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Research Article

Energy-Performance Concrete Roof Slabs in Hot Climates Using Air Ventilation and False Ceiling with Baffles Shape: A Numerical and Modeling Study

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Abstract

The thermal performance of a concrete roof between the main slab (concrete slab) and secondary slab (gypsum board) has been investigated in this work with and without a ventilator. The hourly averaged climatic data (combined optical and thermal condition) of the external roof surface was used as the resource for the boundary conditions of Erbil city (Kurdistan Region, Iraq). The results of measuring the effects of using a ventilator between the concrete slabs and gypsum boards indicated that the moving air in the layer between slabs by using the ventilation process has more effect in cooling roofs and the room temperature had less than that of slabs that do not use ventilation, and so using baffle shape gypsum board as the secondary slabs for air turbulence to increase air velocity, the number of mass flow rates have more efficient in the cooling process and fast the cooling process, the surface temperature was reduced by (4.5oC and 3.6 oC) with the mass flow rates of (3.5kg/s) and (2kg/s) respectively, this is due to moving air makes roof slab cool and loss the heat that transfers through the slabs, so using this technique for an exciting roof is a good choice.

1. Introduction

Buildings are increasingly contributing to the world's energy consumption by up to 40% and related greenhouse gas emissions, which directly impact climate change [1,2]. Buildings consume the world's primary energy source and provide nearly one-third of global CO2 emissions [3]. Due to the significant importance of heat gain and loss in buildings, which separate the outdoor climate from the indoor environment, building envelopes account for 45% of total energy consumption. Demand for heating, air conditioning, and ventilation accounts for 40% of the total (HVAC) [4]. Heating, air conditioning, and ventilation (HVAC) systems mostly account for high energy consumption in buildings due to their widespread use to improve the indoor ambiance and provide better thermally comfortable conditions [5]. Sustainable development goals emphasize the necessity of immediate action to combat climate change [6,7]. Energy conservation is one of the main challenges facing sustainable development today.

Recently, different technological solutions have been investigated and developed to lower the high energy consumption in buildings by utilizing various passive and active techniques. For example, a Trombe wall may absorb solar heat efficiently for room heating, resulting in energy savings throughout the heating season. However, because of its limited control abilities, the system causes undesired heat accumulation throughout the cooling season [8]. Moreover, Mustapha Salihi et al. [9] have used phase change materials (PCM) to create a practical choice for minimizing energy demand and controlling thermal comfort in buildings. Researchers have found that PCM-integrated walls improve indoor comfort while minimizing cooling and heating loads and temperature fluctuations. In terms of energy efficiency and load shifting during the summer, a triple-layer system with mechanical ventilation performed best [9].

According to the findings of another study using PCM-based composites produced for exterior wall finishes, applying PCM to foamed concrete decreased density and thermal conductivity to 896 kg/m3 and 0.18 W/mK, respectively. These values are lower by 50% and 86% than conventional cement render [10]. Using geopolymer concrete instead of OPC is an important way to minimize CO2 emissions and the sustainability of buildings. Using phase change materials, including geopolymer concrete, can reduce heat conductivity and power consumption [11]. Gowsijan et al. used waste bagasse and rice husk ashes with good thermal and mechanical properties in another study. The results showed that when waste bagasse and rice husk ashes (15% each) were mixed with conventional mortar, thermal conductivity was lowered by up to 31% [12]. The roof is one of the most critical parts of building envelopes, absorbing the most heat in the summer and accounting for 20-25% of the total large urban surface area.

Passive methods such as evaporative cooling (rooftops), vegetation (green roofs), thermal insulation, and reflecting coatings are used to minimize heat gains in buildings because the roof is the component most exposed to solar radiation (cool roofs) [13]. The hybrid green roof combines evaporative cooling with an integrated radiant system to increase its cooling capability [14]. A conventional roof is described as a cold roof with a reflective layer, high solar reflectivity, and high heat emission. Due to these properties, the roof can maintain its temperature lower than a conventional roof in the same conditions since it reflects and absorbs most of the solar energy that reaches it [15]. In this approach, cool roofs are recognized as one of the environmentally friendly ways to keep buildings at a comfortable temperature. The lower temperature of a cool roof lowers the amount of heat transmitted into the building, resulting in energy savings in buildings. A study conducted on cold roofs and green roof technologies showed that each had advantages and disadvantages of its own and uses. This research significantly increased the building environment's ability to save energy [4]. One of the elements causing a roof's heat gain is the albedo, or reflection, of the materials used to construct it. However, the ability of a material to reach its surface temperature and emittance—which regulates the amount of thermal radiation trans-mitted into its environment and oversees lowering its radioactivity—is used to describe a material's thermal performance [16]. Several materials were used for improving the thermal performance of roofing concrete slabs, such as (expanded polystyrene (EPS) based lightweight concrete panel) by Meddage et al. [17]. They suggested it as an insulation solution that is both environmentally and economically acceptable in tropical climates.

