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Research Article

The effect on thermal efficiency of the height of a radiator above the floor

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ABSTRACT

In this study, a numerical investigation has been performed to examine the effect of the height of panel radiators above the floor. A radiator of the Panel-Convector-Convector-Panel (PCCP-type 22) was located in front of the wall where a window was placed in the 3D computational domain. Analyses were made using distances of 0.0, 1.0, 2.5, 5.0, 7.5 and 10.0 cm between radiator and floor. The results suggest that the thermal efficiency of the radiator is lowest at a level of 0 cm, which is the case when the radiator is placed on the floor. When the radiator level is insufficient, the air intake is not enough to obtain maximum heat transfer between the panels. If the radiator level is more than the optimum level, although the temperature decreases in the occupied zone, it is accumulated in the ceiling part of the room. This study also suggests that the air velocity in the collectors between the panels is a dominant parameter that affects the efficiency of the radiator.

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INTRODUCTION

In most parts of the world, and specifically in Turkey, the heating of living spaces is necessary to provide thermal comfort. Heating is needed in winter and autumn, and often in spring. In Turkey, most of the energy need is obtained from abroad. Turkey's natural gas import dependency ratio is around 99% [1]. This imported natural gas is mostly used for residential and workplace heating. This requires efficient use of energy. A huge gain in energy can be achieved in total with small improvements and precautions.

There is a preference in Turkey for panel radiators when heating living spaces due to their advantages, such as aesthetic appearance, high thermal power and easy installation, allowing for floor mounting and a high cost/life ratio [2]. Natural gas boilers are used to heat the water circulating in these radiators in the temperature range of 35–70°C. The panels are heated by the heat transfer between the panels and the hot water circulating in them. Convectors are used between the panels to increase the surface area and

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thus the amount of heat that can be transferred to the air. Heat transfer occurs between convectors and panels, which contact the panels. Space is heated due to the natural convection heat transfer between the panels/convectors and the air in the space.

Panel radiators heat the space due to natural convection (70-80%) and radiation (20-30%) heat transfers. In natural convection, a density gradient is formed between the high temperature radiator's surface and the low temperature ambient air with the effect of gravity. In order to provide efficient air circulation in the space to be heated, radiator position and placement must be designed to meet certain conditions [3]. It is recommended to install the radiator in front of a cold wall, where the window is mostly located [4]. In addition, the gap between the radiator and the wall and the height of the radiator above the floor (radiator level) should be at a certain distance to obtain the necessary efficiency. Panel radiator suppliers suggest advice certain height (ranging from 5 cm to 15 cm at least) for the radiator level. According to TS 2164/2 [5] and TS EN 442-2 [6], the nominal radiator levels are considered to be 10 and 11 cm, respectively.

Panel radiators have some disadvantages. Kibar [7] indicated that it was inappropriate to use panel radiators for the heating of spaces with high ceilings. It was stated in this study that the unused volume was at higher temperatures than the occupied zone (living area) throughout the heating process. Calisir et al. [8] studied the heat output of panel radiators which had different convector designs experimentally and numerically. They observed that convector sheet thickness and tip radius had a favorable effect on heat transfer. Kibar and Veziroglu [2] numerically and Üçler et al [3] experimentally studied the effect of obstacles/niches around the radiator on thermal efficiency. They indicated that the area around the radiator should have been open in order to achieve the highest efficiency in panel radiator heating systems [9]. Çelik et al [10] examined the heat transfer performance of the radiator numerically by adding propylene glycol to the water. They stated that although mixed water had a lower performance than pure water, it was more efficient in terms of thermal comfort.

Calisir and Baskaya [11] conducted a numerical study using convectors with different geometries (such as height, sheet thickness and tip width) to examine the heat transfer of panel radiators. They stated that the increase in convector thickness and height increased heat transfer, but this situation also increased the amount of sheet metal. Calisir et al [12] analyzed the heated air from the radiator numerically, using different convector dimensions. They specified that the flow conditions on the radiator did not change much with the change of convector dimensions and thus similar comfort conditions could be obtained. In some studies, it was emphasized that preventing heat loss from the wall behind the radiator was very important for the efficiency of the radiator [13,14]. However, no significant study has been conducted on the effect of the radiator level on the thermal efficiency. In the literature and applications, the minimum height of the radiator above the floor is emphasized. This seems appropriate to ensure sufficient air circulation inside the radiator. However, the efficiency of the radiator is not taken into account in terms of living space, as the height increases.

