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Loading PCM Into Buildings Envelope to Decrease Heat Gain-Performing Transient Thermal Analysis on Nanofluid Filled Solar System

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The high share of buildings in energy consumption and carbon dioxide emission has led researchers to seek techniques to reduce energy consumption in this sector. In this study, considering a hot and arid climate region, the wall's heat gain was investigated. To reduce energy demand, three techniques of adding PCM, combining absorption chiller with a solar system and dispersing nanoparticles were used and the results were evaluated transiently. In July, the addition of PCM to the building's walls reduced the heat exchange between interior and exterior spaces up to 21%. To cool the interior spaces, the combination of absorption chiller + fan coil was used and several flat plate collectors were integrated with it to reduce energy demand. By collecting energy in solar collectors and using a stratified tank, energy consumption in the generator section was reduced by 450 kWh. Nanoparticles were used to improve the solar system performance and it was found that loading ZnO and Al_2O_3 nanoparticles is useful. Dispersing ZnO into water increased the energy-saving by 9.5% while the second nanoparticle improved it by 14.5%.

Keywords: saving-energy, building, pcm, solar collector, nanofluids

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INTRODUCTION

Buildings contribute a lot to pollution production and energy consumption (Jahangiri et al., 2016; Mostafaeipour et al., 2020; Kalbasi et al., 2021; Parsa, 2021; Song et al., 2021). Many solutions have been recommended by various researchers to reduce energy consumption (Ahmadi et al., 2017; Ahmad et al., 2018; Nwaji et al., 2019; Sarafraz et al., 2019; Azimi Fereidani et al., 2021; Nundy et al., 2021). Techniques include installing PCM (Ahangari and Maerefat, 2019; Lizana et al., 2019; Ziasistani and Fazelpour, 2019; Ben Romdhane et al., 2020; Miansari et al., 2020; Saxena et al., 2020), heat recovery (Liu et al., 2020; Shahsavar Goldanlou et al., 2020), using solar energy (Toghraie et al., 2018; Gagliano et al., 2019; Parsa et al., 2019; Gholipour et al., 2020; Menni et al., 2020; Parsa et al., 2020; Poon et al., 2020; Gholipour et al., 2021), other renewables such as wind (Jahangiri et al., 2019; Mostafaeipour et al., 2019; Kalbasi et al., 2021), geothermal sources (Kang et al., 2013; Palmero-Marrero et al., 2020) and finally using nanofluid (Kulkarni et al., 2009; Strandberg and Das, 2010; Moradi et al., 2019; Soltani et al., 2020; Mustafa et al., 2021). Considering the hot and dry climate, Li et al. (2019) by conducting a numerical study examined the effect of adding RT-27 PCM to a wall with 20 cm thickness. This material undergoes a phase change at 28–30°C and has a latent heat of 179,000 J/kg. They added RT-27 to the wall in three thicknesses of 1, 2 and 4 cm and found that the heat gain through wall (HGTW) diminished by 3737, 7050 and 11971 $kJ/July.m^2$. In other words, if RT-27 is installed within a 20-cm wall, then it diminished HGTW by 12.06% (for 1 cm RT-27 thickness). If the effect of RT-27 thickness is considered in the numeric calculations, it can be seen that

HGTW reduced by 3737, 3525, 2992.75 $kJ/July.m^2$ per RT-27 thickness. This means that the RT-27 positive effects are lowered as the thickness rises. They moved the RT-27 installation location and found that the closer it was to the outside, the better its performance. Because the calculations showed that HGTW was lowered by 12.06% for a location just adjacent to the room space and 13.38% for installation near the exterior. In a similar study, Nariman et al. (2020) added PCM of $C_{16} - C_{18}$ to a 23-cm wall and calculated HGTW in July. They also considered the solar intensity over the wall faced to north, south, east and west directions. Calculations showed that in the main directions, this material can reduce HGTW parameter by 11,136 (N), 12,538 (S), 12,991 (E) and 13,907 $kJ/July.m^2$ for west direction. If these values compare with the base wall heat transfer [i.e., 42,378 (N), 47,652 (S), 49,509 (E) and 49,867 (W) $kJ/July.m^2$] it is found that loading $C_{16} - C_{18}$ leads to 26.27% reduction in HGTW for north-facing wall. For other walls, this figure was 26.31% (S), 26.23% (E) and 26.27% (W). This means that for evaluation the PCM efficacy on HGTW, the wall direction is not much important. Li et al. (Ghaffarkhah et al., 2020) investigated the effects of adding a 1-cm thickness PCM layer adjacent to the inner space and a 1-cm thickness PCM layer adjacent to the exterior space. They examined many PCMs composition and found that for hot summer/mild winter climate (the authors called zone A) the best effectiveness was related to Enerciel 22 (close to interior space) + Capric (close to exterior space). Under the best effectiveness, HGTW was lowered by 26.85% in July. Moreover, an 18.64-percent reduction (worst conditions) in HGTW was reported for the composition of Capric + HS-21. The authors repeated the simulation for mild summer/very cold winter (i.e., zone B) and reported that Enerciel 22 for inner and exterior layers has the best performance (taking into account 27% HGTW decrease). The minimum PCM efficacy on HGTW reduction corresponded to S7 for both layers (11.31%). For warm summer/cold winter (zone C) the authors reported the best and worst results have corresponded to compositions of Enerciel 22 + Capric and S7 + S7. The former composition decreased HGTW by 30.5% while using the latter composition led to a 14.5% reduction. Abu-Hamdeh et al. studied the thermal performance of a wall filled with PCM A13, with a phase change temperature of 13°C to inspect that whether adding PCM to the wall is useful in winter. Their results were performed in the coldest 3 months of the year (Dec, Jan and Feb) and it was observed that in the 1st month, heat loss from the interior reduced by 11%. In the 2nd and 3rd months, this figure ended at 10.6 and 10.2%. To examine the PCM phase change temperature, they used A8 (T_m = 8°C) and found that this material can lower the heat loss by 11.1, 11.2 and 10.2% in Dec, Jan and Feb. These results prove that PCM of A13 can be used in winter as well. Winter analysis showed that if A13 was used, heat loss would be reduced by 10.7%. Moreover, they also reported that A8 filled wall has a similar thermal performance taken into account 10.86% in heat loss. An economic analysis was also conducted in their study, and considering the price of gas $\left(3.06 \frac{\$}{10^6\,BTU}\right)$, the authors showed that if A13 is used, it will take approximately 20 years for additional costs, to be compensated. This figure was 19 years for A8 PCM.

