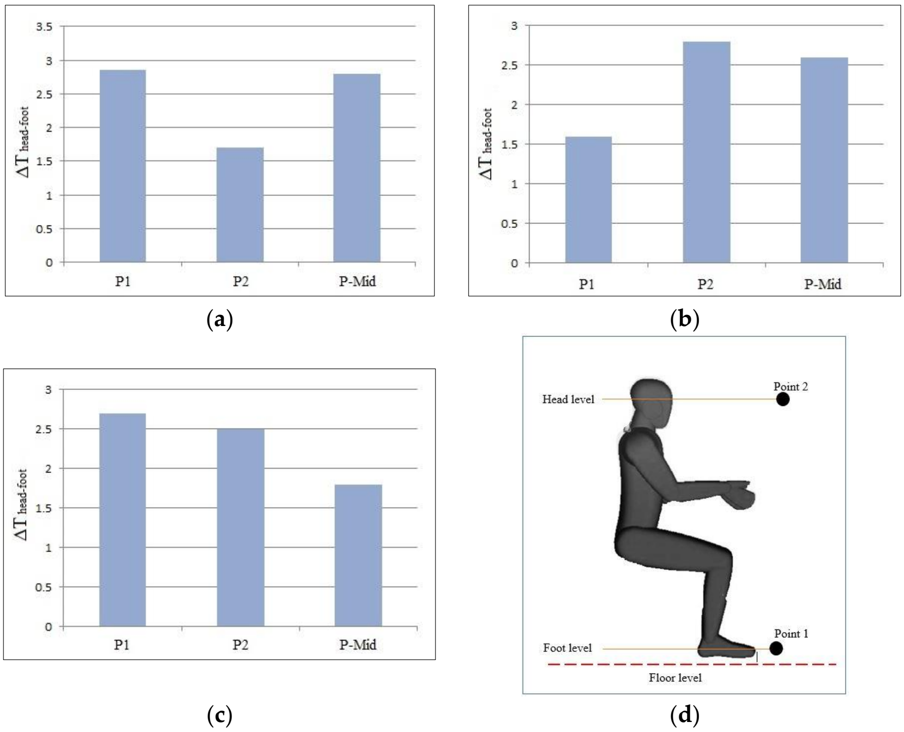

Figure 14. Temperature differences between the occupant head and foot level; (**a**) for case 2; (**b**) for case 3; (**c**) for case 4; (**d**) location of measurement point.

5. Conclusions

In this research, the impact of a local UFAD system on human thermal comfort and energy enhancement was studied numerically and compared with the reference case. From these tests, the following conclusions can be drawn:

1. Utilizing the proposed local underground air distribution system will improve the indoor thermal comfort of residents and minimize energy consumption. This has been demonstrated in various proposed scenarios, such as cases 2, 3, and 4, as opposed to the reference case, case 1, where efficient air distribution will create a comfortable environment for seated occupants at low consumption of energy.
2. The air temperature and air velocity for every case were within acceptable ranges to achieve comfort conditions for occupants.
3. In all cases, the supplied air temperature has been reduced from 29 °C in case 2 to 28 °C and 27 °C in case 3 and case 4, respectively, for saving energy with a constant of air velocity. Therefore, the proposed system will improve energy consumption at acceptable thermal comfort.

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