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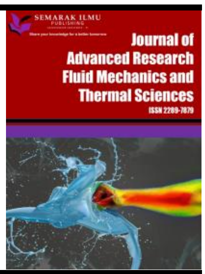

Analytical and Numerical Approaches to Optimize the Air Vents Location of Office Space at Different Surrounding Conditions

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ABSTRACT

Optimization becomes an essential tool in all aspects of life. Air entrances and exits locations in any building are one of them that need to be optimized to reduce the energy consumption. Hence, a numerical and analytical investigations of two Models were performed to a teaching assistantship (TA's) office. The original office design (Model 1) has all the hot and cold air inlets beside the air outlet in the mid-position of the room ceiling. The suggested model of the office (Model 2) is designed by putting the cold air inlet in the middle of the ceiling, whereas the hot air inlet in the middle of the floor close to the widow of the office. The air outlet was kept in the middle of the room ceiling. These models analysed as a function of the ambient temperatures in the 21st of four months (December, March, June, and September) within the periods 9:00, 12:00, and 16:00 h. For more validation, the comparison between the analytical and numerical results of Model 2 is validated with a maximum variation of about 7%. In addition, the analytical room temperature results of Model 1 are higher than Model 2 by 10.3%. Finally, the best average comfortable temperature for humans had been discovered in Model 2 for all cases around 23 ˚C with a maximum error percentage of less than 10%.

1. Introduction

The concern about climate change has been rising around the world due to the consequent effects of energy consumption. Building conditioning consumption represents more than 40% of the total demand energy around the world [1]. Enhancing the thermal performance of the buildings becomes an important option to reduce the consumption of this type of energy [2,3]. Energy analysis is the first step to start with, so many researchers begin to apply the study and analyze rooms and buildings that lead to achieve the best performance [4]. Choosing suitable locations of Air ports is one of improving option Hence, many researchers have investigated to find efficient strategies for modulation and styling to predict energy consumption under different comfortable conditions.

One of them was Harish [1] which conducted a simulation of an office environment to improve the thermal comfort conditions at the initial room temperature was 30 ˚C. The simulation was applied

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numerically by using SimScale software on the 200,000 m^3 room. In addition, the numerical simulation is achieved to improve thermal comfort in a room with a roof height of 2.5 m with a thousand windows and 400 persons. Many cases were discussed that lead to the best room comfort cooling conditions. Then, Rabani *et al.,* [2] Submitted a comprehensive framework study for energy optimization of the building process. Their study depended on the CFD daylight simulations on the retrofitting of the building. Many scenarios are presented and the results showed a total energy demand reduction of 77% and 79% for the first two scenarios with improving the thermal comfort requirements of the humans.

After that, the framework design of moderate school based on performance optimization by Wang *et al.,* [5]. The optimization of the building's performance is achieved by using a genetic algorithm that depends on different parameters such as energy consumption, thermal comfort, and daylighting. The analytical results of the five groups of the design parameters offered a good agreement compared to the simulated results. Moreover, Li *et al.,* [6] found the consumption of buildings' energy consumption reaches 15% of the world's total energy. The review aims to summarize the effect of some factors such as heating, cooling, and modern windows on zero-energy buildings and comfort conditions. Handicaps and technical challenges related to future estimations in this field are also discussed.

Tunçbilek *et al.,* [7] conducted a study to enhance the performance and comfort conditions by using an external room wall that contains PCM material under cooling conditions. Then, the simulations were performed for each month of the summer season to know the impact of adding the PCM material into the wall on the comfort conditions and air-conditioner operation. The best operation temperature was 25 ˚C, while a wall temperature larger than 26 ˚C presented negatively influenced the energy saving. The results of the energy-keeping offered an enhancement of 12.8% for the wall with PCM material compared to the wall without PCM. Keskin and Mengüç [8] presented an innovative system of ventilation that can provide suitable thermal conditions in buildings. Experimental and numerical analyses were applied to an office in an academic building to show that it is possible to get different degrees of temperature at different locations of the office. The results showed that controlling the office temperature distribution can reduce the total energy demand. Finally, the new system with action citizens and their behavior led to positive change in energy efficiency by simplifying a new practice of resident's interaction with the heating, ventilation, and air conditioning system.