In this study, considering the hot and arid climate for Najran region (17.56°N, 44.22°E), a suitable PCM is selected and then by performing a transient analysis, the thermal behavior of this building is investigated. To cool the building in July, an absorption chiller with several solar collectors is combined to reduce energy demand. Then, nanofluids of $ZnO/w$and Al_2O_3/wwere added to the water inside the collector to boost the amount of saving-energy.

PROBLEM DESCRIPTION

In this research, the main goal is to reduce energy demand in buildings, which is examined using two scenarios. In the first scenario, by reducing HGTW, the energy usage in HVAC sector reduces. In the second scenario, an absorption chiller is used to cool the building. For meeting the energy usage in the generator section, a solar collector filled with ZnO/water is used. **Figure 1** shows that by adding PCM to the walls, the thermal resistance of the building rises and thus HGTW reduces both in winter and summer. **Figure 1** shows that an absorption chiller enters the circuit to provide cooling in summer. In the evaporator, cold water within the temperature of 6-7°C enters the fan coil and returns to the evaporator by taking heat from the building. An evaporative cooling tower is used to cool the condenser. In an absorption chiller in the generator section, a hot water flow can be used to supply thermal energy.

MATHEMATICAL FORMULATION

The governing equations are presented in two parts. In the first part, due to the PCM phase change inside the wall, the governing equations are solved in such a way that the temperature distribution inside the wall can be obtained. To obtain the temperature, it is required to solve the continuity, momentum and energy equation:

$$\begin{aligned}\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x}(\rho u h) + \frac{\partial}{\partial y}(\rho v h) + \frac{\partial}{\partial y}(\rho w h) \\ = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) - \xi\end{aligned} \tag{1}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

$$\begin{aligned}&\frac{\partial(\rho u)}{\partial t} + u\frac{\partial(\rho u)}{\partial x} + v\frac{\partial(\rho u)}{\partial y} + w\frac{\partial(\rho u)}{\partial z} \\ &= -\frac{\partial P}{\partial x} + \rho g_x + \frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right) \\ &\quad - f(u)\frac{\partial(\rho v)}{\partial t} + u\frac{\partial(\rho v)}{\partial x} + v\frac{\partial(\rho v)}{\partial y} + w\frac{\partial(\rho v)}{\partial z} \\ &= -\frac{\partial P}{\partial y} + \rho g_y + \frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu\frac{\partial v}{\partial z}\right) \\ &\quad - f(v)\frac{\partial(\rho w)}{\partial t} + u\frac{\partial(\rho w)}{\partial x} + v\frac{\partial(\rho w)}{\partial y} + w\frac{\partial(\rho w)}{\partial z} \\ &= -\frac{\partial P}{\partial z} + \rho g_z + \frac{\partial}{\partial x}\left(\mu\frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial z}\right) - f(w)\end{aligned} \tag{3}$$