For the efficiency calculation, the efficiency of the 10 cm radiator height case is considered to be 100%, as TS 2164/2 pointed out [5], and the efficiency of the other cases is calculated using Equation (1) accordingly [2].

$$\%\eta = 100 \times \frac{T_{case} - T_{initial}}{T_{10cm} - T_{initial}} \tag{1}$$

where T_{case} and T_{10cm} are the average temperatures of the room volume for the calculated case and the 10 cm case at the end of the analysis, respectively. $T_{initial}$ is the temperature of the room at the beginning of the analysis.

The novelty of this study is to determine the effect of the radiator level on thermal efficiency, taking into account the occupied zone. For this purpose, the factors affecting efficiency are examined in detail using numerical results. Besides, the optimum height has been determined for both situations, including the whole volume and occupied space.

NUMERICAL MODELLING

In this study, Simcenter STAR-CCM+ software was used for numerical simulation. An incompressible Navier–Stokes equation was solved numerically to examine the gas flow in a 3D space. Mass (Equation 2), momentum (Equation 3) and energy conservation (Equation 4) equations are used to model the flow, respectively.

$$\frac{d(\rho)}{dt} + \nabla \cdot (\rho\vec{v}) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla .(\rho\vec{v}\,\vec{v}) = -\nabla p + \nabla . [\mu(\nabla\vec{v} + \nabla\vec{v}^{T})] + f_b \tag{3}$$

$$\frac{\partial}{\partial t}(\rho E) + \nabla . (\rho\vec{v}\mathrm{H}) + \nabla . (\vec{v}p) = \nabla(k_{eff}\nabla T) + \nabla(\bar{\tau}\vec{v}) + f_b\vec{v} + S_U \tag{4}$$

where μ, p, v, f_b, T, E, H, τ, S_U and k_{eff} are the dynamic viscosity, pressure, velocity vector, external body force (such as gravity), temperature, total energy, total enthalpy, viscous strain tensor, energy source and effective thermal conductivity, respectively.

The simulation was defined as time dependent (implicit unsteady) and laminar in a 3D domain. The Segregated Fluid Temperature model was used, which was solves the equation of total energy with temperature as the independent variable. In this model, enthalpy was then computed using temperature considering the equation of state where the density was calculated. Air was used as the fluid assumed to exhibit ideal gas behavior. The change of density was provided by the incompressible ideal gas equation depending on the temperature. Thus, the Boussinesq method shown in Equation (5) was used for buoyancy for the natural convection.

$$f_g = \rho g \beta (T_{ref} - T) \tag{5}$$

where β, g and ρ are the coefficient of thermal expansion, gravitational acceleration and fluid density, respectively. T_{ref} is the reference temperature. The governed equations were solved by using the SIMPLE algorithm and the second order upwind scheme. Only the convective heat transfer was considered. The radiation heat transfer was ignored in the present study.

In natural convection, the characteristic of the fluid flow was determined by the Rayleigh number (Ra), which was defined as the product of the Prandtl (Pr) and Grashof (Gr) numbers:

$$Ra = GrPr = \frac{\beta g L^3 (T_s - \mathrm{T}_{r,\infty})}{\upsilon^2} Pr \tag{6}$$

where g, L and υ are the acceleration of gravity, radiator height and the kinematic viscosity of air, respectively. T_s and $T_{r,\infty}$ are the surface and surrounding temperatures of the radiator, respectively.

In the case of natural convection, the transition of fluid flow occurs at Ra~10^9 from laminar to turbulent on the vertical wall [15]. The flow characteristic is defined as follows:

$10^4 < \mathrm{Ra} < 10^9$ laminar flow, $10^9 < \mathrm{Ra} < 10^{12}$ turbulent flow [15]. The laminar model was used to solve simulation since the Ra was 4.76×10^8 in the present study.

Boundary Conditions and Mesh Domain

The simulations were carried out in the 3D domain, which is 4.4 × 3.4 × 2.8 m (length × width × height) in dimensions, as shown in Figure 1a. The dimensions of the window are 1.85 m width and 1.4 m height. The lower edge of the window is 1 m above the floor. There is a gap (12 cm) between the wall and the window. The PCCP (type 22) panel radiator is located below the window. The distance is determined as 5 cm between the wall and the panel. Analyses were performed varying the distance of the radiator above the floor as 0.0, 1.0, 2.5, 5.0, 7.5 and 10.0 cm. Simulations were performed using 6 different domains in total. The dimensions of the panels and convectors are 1.0 m length × 0.6 m height and 1.0 m length × 0.45 m height, respectively (Figure 2). The total surface areas of panels and convectors are 3.1 and 6.6 m², respectively.