Additionally, producing EPS concrete is environmentally beneficial because there is fewer EPS waste. AL-Yasiri and Szabó [18] investigated the optimum thickness of a phase change material (PCM) layer. They found that a thicker PCM layer provides better thermal performance and that in-stalling a large quantity of PCM into buildings should consider economic factors. Another study by A. Synnefa et al. [19] used cool roof coatings for residential buildings in different climatic conditions. According to the findings, increasing roof solar reflectance reduces peak cooling demand in air-conditioned buildings by 11-27% and cooling loads by 18–93%. Hamed et al. [20] experimentally and numerically investigated the effect of dust/dirt accumulation on the solar reflectivity of the reflective coating material (RCM). The test results showed that dust and dirt could significantly contribute to reducing the solar reflectivity of the RCM. Singh and Rawat [21] highlight the thermal performance of cool roofs with various surface coatings in different climate zones for buildings, along with additional advantages, limitations, and recommendations for further study. The average energy-saving impact of the roof varies by climate zone and ranges from 15% to 35.7%, according to the literature review findings (Composite, Temperate, Tropical, Hot, and Warm-Humid).

Additionally, using cool roof technology, the average roof surface temperature can be reduced from 1.4 0C to a maximum of 4.7 0C. Most of the roofs of the Kurdistan region, a part of Iraq in the Middle East countries, are built with concrete slabs. In summer, the slabs transfer heat to indoor temperature, so they are not energy efficient and have high energy consumption rates. However, research in identifying problems and effective factors and analyzing and evaluating possible solutions to this issue is insufficient. In this article, the common design of houses and buildings in this area is to have a concrete roof with a gypsum board false ceiling, with gaps between these two. Also, if the air inside the gaps is replaced with a ventilator, it can help cool the surface, using a baffle for air turbulence to increase air velocity and affect the cool roofs.

2. Physical and mathematical model

2.1. Physical model

The physical model of the home is shown in Figure 1. A., and the section of the slabs is shown in Figure 1. B. It consists of a three-dimensional model (4m*4m*3m) of the room with a concrete slab functioning as the roof and a gypsum board functioning as the false ceiling. The gap between these two layers with and without ventilation systems is shown. The physical model of parts is considered homogeneous, and each wall is assumed to be isolated. The channels for the ventilation system were (20 cm in height with 40 cm in width), and the material properties are shown in Table 1.