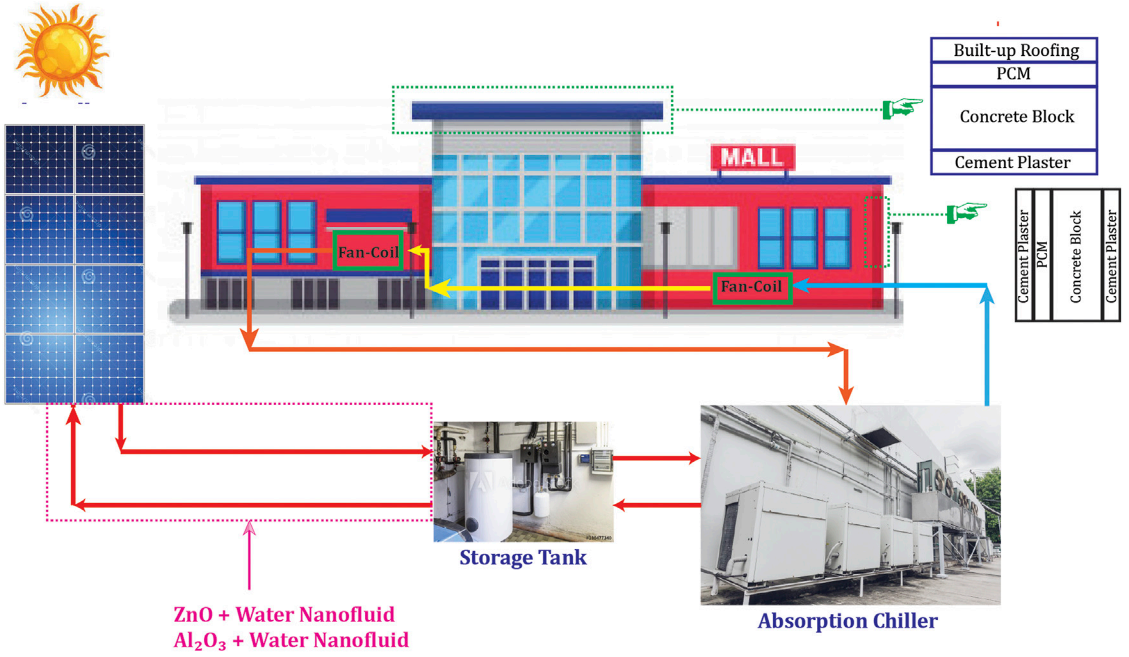

FIGURE 1 | PCM-based building integrated with a nanofluid filled solar system.

where $\xi = \rho L \frac{\partial \varepsilon}{\partial t} + \rho L \nabla.(\varepsilon \overrightarrow{V})$ is the heat sink for energy equation to show the effects of phase change, $f(u), f(v)$ and $f(w)$ are sink terms for momentum equations to make zero velocity in cells contain solid phase.

$$f(u) = m\frac{(1-\varepsilon)^2}{\varepsilon^3 + 0.001}u \tag{4}$$

$$f(v) = m\frac{(1-\varepsilon)^2}{\varepsilon^3 + 0.001}v \tag{5}$$

$$f(w) = m\frac{(1-\varepsilon)^2}{\varepsilon^3 + 0.001}w \tag{6}$$

The boundary conditions in x-direction as shown in are written as follows:

$$-k\frac{\partial T(w)}{\partial x}\Bigg)_{x=w} = h_{inner}\left(T(w) - T_{room}\right) \tag{7}$$

$$-k_w\frac{\partial T_w}{\partial x}\Bigg)_{x=0} = h_o\left(T_a - T_{w,o}\right) + (1-\rho)G(t) \tag{8}$$

where $h_{inner} = 8.6\frac{W}{m.K}$ and $h_o = 25\frac{W}{m.K}$ are the convective coefficients (Li et al., 2019). For other directions (i.e., y and z) the similar equations should be written. Note that ρ is the reflection coefficients and $G(t)$ is the radiation over vertical walls (**Figure 2**).

In solar collectors, the main parameter is the heat gain (HG) which is obtained from the following equation:

$$HG = \left(F_R(\alpha\tau) - c_1\frac{T_i - T_a}{I(t)} - c_2\left[\frac{T_i - T_a}{I(t)}\right]^2\right) \times \underset{collector\ area}{A_c} \times I(t) \tag{9}$$

where $I(t)$ denote the radiation over the collector, T_a is the ambient temperature. The details of **Eq. 9** are described in (Mustafa et al., 2021). The variations of T_a and $I(t)$ are illustrated in **Figure 3** and **Figure 4**.

RESULTS

PCM Efficacy on Heat Gain Through Wall

PCMs are substances that can store energy and then release it. The process of storing/releasing energy depends on the phase change temperature range (T_m). Therefore, if PCM is chosen without considering T_m, it may not be useful for the building. The appropriate temperature is selected according to the geographical conditions of the building. **Figure 3** showed that in July, the temperature fluctuates with 25–40°C, so the PCM has chosen so that its T_m should be in this range. In this study, RT-27 (**Table 1**) is used. Now, to evaluate the proper functioning of PCM, its effect on HGTW should be examined. Note that heat transfer to the room depends on several parameters. In summer, the occupancy parameter can drastically change the sensible/latent loads of the room. If the number of people increases or the time of their presence or even their level of activity changes, both parameters of sensible/latent loads change quite obviously. PCM inside the wall does not affect this parameter. Electrical equipment along with lighting also has a great impact on the building's heating. PCM does not affect these two parameters either. However, the variations in the amount of thermal energy entering the room are illustrated in **Figure 5**.