In order to make comparisons between the analyses, whole volume to be heated, occupied zone (living space) and middle plane were used, as shown in Figure 1b. The ASHRAE Handbook recommends 6 ft level above the floor

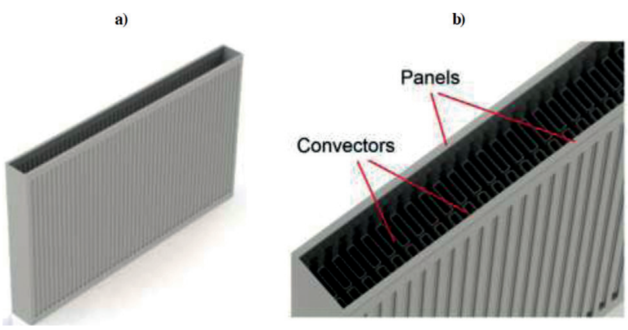

Figure 2. a) Panel radiator **b)** panels and convectors.

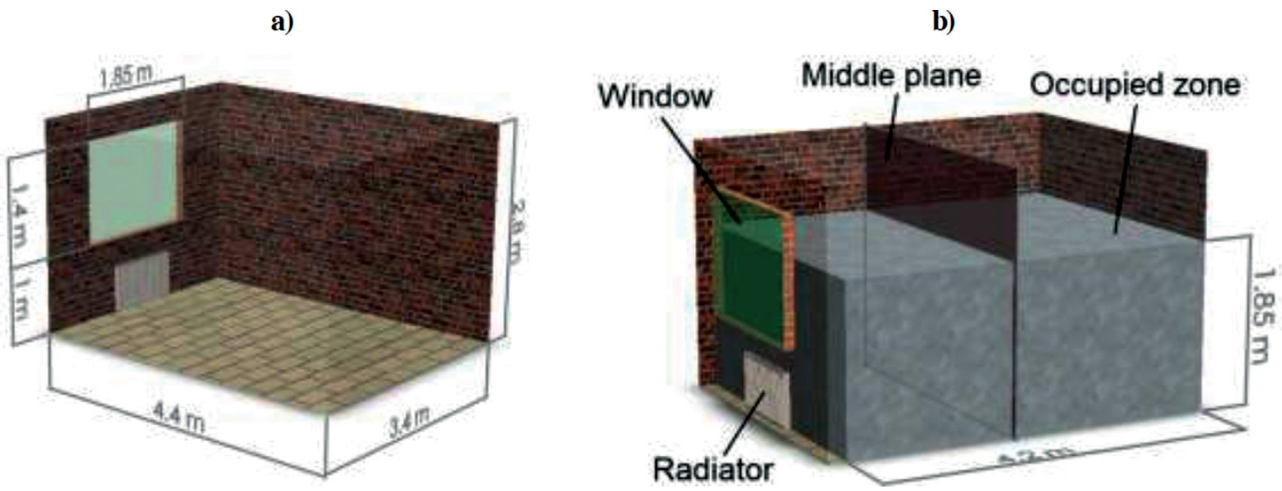

Figure 1. a) Geometrical domain **b)** positions and sizes of middle plane and occupied zone.