The automation system's effect on the thermal performance of buildings using a dynamic evaluation method was investigated by Sozer and Tusyuz [9]. Therefore, to enhance the building performance by using dynamic set points for equipping convenient conditions in the building and get more exact results in heating and cooling cases. The results achieved the maximum reduction in energy consumption was 82.71 kWh/m^2 and 20.26 kWh/m^2 in heating and cooling seasons respectively. Whereas 4.46% and 9.39% % were the depression of the dynamic set point in the heating and cooling cases respectively. Bünning *et al.,* [10] innovated a new low-temperature network method to achieve more efficient of thermal building performance for heating and cooling states in San Francisco and Cologne. The results of building performance are validated by using dynamic modelling and Modelica simulation compared to other heating and cooling technologies. The emissions result illustrated a reduction of 26% and 63% in the San Francisco and Cologne scenarios respectively by using low-temperature networks compared to the other technologies. In addition, the results showed larger costs of energy savings and lower energy consumption 46% and 52%, respectively in San Francisco.

Zhang *et al.,* [11] studied a new design for controlling the heating, ventilation, and air conditioning (HVAC) systems in energy-efficient buildings. The thermodynamic model of building systems is formulated in a steady state to reduce the variation between spot temperatures and their setpoints. Finally, the thermal dynamics can be reached to thermal equilibrium that represents optimal solutions to the problems associated with steady-state optimization problems in building ventilation. Nazi *et al.,* [12] conducted a numerical and experimental study on the comprehensive renovation of buildings that is based on the thermal analysis of the buildings in Malaysia. The results demonstrated reducing the cooling load by 40.2% led to a decrease in the overall energy consumption of 47% in buildings. The validation of the energy results in the building was achieved by comparison between the experimental and simulated results that offered less variation by 4.3%. Moreover, Mahmud *et al.,* [13] tried to reduce cooling and lighting consumption by applying smart devices in a building. A comparison of this methods results and insensitive to occupancy results were made. 12.7% – 36.15% of cooling loads can be reduced by applying his proposed method, whereas, the lighting loads can be lowed 35% – 87.5%.

Also in 2022, A classroom conditions and thermal comfort has been investigated by Hussin *et al.,* [14] applying the IES VE software. 4 cases were studied by recording the temperature and humidity. It has been showed that the 2nd case has the best performance that consumed 1,819 kWh/month. By comparing the average value for each case study, the classroom can be classified as a very inefficient building in terms of energy consumption because of the high number of occupations which leads to increase the energy to achieve the thermal comfort. At the end, many suggestions by replacing the classroom components were provided to improve the thermal performance of it.

At the same year, Fohimi *et al.,* [15] investigated a laboratory of the Faculty of Mechanical Engineering (FME), University Technology MARA (UiTM) Pulau Pinang. An evaluation of indoor air temperature in selected laboratories was presented. The required data was record for the Lab and compared to the limits stated in the Malaysia Standard regarding thermal comfort. The study concluded that the thermal comfort of the lab was not satisfaction and some enhancements should be done. A year later Ha *et al.,* [16] also worked in this field. Their study analyzed the green building development in Malaysia at that time. The results showed that, the number of green buildings in Malaysia is comparatively low. Moreover, benchmark for policy makers and construction key stakeholders about the status of green building development in Malaysia which can be utilized as a guideline in promoting green building development has been provided.