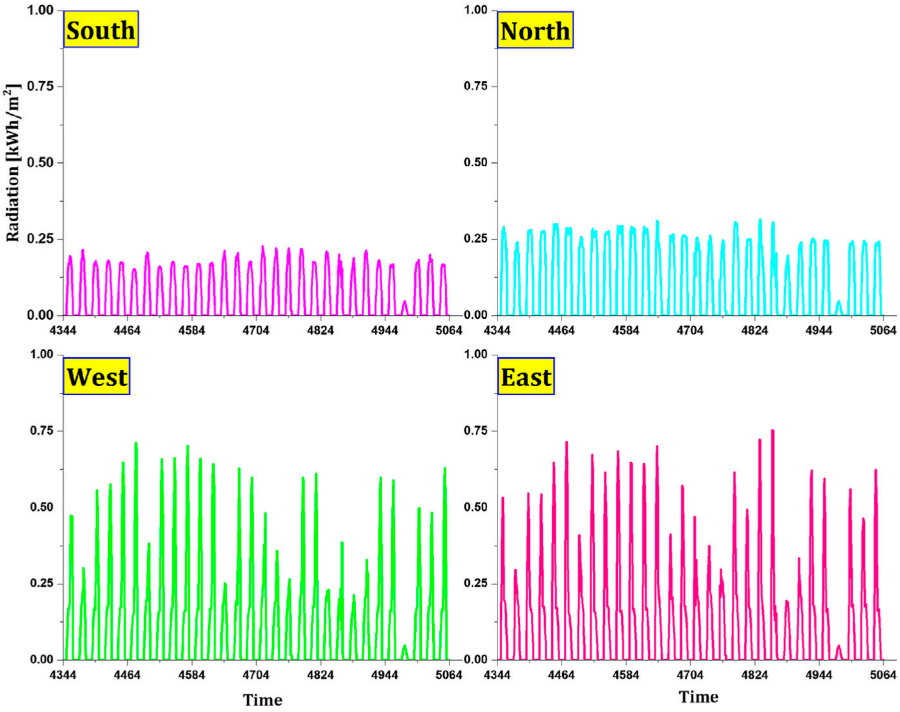

FIGURE 2 | The variations in $G(t)$ for various directions.

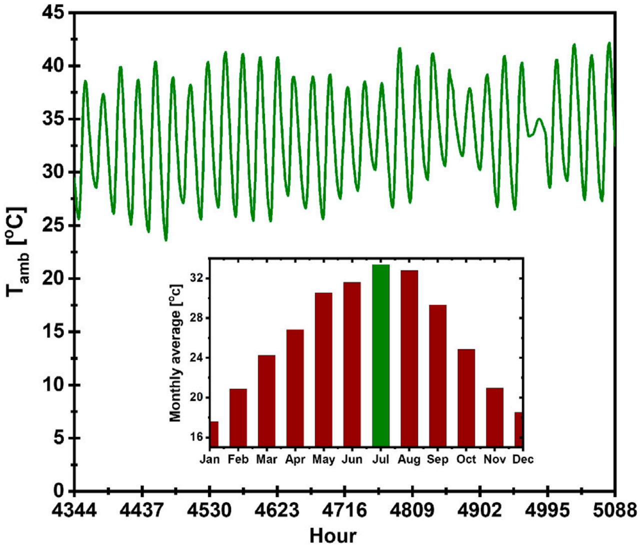

FIGURE 3 | The variations in T_a (17.56°N, 44.22°E).

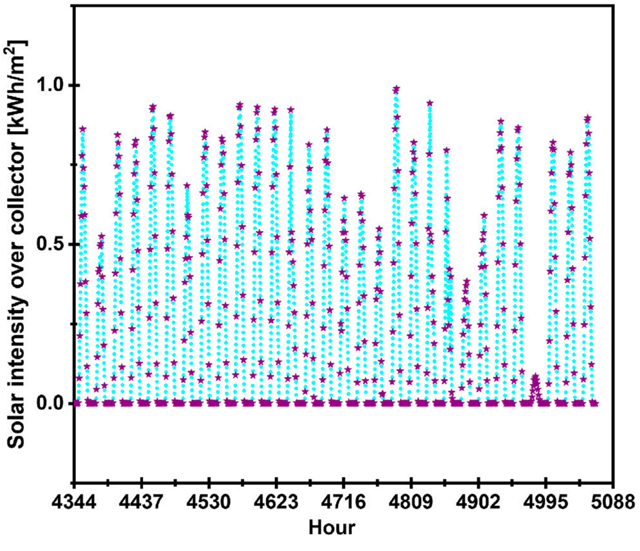

FIGURE 4 | The variations in $I(t)$

In this study, considering that the building is an office, so the schedule was chosen in such a way that between 8 a.m and 8 p.m, parameters of occupancy, lighting and equipment affect.

The only parameter that is affected by the presence of PCM is HGTW. The variations in HGTW for simple building and building + RT-27 are illustrated in **Figure 6**.