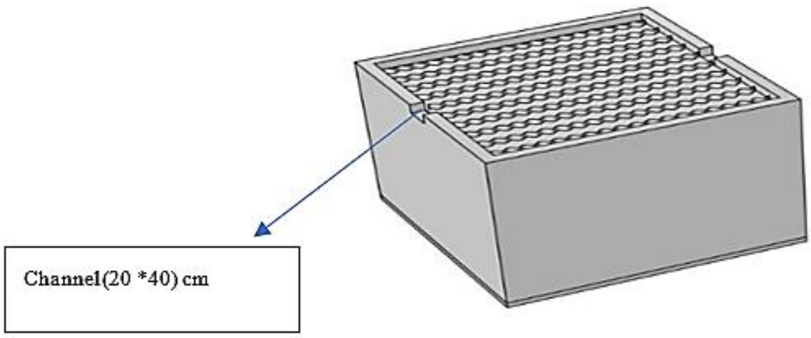

Figure 1. A. physical models of the room

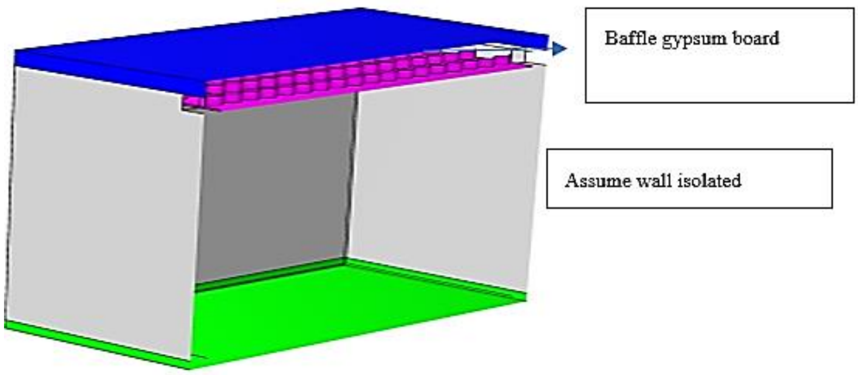

Figure 1. B. section of the room with ventilation

Table 1. The properties of the material

No	Material	Thermal conductivity (k [W/m$_K$])	Density (kg/m^3)	Thickness(cm)	Emissivity
1	Concrete slab	1.8	2300	18	0.85
2	Gypsum Board	0.254	574	1	0.8
3	Air	0.025	1.225	20	---------

2.2. Climatic conditions data

This research was conducted during a regular climatic year in Erbil (Kurdistan Region-Iraq). According to the Koppen climate classification system, Erbil has a hot-summer Mediterranean climate (Csa) with very hot summers and cool wet winters. The weather was largely sunny, and the office monitoring climate in Erbil measured the data. In the modelling, we chose the crucial point, which is the maximum air temperatures recorded in the year 2021, and the data are shown in Figure 2.

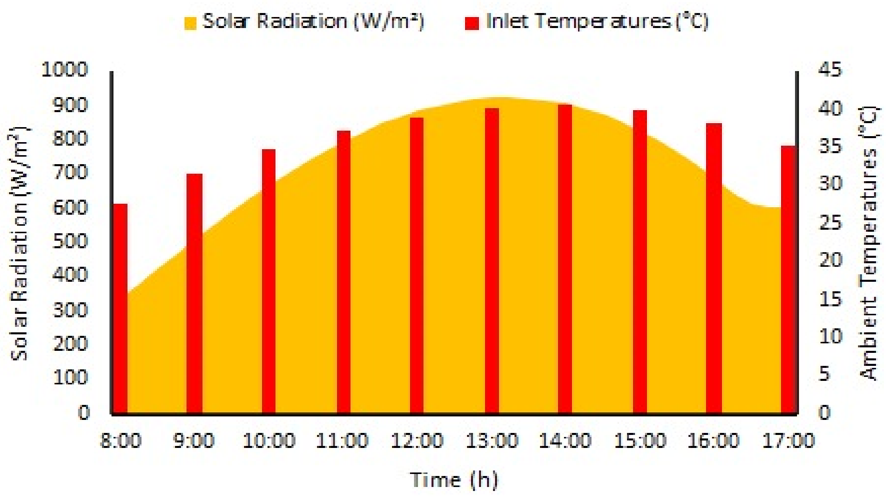

Figure 2. Solar Radiation and ambient Temperatures over a typical day [20].

2.3. Mathematical model:

Under unsteady-state conditions, the system's energy balance is estimated as the incoming solar irradiation changes over time due to ambient and time variations. The overall system's governing energy balance is as follows: [22]

$$\frac{\partial(\rho C_p T)}{\partial t} + \rho C_p u.\nabla T + \nabla.(-k\nabla T) = 0 \quad (1)$$

In this formula, ρ is density C_p is thermal capacity, and k is thermal conductivity. u presents the velocity field of the flow of air through the box. The following formulas quantify this: k-ε is kinetic energy and heat dissipation, respectively, given by Eqs.

$$\rho\frac{\partial k}{\partial t} + \rho(u.\nabla)k = \nabla.\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + p_k - \rho\varepsilon \tag{2}$$

μ is the turbulence viscosity in equation (8). It is given as:

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \tag{3}$$

The production term P_k is modelled as follows:

$$P_k = \mu_T[\nabla u: (\nabla u + (\nabla u)^T)] \tag{4}$$

Newton's cooling law is applied to estimate how much convective heat is lost from the top surface of the concrete surface to the ambient.

$$Q_{loss,conv} = h_{conv}A_{glass}\left[T_{glass}(t) - T_{amb}(t)\right] \tag{5}$$