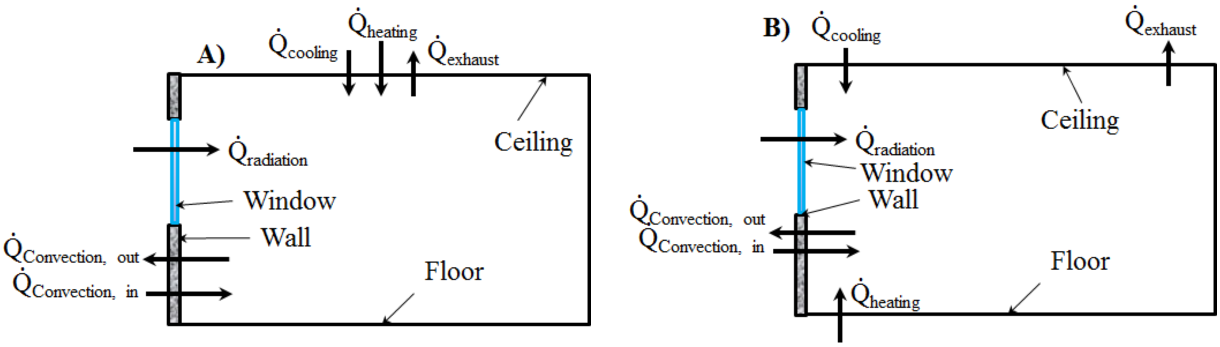
Based on the previous discussion, an amelioration of Air entry and exit locations need to be considered by designers' calculations. This significance would reduce the energy consumption. This reduction is the target of this study, by assuming a new Air entry and exit gate locations (Model 2) of the testing room in order to achieve an enhancement that leads to better comfortable temperatures of the humans and comparing its results with the original design (Model 1). A real exist room was chosen to be the model of this study.

2. Analytical Approach

The dimensions of the office that has been chosen to be sample of this work are 2.8×4.1×2.5 m and the window are located 1m above the ground with dimensions of 1.2×2.8 m (Figure 1). Only the facade is assumed to have heat transfer with the ambient. Heat transfer at the floor, ceiling and interior walls is neglected because the temperature will be the same inside the building and there will be minimal heat transfer from these surfaces to other spaces inside the building. The wall of the facade has two layers which are brick and insulation and the window is a double-glazed window with Argon gas in between the glasses to drop the heat loss through convection. The room contains two laptop computers with power output of 100 W each and two TA's each have power output of 100 W. The office is being used between 8:30-17:00, so our analysis will be according to these hours. The heating inlet is located on the ground right behind the window to minimize the heat losses from the window during the wintry weather, the reason to locate it on the ground is the fact that warm air will rise to be top, and it will be more efficient to heat up the office. The cooling inlet is in the ceiling right behind the window to prevent the heat coming from the façade in the summertime. The heater and Cooler supplied the fresh air to the room at 25 °C and 18 °C respectively. Finally, there is an exhaust outlet located in the middle of the ceiling to let the air circulate. In addition, the inlet mass flow rate was assumed equal to the outlet mass transfer to prevent the pressure change inside the office.

Fig. 1. The TA's office at the Ozyegin University

For the analytical approach, the office is assumed to have heat transfer from the façade, inlets and the outlet. The application of energy conservation on the two designs Model 1 and Model 2 of TA's office is shown in Figure 2(a) and Figure 2(b).



(a) (b)

Fig. 2. Cross-sectional schematic of the TA's office (a) Model 1, (b) Model 2

The left side represents the façade with the wall and the window. The direction of convection through the façade is dependent on the ambient temperature and the room temperature for the two models. The resistance network of the meeting office is shown in Figure 3.

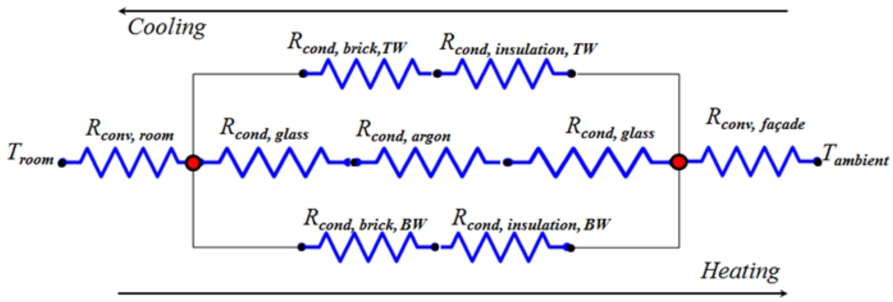


Fig. 3. Resistance network for the convection through the façade

2.1 Calculation of Solar Irradiance

The solar irradiance is calculated using the coordinates and the direction of the office, which are 41°01'48.7"N29°15'33.2"E and the window faces in the East direction. The air mass value of the case time is used to calculate the solar irradiance on the location and the irradiance equation is shown below. The air mass (Am) value is defined by the temperature and the vapor content of air [17-20].