The amount of thermal energy entering the building interior through the wall depends on the number of thermal layers of the wall as well as thermal resistance of the layers. Less thermal conductivity is more desirable for layers because thermal energy faces more barriers to entering the interior space. However, as shown in **Figure 6**, for a building that uses RT-27 inside walls/ceiling, less thermal energy is exchanged which is very acceptable.

TABLE 1 | Properties of the construction materials and studied PCMs (ASHRAEAmerican Society of Heating and Engineers, 2016; Tian et al., 2020a).

Material	Thermal conductivity $\left[\frac{W}{m.K}\right]$	Melting temperature [K]	Specific heat $\left[\frac{kJ}{kg.K}\right]$	Density $\left[\frac{kg}{m^3}\right]$	Phase change enthalpy $\left[\frac{kJ}{kg}\right]$
Concrete	1.4	—	880	2,300	—
Built-up roofing	0.17	—	1,460	1,100	—
Plaster	0.22	—	1,085	1,680	—
RT-27	0.23	301.15–303.15	2,400	870	179
	0.18		1,800	760	

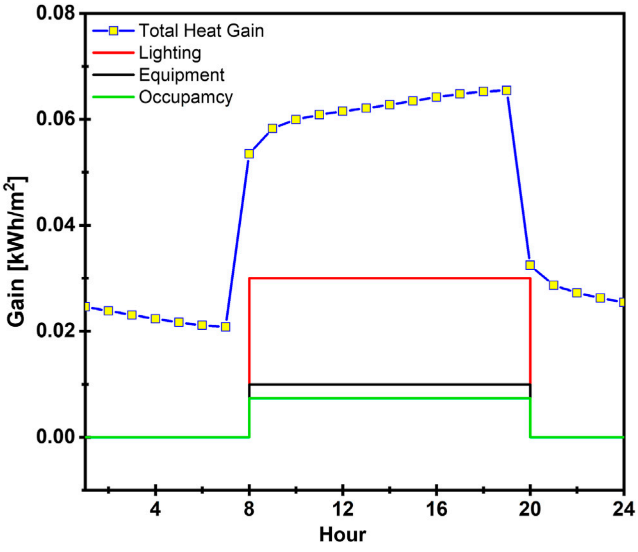

FIGURE 5 | The variations in the various heat transfer mechanism.

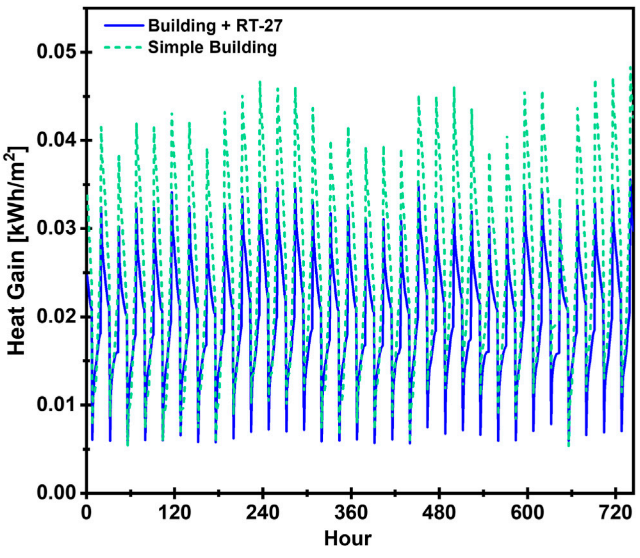

FIGURE 6 | Heat gain for simple building and building filled with RT-27.