Specifically, h_{conv} represents the convection coefficient between a concrete surface and the surrounding air. The radiative heat loss from the top surface of the roof is calculated using the Stefan-Boltzmann radiation exchange law:

$$Q_{loss,rad}(t) = \varepsilon\sigma A_{abs}\left[T^4_{s,abs}(t) - T^4_{amb}(t)\right] \tag{6}$$

The ε parameter refers to the emissivity of the roof surface, and σ is the Stefan-Boltzmann constant. The bottom, sides, and walls are all thermally insulated. This study's inlet air mass flow rate ranges between 0.04 and 0.1 kg/therefore, the fluid flow model module should be selected depending on the air Reynolds number. Using the turbulence k − ε model, we can calculate the air velocity inside the box. Its equation is as follows:

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho u) = 0 \tag{7}$$

The momentum formula for air movement in the collector is given as follows:

$$\rho\frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.[-pI + (\mu + \mu_T)(\nabla u + (\nabla u)^T)] + \rho g \tag{8}$$

2.4. Boundary conditions:

These boundary conditions control airflow between the roof and gypsum board air heat transfer:

$$-\int \rho(u.n)ds|_{inlet} = \dot{m} \quad (9)$$

$$T_{in}(t) = T_{amb}(t) \quad (10)$$

On the absorber concrete, the amount of heat absorbed is shown in the following way:

$$-n.k\nabla T|_{boundary} = Q_b \quad (11)$$

To the initial condition, it is assumed that the actual ambient temperature when the system began operation is considered when solving time-dependent governing equations.

$$T_{In} = T_{amb} \qquad At\, system\, start \quad (12)$$

3. Results of Model Validation

COMSOL Multiphysics is one of the most powerful computer-aided engineering software for finite element analysis. COMOSL Multiphysics can solve problems. This software has a wide range of elements that can model any geometry. It also has a lot of behavioural patterns. In this research, this software has been used to analyse the efficiency of the heat transmitted through the roof of the exciting house. After its development and mesh independence analysis, the model should be validated for parametric sensitivity analysis and then used to predict how to decrease air room temperatures. Model validation results for average air outlet temperature are presented in Table **2**2. Data obtained from the experimental work [23] were compared with those obtained from this study. Air temperatures show a relative error of less than 3.5 % on average based on relative error analysis. It is evident from these results that the model is capable of predicting the temperature distribution within the system within a reasonable error range and that parametric system analyses can be performed trustworthily by using it.

4. Results and Discussions

Figure 3 displays the temperature profile of the experimental models as a function of the surface roof temperatures at the time (16:00) in the days with and without varying air velocities using the ventilation channel between the slab and false ceiling manufactured of gypsum under roof slabs. The figure showed that the mass flow rates with the value of 3.5kg/s and 2 kg/s affect the roof's surface temperature and reduce the roof's surface temperature by (4.5^{o}C and 3.6 ^{o}C) respectively. This is due to moving air making the roof slab cool and causing loss of the heat that transfers through the slabs.

Table 2. Results of model validation for solar air heater average temperature compared with the results in [23].