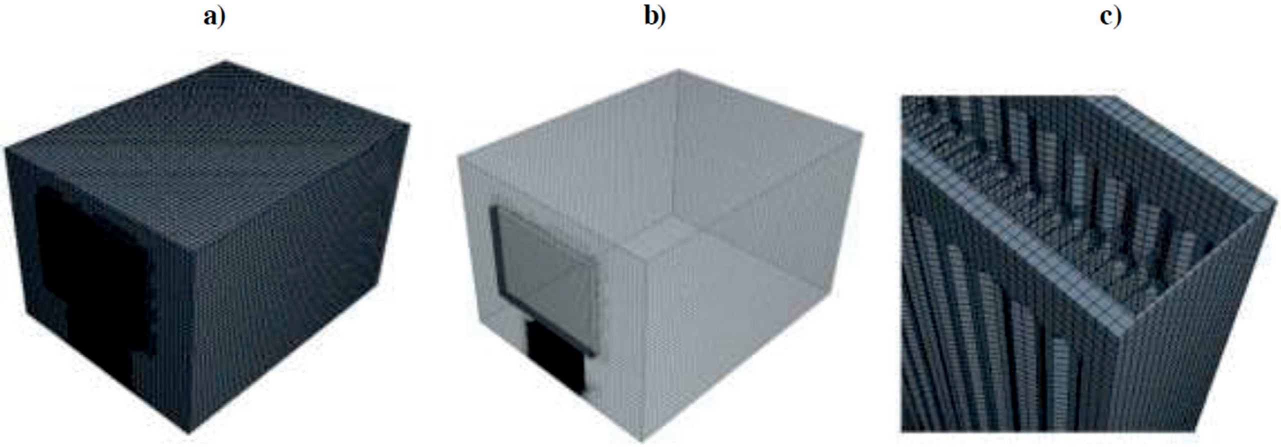

Figure 3. Mesh domain **a)** opaque **b)** transparent **c)** radiator.

for the occupied zone [16]. This value is taken as 1.85 m in this study. Therefore, a volume of 4.2 × 3.4 × 1.85 m (length × width × height) is used for the occupied zone. There is a 6 cm gap between this volume and the radiator (Figure 1b). The middle plane is located in the middle of the volume longitudinally.

All walls are considered adiabatic except for the outer wall, where the window is located, as the boundary conditions. The temperatures of the window, outer wall, convectors and radiator are determined as 5, 10, 33 and 45 °C constant, respectively for all simulations. These temperatures remain constant throughout the numerical solution. The definition of fixed window temperatures has often been used in similar studies [2,17,18]. The temperature of the room was determined as 10°C at the beginning of the analysis. Therefore, while the radiator at a higher temperature than the environment increases the temperature of the room, the window decreases since it is at a lower temperature. Since the outer wall is at the same temperature as the room at the beginning, it does not have any effect initially. In later periods, the outer wall starts to decrease the temperature of the room as the temperature of the room rises. There is no fluid inlet and outlet into the 3D domain. The implicit unsteady time step was chosen as 1 second. The simulation is completed at the end of 3.600 seconds.

Hexahedral cells are used for the mesh structure, as shown in Figure 3. Volumetric control is used to obtain fine mesh around the radiator and window (Figures 3a and 3c). The total volume consists of approximately 1.450.000 cells.

Experimental Study for Validation

The same size of the radiator was used to validate the numerical results. Experiments were performed at average temperature of the room as 22 °C. The radiator was kept at a constant temperature of 45±1 °C, by adjusting the boiler. Then, it was determined that the convector temperature remained at around 33 °C during the heating process. Thus,

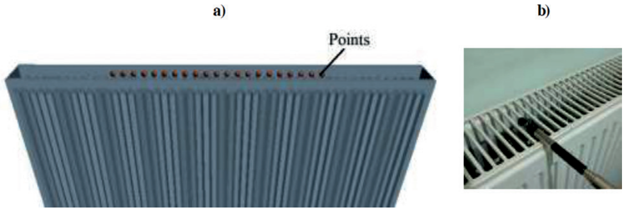

Figure 4. a) Velocity points in the middle just above the radiator, b) velocity measurement experiment for the validation of the analysis.