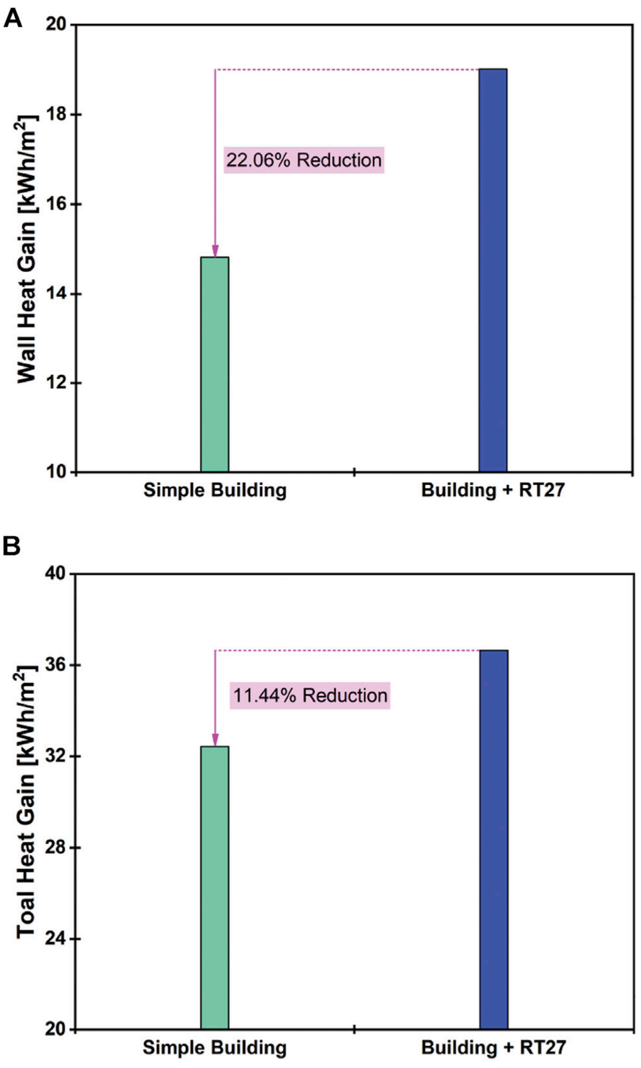

FIGURE 7 | PCM efficacy on building energy usage in two conditions. **(A)**: wall heat gain, **(B)**: total heat gain.

Although **Figure 6** proved that RT-27, as a thermal barrier, reduces the thermal energy, but the amount of thermal energy reduction is more important. In the previous section, it was mentioned that PCM does not affect the thermal energy caused by occupancy, lighting and equipment and only

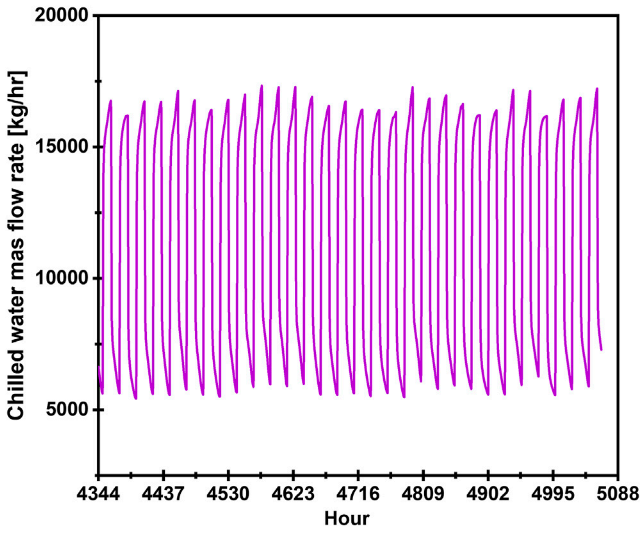

FIGURE 8 | Chilled water mass flow rate variations.

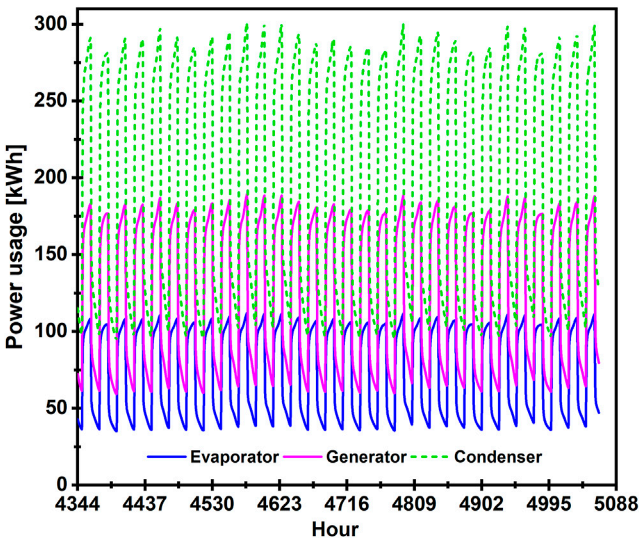

FIGURE 9 | The variations in power usage in evaporator, generator and condenser units.

changes HGTW. **Figure 7A** reports the effect of RT-27 on HGTW and it is clear that this parameter decreased by 22.06%.

If the total entering thermal energy to the building is examined, it can be seen that the amount of reduction is changed from 22.06 to 11.44%.

The incoming thermal energy rises the building temperature over time. An air conditioning unit must be used to regulate the temperature. In this study, as shown in **Figure 1**, the system of fan coil + absorption chiller is used to cool the building. Absorption chillers have low electrical power consumption and instead require a lot of thermal energy. In this study, chilled water is produced at 6.6°C. Chilled water enters the building through the fan coil and absorbs the room's thermal energy to cool it. The mass flow rate of the chilled water depends on the total amount of room thermal energy and obtained from $\dot{m}_{chilled} = \frac{total\ heat\ gian}{4.18 \times T}$. If a temperature difference of $T = 5.5$°C is considered, the chilled water flow rate in the evaporator will change as shown in **Figure 8**.

The power exchanged in the evaporator is determined by the total heat gain. Energy consumption in the absorber is also determined according to COP value. Neglecting the energy consumption in the pumps, the energy consumption in the condenser can be obtained. The changes in energy consumption are shown in **Figure 9**.

A cooling tower is needed to dissipate energy in the condenser. Of course, the wet-bulb ambient temperature should always be taken into account in the calculations to ensure the accuracy of the results. The cooling tower outlet water temperature should be greater than the ambient wet-bulb temperature. **Figure 10** shows that this criterion meets in this study.