Ta_in (0C)	Model.T1 (0C)	Exp.T1 (0C)	R_Error (%)	Model.T2 (0C)	Exp.T2 (0C)	R_Error (%)	Model.T3 (0C)	Exp.T3 (0C)	R_Error (%)	Model.T4 (0C)	Exp.T4 (0C)	R_Error (%)	Model.T_out (0C)	Exp.T_out (0C)	R_Error (%)
23.1	25.00	25.30	1.19	25.00	26.20	4.58	26.00	27.10	4.06	25.00	26.20	4.58	28.00	29.00	3.45
27.1	28.15	29.40	4.27	30.00	31.28	4.10	31.40	32.93	4.64	33.18	34.19	2.95	34.46	35.22	2.14
31.2	30.80	31.87	3.36	32.18	34.16	5.80	34.44	35.85	3.93	35.75	37.18	3.84	36.78	38.06	3.37
33.8	32.44	33.67	3.65	34.18	36.18	5.54	37.04	37.75	1.87	38.70	39.01	0.80	40.46	39.78	1.71
35	34.15	35.40	3.55	36.09	38.20	5.54	39.35	39.80	1.14	41.24	41.10	0.34	43.56	41.90	3.97
36.6	35.56	37.34	4.77	38.66	40.64	4.88	41.21	42.77	3.66	43.26	44.45	2.68	45.92	45.87	0.12
37.9	36.87	38.25	3.60	39.14	42.05	6.93	42.97	44.28	2.95	45.18	45.93	1.64	48.15	47.61	1.14
39.2	38.18	38.78	1.55	40.62	43.03	5.62	44.74	45.19	1.01	47.10	46.75	0.76	50.38	48.56	3.74
39.9	39.29	39.50	0.53	41.88	44.00	4.83	46.26	46.50	0.53	48.79	48.00	1.64	52.30	49.90	4.81
38.6	40.39	41.09	1.71	43.13	45.11	4.40	47.77	49.75	3.99	50.46	51.80	2.58	54.21	53.13	2.05
37	41.43	41.71	0.66	44.32	45.92	3.49	49.19	51.23	3.98	52.04	53.31	2.37	56.02	54.72	2.39
35.6	42.17	42.00	0.40	45.16	46.57	3.03	50.19	52.07	3.62	53.17	54.07	1.67	57.31	55.65	2.98
34	42.90	42.50	0.95	45.99	47.20	2.56	51.19	53.00	3.41	54.29	55.10	1.47	58.60	56.90	2.99
33.4	43.56	44.45	2.01	46.74	47.88	2.38	52.07	54.38	4.24	55.27	57.52	3.91	59.73	59.60	0.21
29.8	44.08	45.25	2.59	47.31	48.54	2.54	52.74	55.39	4.79	56.01	58.44	4.17	60.57	61.22	1.05
Relative Error (%)			**2.17**			**2.93**			**3.37**			**2.63**			**2.5**

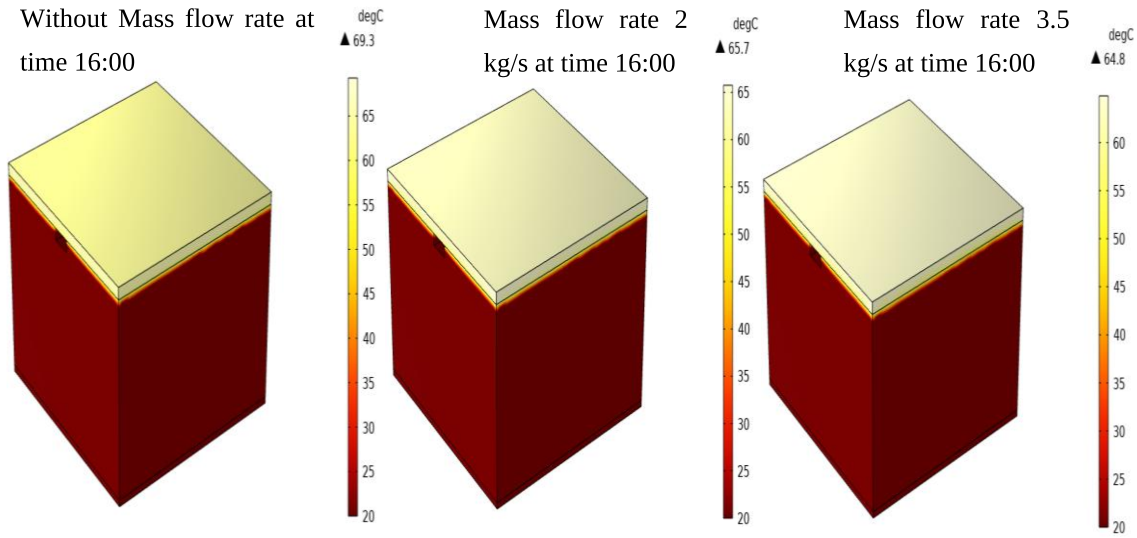

Figure 3. surface roof temperature at the time (16:00) on the days with and without mass flow rates.

The graph in Figure 4 shows the temperature under the roof with different mass flow rates. The result showed that when it does not have a mass flow rate, the temperature under the roof was increased until (22:00) and reached (67.68 ^{o}C) after that, the temperature also decreased. The results showed that the temperature under the roof gradually increased due to the heat by the concrete roof slowly decreasing heat. Still, when using ventilation to create the mass flow rate with the value of (3.5 kg/s), the maximum temperature was obtained at a time (14:00) with the value of (40.78 oC) after the time (14:00) the temperature was decreased, it is shown that the mass flow rates have an effect on cooling the roofs and also fast the cooling process.