$$I_D = 1353 \times 0.7^{AM^{0.678}} \quad (1)$$

After calculating the irradiance on the location, the values were re-adjusted according to the viewing angle of the window facing the East direction using the Azimuth angle and the following equation.

$$F_{1\to 2} = 1 - \sin\frac{\varphi}{2} \quad (2)$$

The azimuth angle is the angle from the north direction; therefore, angles larger than 180° will not have any effect on the office because the sunlight will not directly hit the window. This is the reason some irradiance values are not available in Table 1 below. Ambient temperature values are average values for the specified times.

Table 1
The values of air mass, azimuth angle, ambient temperature and solar irradiance [21,22]

Case	Date	Time	Inlet condition	Air mass flowrate, $\dot{m}$	Azimuth angle, ϕ	Ambient temperature, T_{amb}	Solar irradiance, I_D
1	21st December	9:00	Heating	4.11 kg/s	139.2 ˚	3°C	311.8 W/m^2
2	21st December	12:00	Heating	2.31 kg/s	1.81.2 ˚	13°C	-
3	21st December	16:00	Heating	11.52 kg/s	233.7 ˚	8°C	-
4	21st March	9:00	Heating	1.89 kg/s	122.0 ˚	5°C	564.3 W/m^2
5	21st March	12:00	Heating	1.32 kg/s	178.4 ˚	15°C	266.2 W/m^2
6	21st March	16:00	Heating	2.52 kg/s	248.9 ˚	10°C	-
7	21st June	9:00	Heating	1.33 kg/s	101.2 ˚	17°C	707.6 W/m^2
8	21st June	12:00	Cooling	1.05 kg/s	180.8 ˚	30°C	-
9	21st June	16:00	Cooling	1.65 kg/s	270.1 ˚	22°C	-
10	21st September	9:00	Heating	1.77 kg/s	125.2 ˚	14°C	577.7 W/m^2
11	21st September	12:00	Cooling	1.32 kg/s	183.8 ˚	26°C	-
12	21st September	16:00	Cooling	2.81 kg/s	251.5 ˚	20°C	-

2.2 The Mathematical Model for the Analytical Calculations

The system is described in Figure 2 using the conservation of energy to find energy rate, (Watt) as below [23].

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = \Delta\dot{E}_{system} \tag{3}$$

For the energy calculations of cooling and heating inlets and exhaust outlet the following equation was used [23].

$$\dot{Q} = \dot{m}\ Cp\ \Delta T \tag{4}$$

The radiation energy calculations were done by multiplying the irradiance value by the area of the window because the irradiance values were calculated as they were entering the window with a 90° angle. For the convection through the façade resistance network was formed as shown in Figure 3. The following equations were used for the energy calculations through the façade [23].

$$R_{cond} = \frac{L}{K\ A} \tag{5}$$

$$R_{conv} = \frac{1}{h\ A} \tag{6}$$

$$Q = \frac{\Delta T}{R_{total}} = \frac{T_2 - T_1}{R_{total}} \tag{7}$$

The heat transfer from the room to the façade and the ambient air and between the double-glazing windows through the argon is transferred by natural convection. The convection coefficients were calculated using Rayleigh and Nusselt numbers in the following equations [23,24].

$$Ra = \frac{g\ \beta\ (T_s - T_\infty) L_c^3}{\alpha\ v} \tag{8}$$

$$Nu = \frac{h\ L_c}{K}\ 0.59\ Ra^{1/4} \quad 10^4 < Ra < 10^9 \tag{9}$$

$$Nu = \frac{h\ L_c}{K}\ 0.1\ Ra^{1/3} \quad 10^{10} < Ra < 10^{11} \tag{10}$$

where Kinematic viscosity, v (m^2/s), Thermal diffusivity, α (m^2/s), Thermal expansion coefficient, β (1/K), heat transfer coefficient, h(W/m^2.K) and characteristic length, L_c (m).