Another important parameter is to check the actual power of the chiller, which is usually expressed in terms of refrigeration ton. By selecting a chiller with a nominal refrigeration ton of 40, the actual power of the chiller changes as shown in **Figure 11**. The parameter of "f" is a variable that indicates how the actual power of the chiller is changing relative to the nominal power. Given the appropriate range of f parameter, a 40 ton of refrigeration is acceptable.

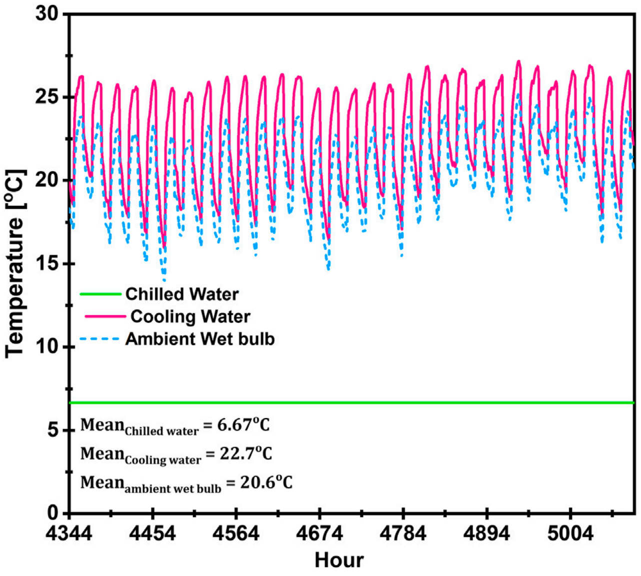

FIGURE 10 | The variations in cooling tower outlet water temperature and wet bulb temperature.

Effects of Nanofluid

Nanoparticles are materials that can improve the thermophysical properties if well dispersed in the fluid and provided they are stable (Esfahani et al., 2018; Keyvani et al., 2018; Asadi et al., 2019; Ranjbarzadeh et al., 2019; Li et al., 2020; Wei et al., 2020). Nanofluids have been studied in many studies (Jahangir et al., 2018; Mahdavi et al., 2019a; Mahdavi et al., 2019b; Giwa et al.,

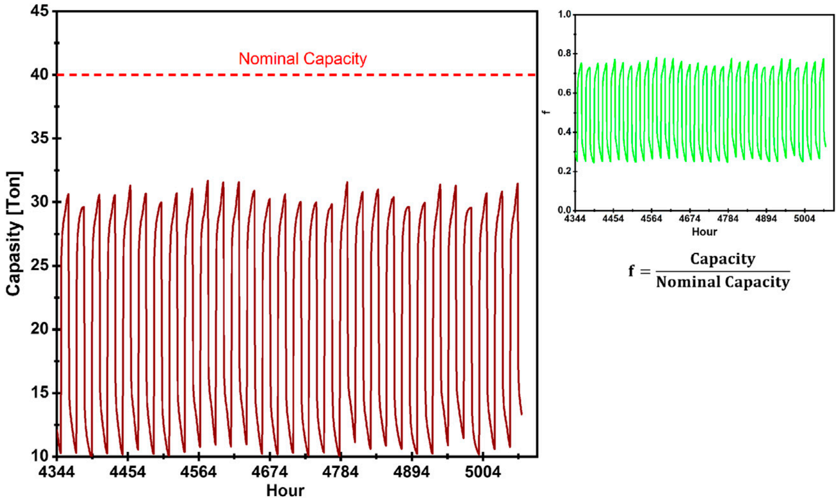

FIGURE 11 | The actual capacity and nominal capacity of the chiller.

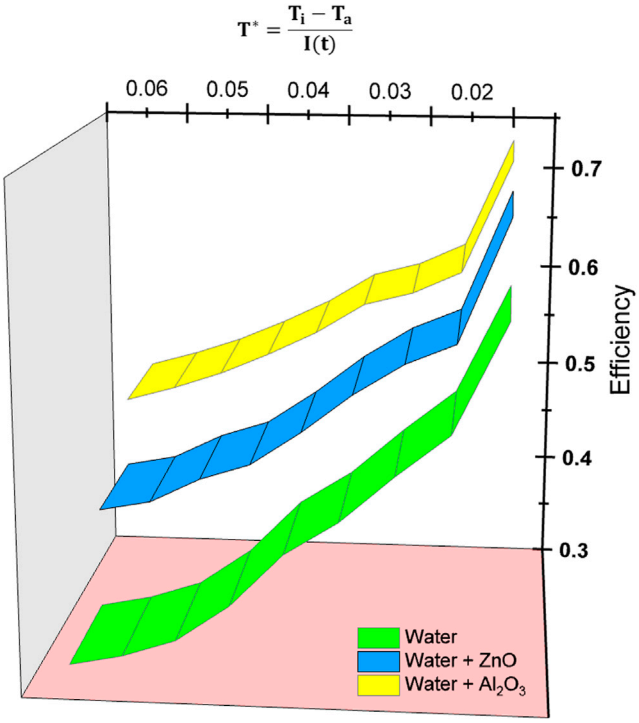

FIGURE 12 | The efficiency of the solar collector.