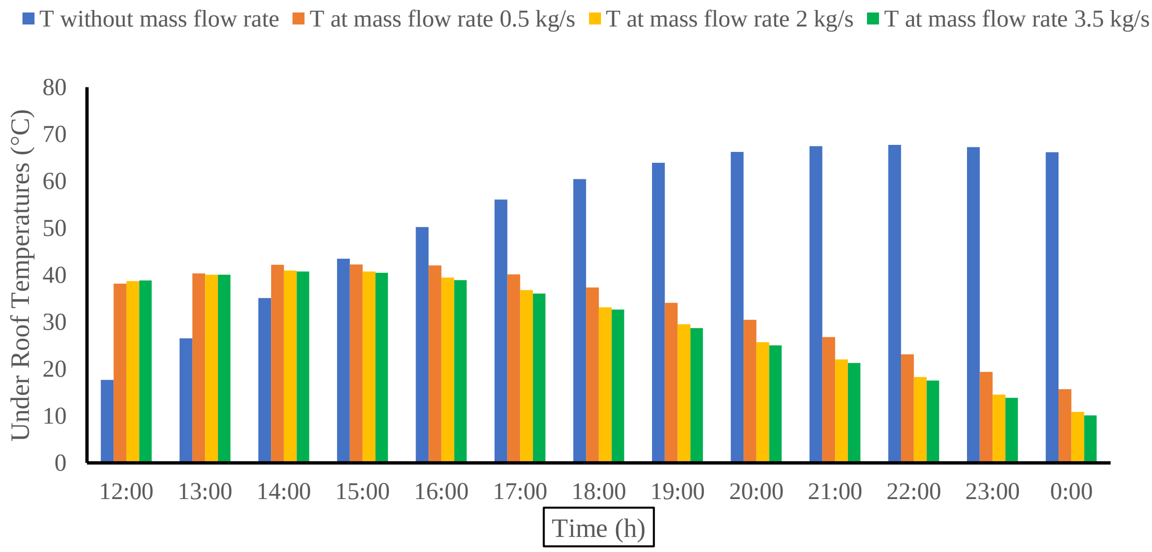

Figure 4. Under roof temperature at different times during the days with and without mass flow rates

Figure 5 displays the air room temperatures over days with varying air velocities using the ventilation channel between the slab and the false ceiling manufactured of gypsum. The graph showed that from the morning hours until the middle of the night (8:00 to 00:00), the roof was cool when using air velocity between two slabs. This cooling slab allowed for a decrease in the air room temperature during the day and a loss of the slabs' ability to absorb solar heat. The amount of air velocity also had an impact on the cooling process and reduced the amount of heat absorption from the slabs. The graph also indicated that slabs cool faster with higher air velocity than with lower air velocity, so the mass flow rate of the value (3.5kg/s) has more effect.