There are 12 cases for this study so, all the variables for each case as a function of the boundary conditions (see Table 1, Figure 2 and Figure 3). Next, the analytical calculations are determined for each model 1 and 2 by using Energy Equation Solver (EES) software for the cooling and heating state. For more accuracy, the error percentage of the room temperature between the analytical and numerical results is calculated for all cases in Model 2 by following the next equation [25]

$$T_{j,Error\ \%} = \left[\frac{|T_{j,numerical} - T_{j,analytical}|}{T_{j,numerical}}\right] \times 100 \tag{11}$$

2.3 Numerical Approach

The numerical simulations of Model 2 were done by using the Ansys Icepak. The room office was modelled as seen in Figure 4. Turbulent flow was chosen with zero equation and gravity vector in the Y-direction. Two cylindrical heat sources that were created to represent each person were 100 W in model 2 of the office room. The radiation was analyzed by using the solar tool of the Icepak program and the sunlight was given directly through the window with a 90° angle. In addition, each glass on the double-glazing window has a thickness of 4 mm and is filled about 12mm with Argon gas. The brick and the insulation materials thickness are 15 cm and 3 cm respectively. The dimensions of the table are 2×1.8×0.05 m and it is made from wood. The thermophysical properties for each component in the meeting office such as (brick, insulator, glass, wood, and argon) that are used in the numerical simulation are demonstrated in Table 2. Before starting the simulation, mesh analysis was done on the geometry to find the optimum mesh of the meeting room for Model 2 as illustrated in Figure 5.

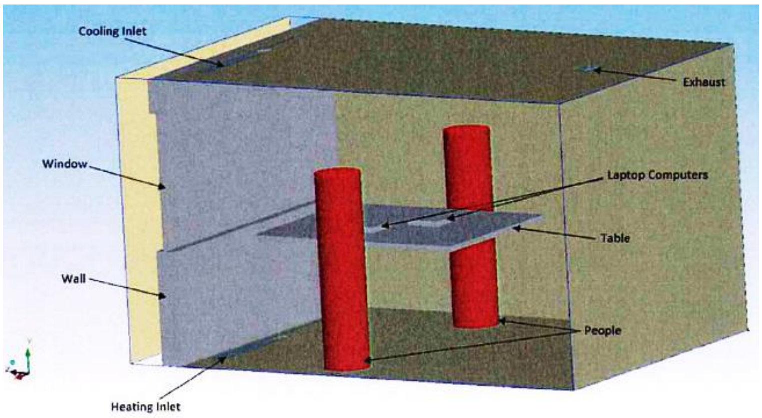


Fig. 4. The new model geometry (Model 2) of TA's office in the ICEPAK simulation

Table 2
Thermophysical properties of the Office material in Icepak simulation [26-31]

Material	Density, ρ	Specific heat, C_p	Thermal conductivity, k	Dynamic viscosity, μ
Brick	1900 kg/m^3	900 J/kg.k	1 W/m.k	----
Insulation	40 kg/m^3	1300 J/kg.k	0.04 W/m.k	----
Glass	2500 kg/m^3	753 J/kg.k	0.8 W/m.k	----
Wood	400 kg/m^3	2300 J/kg.k	0.22 W/m.k	----
Argon gas	1400 kg/m^3	523 J/kg.k	0.0172 W/m.k	1.99*10^{-5} kg/m.s

In Figure 5, it can be remarked that the results of the ambient temperatures reach a steady state after the 3rd value at the mesh count of 97316. The reason we have chosen the 3rd one is to decrease the computational time of the simulations by Icepak because the 4th one will give the same results in a longer time. In addition, Figure 6 shows the room temperature vs iteration counter for all cases. For the simulation, 300 iterations were chosen for each case because the results stabilized around the 150th iteration on all the cases (see Figure 6).