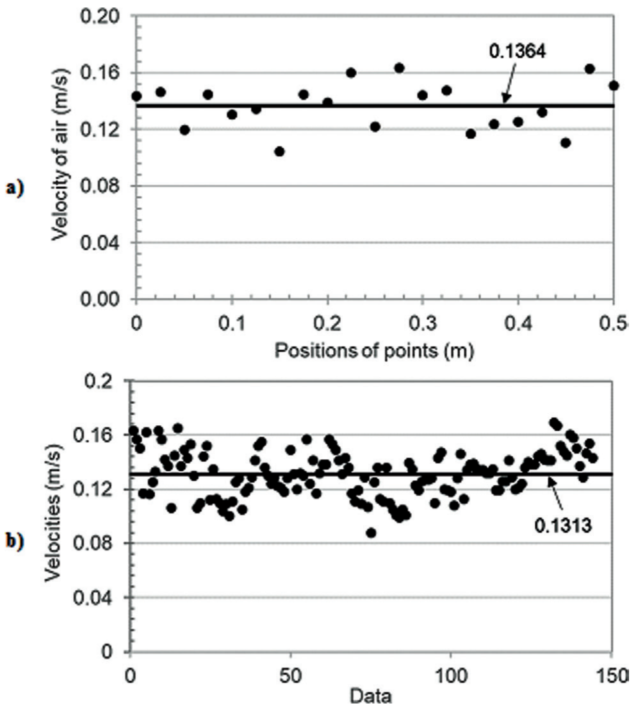

Figure 5. Horizontal line distance at the upper edge align of the radiator a) numerical b) experimental results.

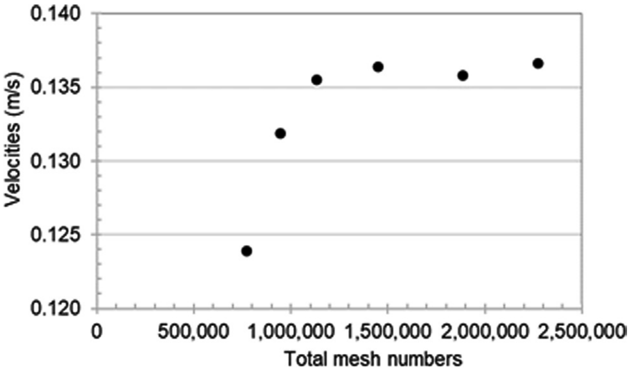

Figure 6. Velocities of the air dependent on the mesh size for mesh independence study.

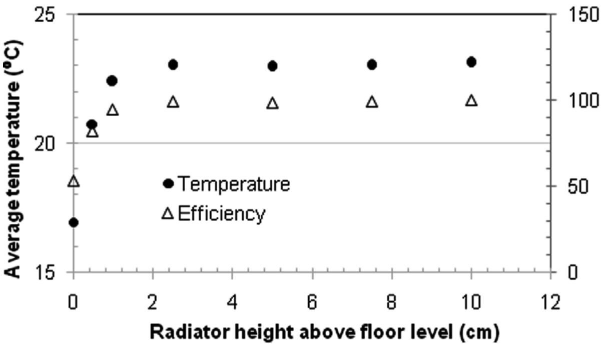

Figure 7. Average temperature of the space and efficiency of the radiator at the end of the 3600 seconds.

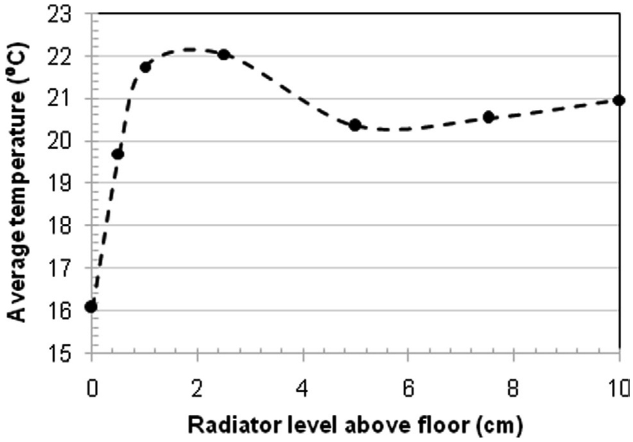

Figure 8. Average temperature of the living volume.

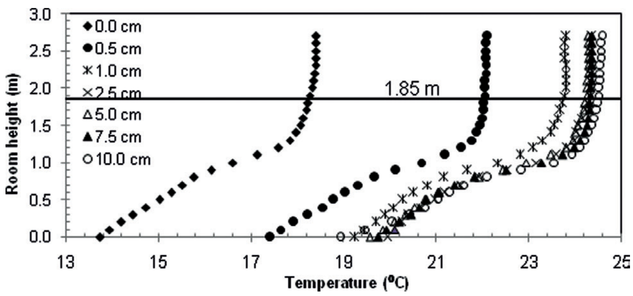

Figure 9. Average temperature of mid-plane.

this value was used for the convector temperature in the simulations.