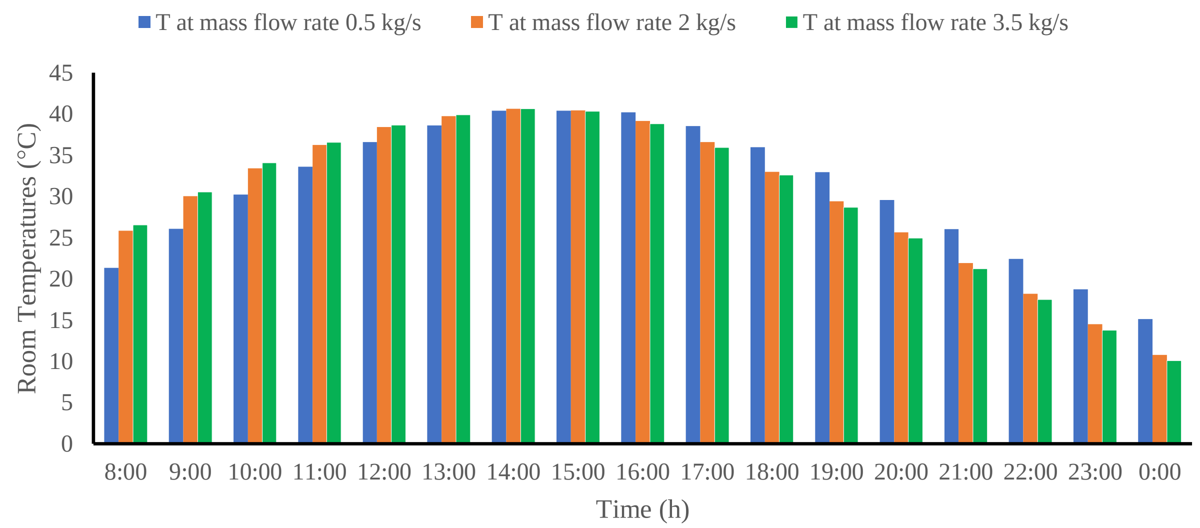

Figure 5. Room temperature at the time in the days with different mass flow rates.

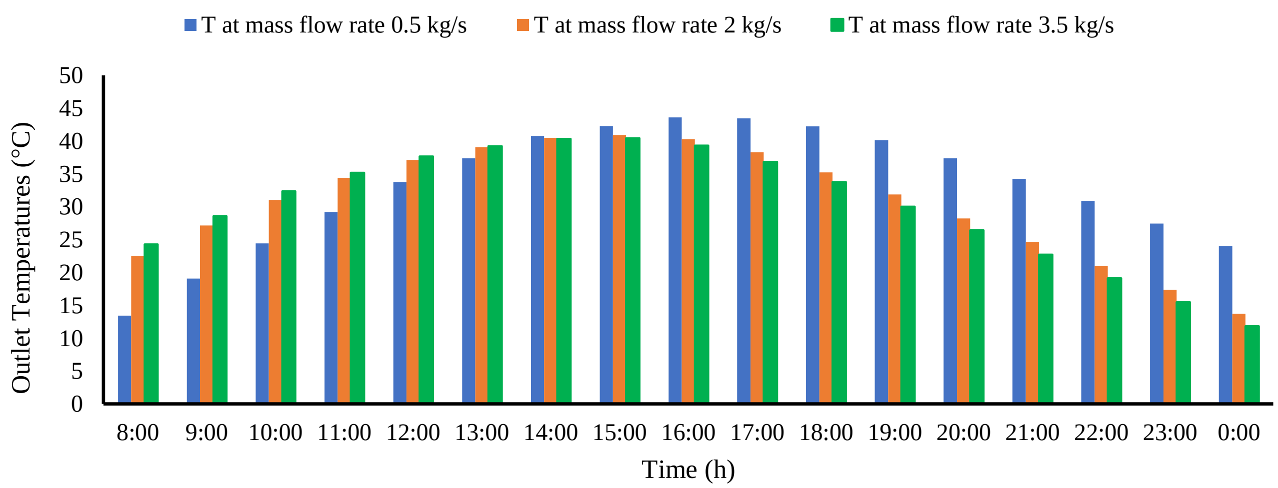

Figure 6. The outlet temperature between the roof and gypsum board

As previously mentioned, the amount of air velocity influenced the cooling process and lowered heat absorption from the slabs. Figure 6 illustrates the outlet temperature between roof slabs and gypsum slabs. It displays that with maximum mass flow rates (3.5kg/s), have more efficient in the outlet temperature, and at a time (15:00) decrease the outlet temperature. In contrast, with a mass flow rate (0.5kg/s) at a time (16:00), outlet temperatures decreased very slowly compared to the mass flow rate (3.5kg/s).

5. Conclusion

In this work, we used the Erbil climatic conditions to evaluate the thermal performance of the exciting roof slab with and without ventilation between the main slab (concrete slab) and the false ceiling (gypsum slab) in the summer. Also, the effects of using a baffle between two slabs and ventilation between slabs have been numerically investigated. It was concluded that; Air exchange between the two slabs causes the concrete slab to cool, and using ventilation to increase air velocity between the two slabs as mass flow rate for the cooling process, the effects of this processing were decreasing the room temperature and fast the surface cooling also loss the heat that absorbed by roof slabs, so it is a technique to save energy in hot climates. Also, using a baffle channel between two slabs increases cooling efficiency because the baffle increases the velocity of air between the slabs, which accelerates the cooling process of the concrete slab. As a result of this numerical modelling, the increased air velocity improves the cooling process of the roofs.

Declaration of Competing Interest The authors declare that they have no known competing of interest.

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