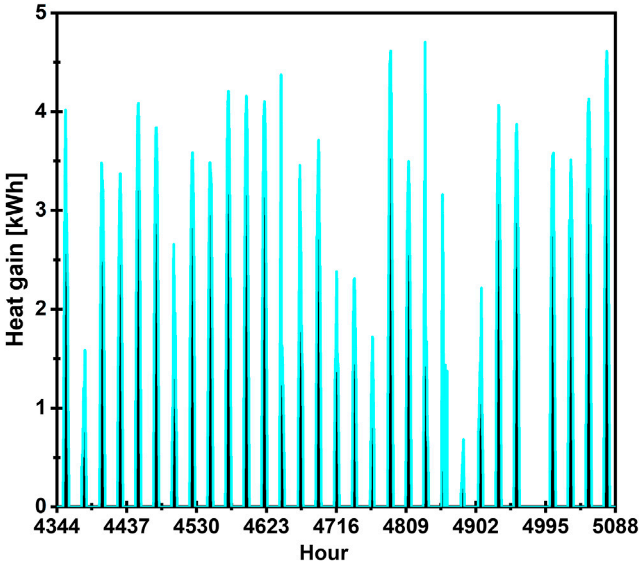

FIGURE 13 | Heat gain in the solar collector.

2020a; Giwa et al., 2020b; Tian et al., 2020b; Yan et al., 2020). In this section, the results of two nanoparticles of ZnO and Al_2O_3 were used to evaluate the effect of nanoparticles. In a study by Arıkan et al. (2018) it was shown that the efficiency increases in the presence of nanoparticles. In the presence of ZnO the efficiency increases but to a lesser extent than that of Al_2O_3. **Figure 12** shows that both nanoparticles can increase the rate of heat absorption by improving efficiency.

Using a solar system reduces energy consumption in the absorption chiller. Since the generator section requires a lot of thermal energy, a part of which can be provided by the solar system. **Figure 13** shows the amount of energy-saving by using the solar system over time. Note that in this case, the inside of the collector is filled with water. The oscillation of the amount of saving energy is attributed to the solar energy oscillation.

To examine the effect of ZnO/Al_2O_3 the amount of energy-saving must be evaluated in July. In **Figure 14**, the energy-saving for the three fluids are compared. In the first case, there is water inside the collector and calculations indicate that the energy-saving is equal to 428 kWh. By adding ZnO, this parameter is improved by 9.2%. According to **Figure 12**, higher efficiencies for

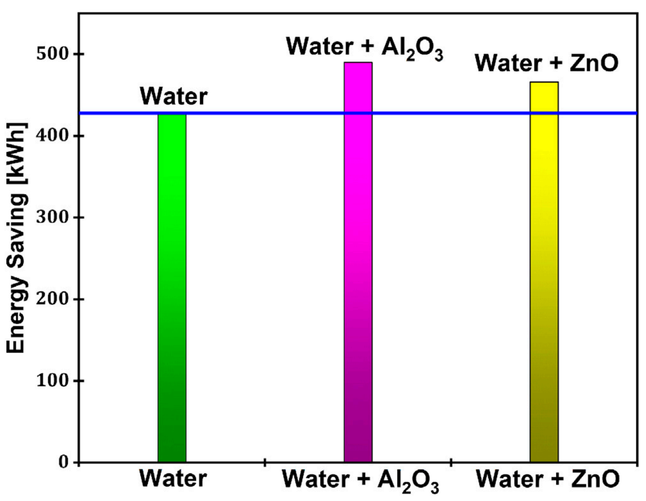

FIGURE 14 | Energy saving in the solar collector.

Al_2O_3 are expected to have a greater effect on saving energy. **Figure 14** confirms this claim, nanoparticles of Al_2O_3 improved energy-saving by 14.5%

CONCLUSION

In this study, the thermal behavior of a building impregnated with PCM was investigated. In July, with a temperature range of 25–40°C, PCM of RT-27 was added to the walls. An absorption chiller + fan coil system was utilized to cool the building. Nanofluid-filled collectors were used to provide thermal energy in the absorption chiller. The most important results were as follows:

- The PCM acted like a heat sink when installed in the wall and reduced the heat transfer through the walls by 22.06%. Taking into account the heat gains of occupancy, lighting and equipment, it was found that the total heat gain decreased by 11.44%.
- The combination of solar collector and absorption chiller reduced energy demand by 428 kWh.
- The energy-saving was affected by the addition of ZnO and Al_2O_3 nanoparticles. In the case of ZnO nanoparticles, the energy-saving was improved by 9.5%. For Al_2O_3 the energy-saving was amended by 14.5%.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AA, AM, JM, and GC wrote the manuscript. AA, AM, JM, and G.C. provided critical feedback and helped shape the research, analysis, and manuscript. All authors discussed the results and commented on the manuscript.

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