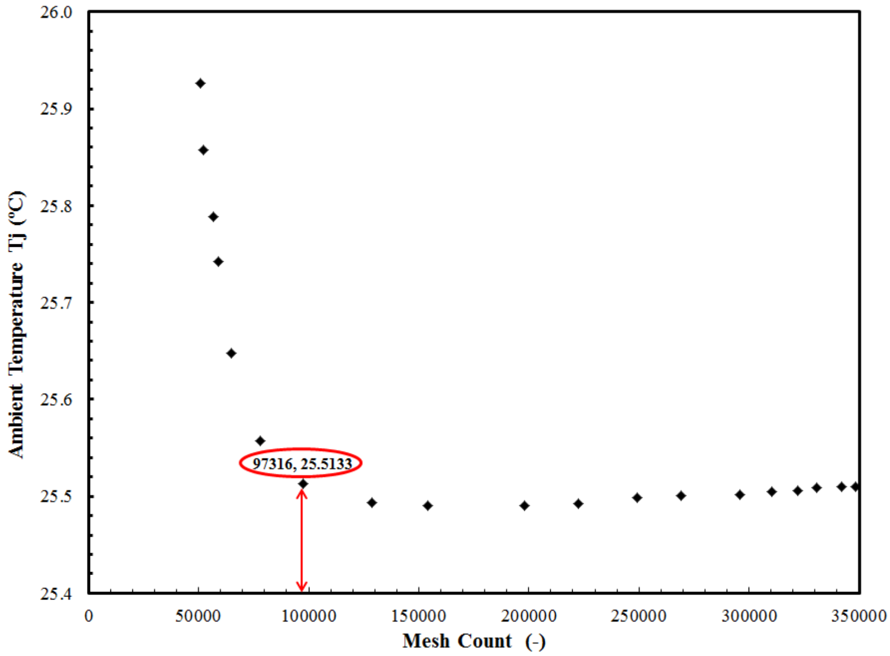


Fig. 5. Mesh analysis for Model 2 of the testing room

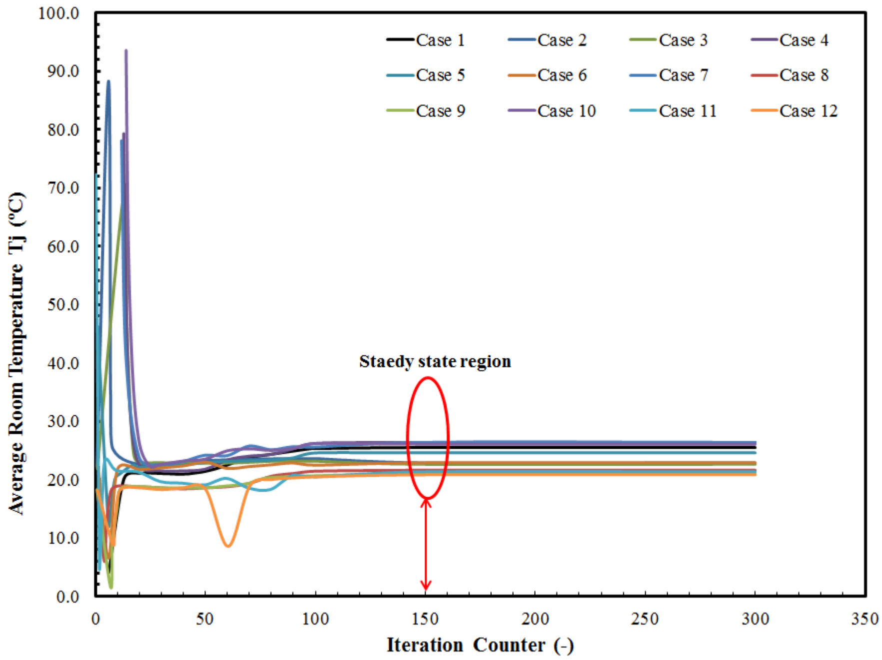


Fig. 6. Average room temperature vs. iteration counter for all Cases in Model 2

3. Results and Discussion

In this study, the main objective was to design the TA's office (Model 2) and compare it with Model 1 analytically to be more thermal comfort by staying around 22 ˚C, which leads to more energy efficiency. Next, the conclusion is achieved that the numerical results are more accurate than the analytical results of Model 2 due to the room temperature being closer to the optimum temperature of 22 ˚C.