In order to validate the experimental results, 21 separate points were determined at 2.5 cm intervals (50 cm length) at the upper level of the radiator, as shown in Figure 4a. Likewise, it was experimentally performed with the CEM DT-8880 (range: 0.1~25 m/s, resolution: 0.01 m/s, accuracy: ±5% ± 0.1)) anemometer, as seen in Figure 4b. The validation process was carried out based on the data obtained at 10 cm radiator level. The velocities obtained with numerical results at these points are shown in Figure 5a. The velocities range from 0.11 to 0.16 m/s bands and their average is 0.1364 m/s. In the experiments, data were taken with the anemometer every second and the experiment was conducted for about 150 seconds. Therefore, the average of these 150 data was obtained as 0.1313 m/s, as shown in Figure 5b.The average error between the experimental and numerical results is 3.7%. Experimental and numerical data were obtained at close to each other to validate the numerical studies. The air velocity above the radiator used for validation was also used for mesh independent study. Six mesh cases were used for this purpose, as shown in Figure 6. 1.450.000 cells were found suitable for the solution of the simulation.

RESULTS AND DISCUSSIONS

Figure 7 shows both the average temperature of the space to be heated and the efficiency of the radiator. The temperature of the space can be raised to 16.96 °C at 0 cm radiator level, which is the case where the radiator is placed on the floor. This temperature value increases as the distance between the radiator and the floor is increased. This increasing slop is very large until the radiator level becomes 2.5 cm. After this level, the temperature remains almost the same. When the level of the radiator is 10 cm, it reaches the highest value with a temperature of 23.13 °C. The radiator efficiency is 53.01% at 0 cm distance, which is the worst case, as seen in Figure 7. The efficiencies are 81.87% and 94.36% at radiator levels of 0.5 cm and 1 cm, respectively. The efficiency reaches to 99.08% after 2.5 cm level. Thus, this result suggests that although the maximum efficiency of a radiator can be obtained at 10 cm level, 2.5 cm level is sufficient to obtain reasonable efficiency. However, the efficiency of the radiator is significantly low at distances less than 2.5 cm.

Figure 8 shows the average temperature of the volume that is called the occupied zone (Figure 1b) in this study. As in the case of whole volume, the lowest temperature is also obtained in the case of 0 cm radiator

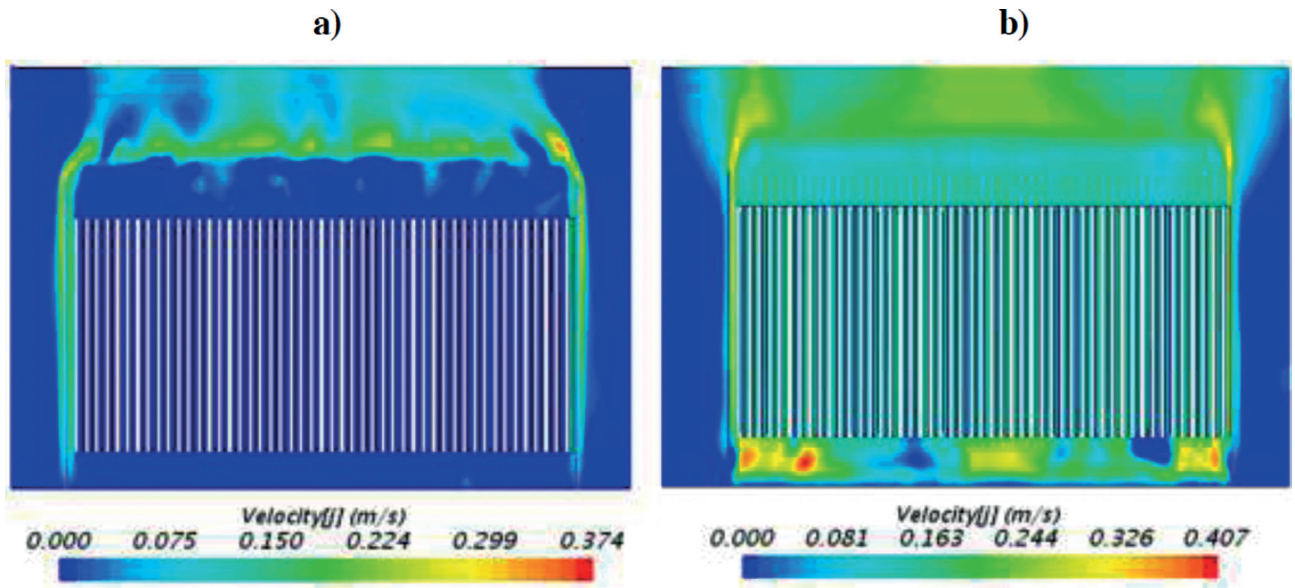

Figure 10. Velocity distribution at mid-plane of the panels, **a)** 0 cm **b)** 2.5 cm. Only the positive vertical velocity (in the opposite direction to gravity) is considered. Blue and red colors indicate zero and maximum speed, respectively.

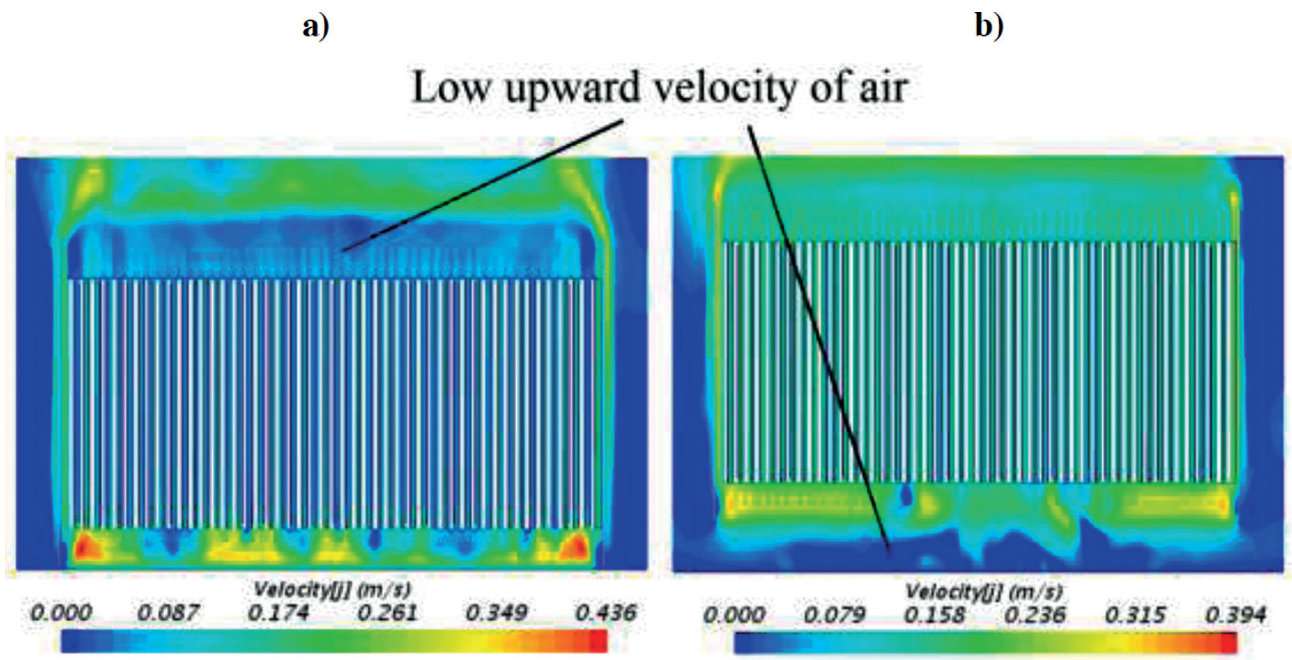

Figure 11. Velocity distribution at mid-plane of the panels, **a)** 0.5 cm **b)** 10 cm.

level that stands on the floor considering occupied zone. The temperature increases with the increasing height of the radiator level. This increase reaches the maximum at a distance of 2.5 cm level. After this level, the temperature starts to decrease with the level. The temperature, which reach the minimum at a radiator level of about 5 cm, starts to increase slightly with an increase in the radiator level. In the case of the occupied zone, a radiator level of 2.5 cm is the ideal height to obtain maximum efficiency.

When Figures 7 and 8 are considered together, when the radiator level is greater than 2.5 cm, the accumulation of high temperature air occurs mostly in the region above 1.85 m, which is the idle zone for heating.

Figure 9 shows the average temperature of mid-plane for different radiator levels. The temperature distribution varying with room height is approximately the same for all cases. The temperature, which is the lowest close to the floor, increases rapidly with the increase in room height. This increasing rate starts to decrease after 1.0–1.2 m room height. The temperature is approximately the same above the occupied zone (1.85 m) for all cases. Especially in the case of 10 cm radiator level, the temperature is low in the regions close to the floor. However, the temperature is considerably higher for a 10 cm radiator level than other cases at regions above the occupied zone. It is understood from the results that as the radiator level increases, the higher temperatures are concentrated above the occupied zone. However, the conditions of the occupied zone are primarily important for thermal comfort.