Then, the room temperatures are determined analytically for each model 1 and 2 and for all cases that are shown in Figure 7. In addition, the analytical results are validated by the numerical results of

Model 2 for all cases with a maximum variation lower than 10%. Besides, Model 1 achieved a bigger average room temperature than Model 2 by 10.3% due to Model 1 taking a longer time for reaching to the comfortable temperature in the TA's office.

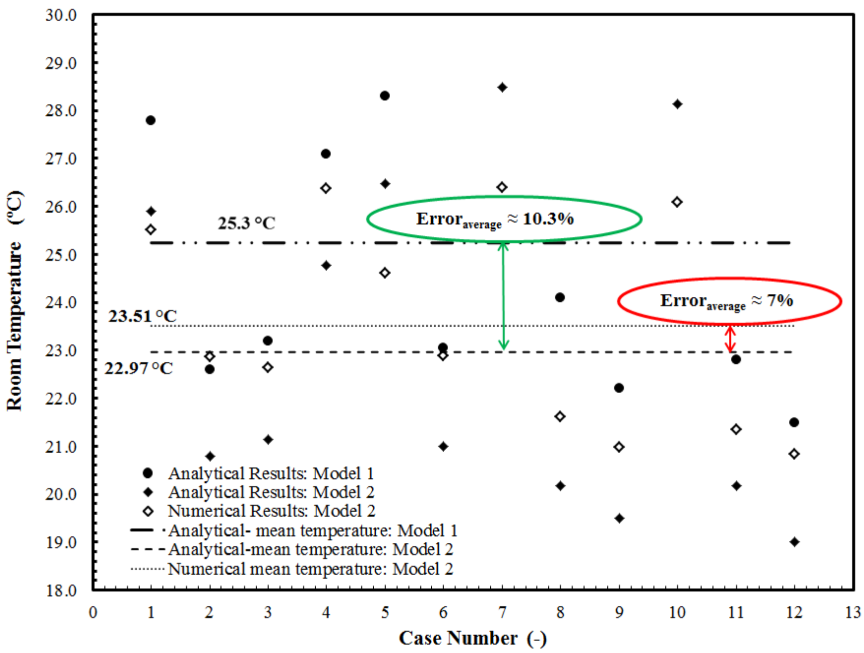


Fig. 7. Average room temperature vs. Case number for analytical and numeric

Figure 8 shows the numerical results of the temperature contour as the cross-sectional view of the office Model 2 to see the heat distribution across the room and outside the window for all cases in heating and cooling states in four months. From the cross-sectional views of the offices, the natural convection on the façade can be observed and the flow from the inlet and outlet can be noticed. For more explanation, the maximum room temperature values are the human temperature inside the testing office during the simulation. The new optimum design is Model 2 of the TA office which has the exhaust in the middle of the ceiling to keep it easy access for all around the office to get rid of the non-fresh air in the room. While, the location of the cooling inlet and the heating inlet in the front of the window for the ceiling and the floor respectively. The reason for putting the air inlet for the heating state in the front of the window due to prevent heat loss from the façade with natural convection in the winter, and the warm air did not need to be pumped for reaching to the ceiling naturally because of reduced the buoyancy force that affecting on the warm air. Moreover, the reason to place the cooling inlet to the ceiling is that the cool air will go down naturally without the need for extra force and to prevent the heat transfer from the ambient to the office through the façade during the summer season. Finally, the numerical results were more touchable than observing how air is moving inside the office, and around the people.