There is almost no upward air movement due to natural convection between the panels at 0 cm radiator level, as shown in Figure 10a. Here, in order for the air to rise, the discharged volume (rising air) should be replaced with the air below it. In this case, this situation cannot be achieved, since the radiator is adjacent to the floor. In order to have sufficient air circulation in the convectors, adequate air flow must be provided between the panels. The natural convection heat transfer occurs mostly between the outer surfaces of the panels and air in the room for this case. When air intake occurs under the radiator, the air between the panels can rise due to natural convection for the 2.5 cm radiator level case, as seen in Figure 10b. Therefore, the air in the room enters and fills the space left behind rising air under the panels. Calisir [12] stated that the effect of the convectors decreases as the height of the radiator increases, and thus changes in the convector structure and dimensions do not change the velocity of the air above a certain height. Therefore, the most important parameter affecting the velocity of the air above the radiator is the height of the radiator above the floor. The efficiency of the radiator decreases with the low air velocity between the panels.

Figure 11 shows the velocity distribution in the mid-plane of the panels with 0.5 and 10 cm radiator level.

When the distance between the radiator and the floor is not at a sufficient level (e.g., 0.5 cm), the air velocity is low between the panels, as shown in Figure 11a, since there is not enough air intake to the convectors between the panels. When the radiator level is a more than sufficient level (e.g., 10 cm), air enters between the panels from the lower edge of the radiator, as shown in Figure 11b. Thus, an upward air flow does not occur in areas close to the floor. In this case, the air velocity is high as the air flow entering between the panels is sufficient, as seen in Figure 11b. However, the higher the radiator level, the lower the floor temperature since there is no air entry between the panels from the areas close to the floor.

CONCLUSIONS

In this study, the heating of a living space by a panel radiator is examined numerically using the Simcenter STAR-CCM+ software. The placements of a panel radiator in the room are of great importance in terms of efficiency. One of them is the height of the radiator above the floor.

Considering the whole volume of the room, although 10 cm distance between the radiator and the floor can be used to obtain maximum efficiency from a radiator, 2.5 cm distance is sufficient to achieve an acceptable efficiency. When the occupied zone of the room is taken into account, while the temperature of the room increases with the level of the radiator, it reaches a maximum value at a certain distance (2.5 cm in this study) and then decreases. The room temperature, which decreases again after peak, reaches a minimum value at a certain distance (5 cm in this study's conditions) and then increases as the radiator level increases.

This study suggested that in order to get maximum efficiency from the radiator, there should be a sufficient distance between the radiator and the floor whereby enough air can enter between the panels. However, the occupied zone temperature decreases and the heated hot air is intensified at an unused zone, as the radiator level increases. Therefore, a certain range should be recommended for the radiator level instead of the minimum value. Air velocity in the convectors between the panels is an important parameter affecting the efficiency of the radiator.

As suggestions for further research the work can be repeated at different radiator temperatures and by changing the distance between the radiator and the wall.

NOMENCLATURE

E	Total energy, J
f_b	External body force, N
g	Gravitational acceleration, m/s^2
H	Total enthalpy, J
k_{eff}	Effective thermal conductivity, W/m.K
L	Radiator height, m
p	Pressure, Pa
S_U	Energy source, J
T_{10cm}	Temperature at the 10 cm case, °C
T_{case}	Case temperature, °C
$T_{initial}$	Initial temperature, °C
T_{ref}	Reference temperature, °C
$T_{r,\infty}$	Surrounding temperatures of radiator, °C
T_s	Surface temperatures of radiator, °C
T	Temperature, °C
v	Velocity, m/s

Greek symbols

τ	Viscous strain tensor, Pa
μ	Dynamic viscosity, Pa.s

β	Coefficient of thermal expansion, 1/K
ρ	Fluid density, kg/m^3
υ	Kinematic viscosity, m^2/s

Abbreviations

3D	Three-dimensional
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
Gr	Grashof number
PCCP	Panel-Convector-Convector-Panel
Pr	Prandtl number
Ra	Rayleigh number
TS	Turkish Standards

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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