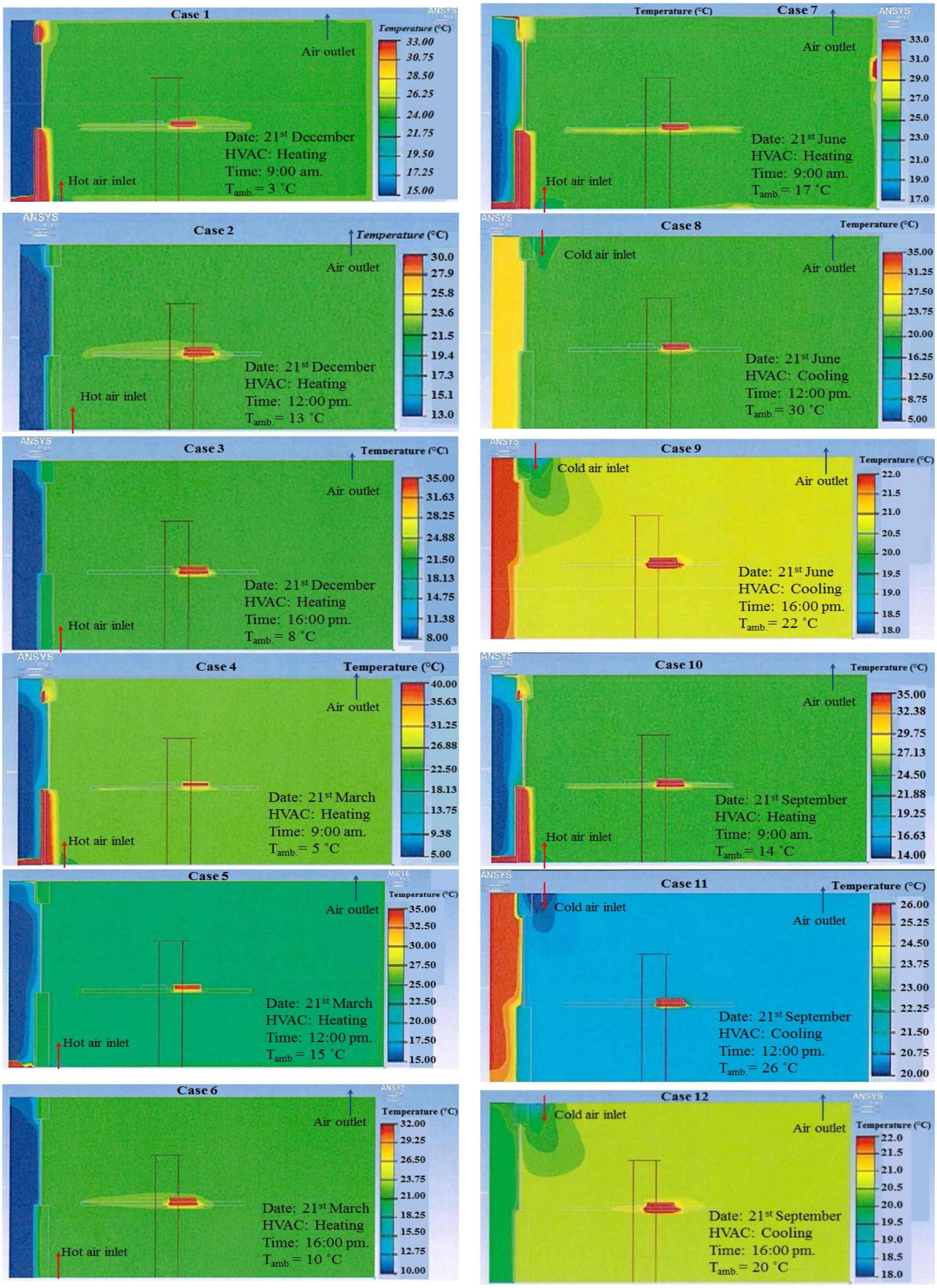


Fig. 8. Temperature contour of the Cross-sectional office view for all cases of Model 2

4. Conclusion

In this study, a TA's office in Ozyegin University is analyzed analytically and numerically by designing a new room Model 2 compared to Model 1 with different cases that lead to enhance efficiency and thermal comfort for humans. Then, the new office design gave the optimum results by keeping the room temperature around 22 ˚C for all cases. In addition, the numerical and analytical results of room temperatures in Model 2 gave a good agreement with the error percentage of about 7%. Moreover, the analytical results of the mean room temperature in Model 2 were lower than in Model 1 by 9.3%. Consequently, the new design Model 2 of the testing room achieved an excellent enhancement for getting the comfortable temperatures of the humans for all cases. The applications made the office more energy efficient from the thermal perspective. Hence, the recommendation of the study is applying the suggested model in Futuristic buildings.

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