The impact of phase change materials assisted night purge ventilation on the indoor thermal conditions of office buildings in hot-arid climates

Ebrahim Solgi ^{a,*}, Behrouz Mohammad Kari ^b, Rima Fayaz ^c, Helia Taheri ^d

^a Department of Architecture, School of Environment, Griffith University, Australia

^b Building and Housing Research Center, Iran

^c Department of Architecture and Energy, Faculty of Architecture and Urbanism, University of Art, Iran

^d Department of Architecture and Energy, University of Tehran, Iran

*Corresponding Author: Tel: +61-55527529, e-mail: ebrahim.solgi@griffithuni.edu.au; solgi_e@yahoo.com

Abstract

Night purge ventilation is an effective technique for passive cooling, which is typically used in office buildings with the aim of reducing the daytime temperature, and thereby reducing the cooling load of HVAC systems. This method uses the cool of the night to release the warmth stored in the thermal mass during the day. That is, this system optimizes the energy storage properties of thermal masses to provide thermal comfort in interior spaces. The purpose of this study is to determine the impact of the use of night purge ventilation in conjunction with PCMs on the indoor thermal conditions of a typical office building located in hot-arid climates. In this article, the impacts of optimal night ventilation on the heat flushing operation, inside room temperature and element thermal conditions are all evaluated. It was found that combining PCMs with night ventilation will significantly improve indoor thermal conditions; however, results vary for different days in general and different structural elements in particular. Moreover, the application of PCMs can reduce night ventilation system problem of occupants feeling cold in the morning, whereas in the majority of work hours the temperature of inside element faces is approximately 0.5°C lower than the room temperature, both of which improve thermal comfort.

Keywords

Night ventilation, Phase change materials, Office buildings, Hot-arid climates, Indoor thermal conditions

1. Introduction

Night ventilation is one of the most successful methods of passive cooling in buildings, especially office buildings, where the absence of personnel at night allows the attainment of higher air change rates. Due to its ease of implementation and minimal impact on the architecture, this method has found extensive applications [1-6]. At night, the cool of the night air passing through the building reduces the temperature of the thermal mass, and during the day this cooled thermal mass absorbs the internal and external heat gains; however, this process requires adequate utilization of heat storage capacity combined with proper fitting of insulation [7]. Thus, when used properly in conjunction with night ventilation, the thermal mass of the building not only reduces the cooling energy consumption but also provides thermal comfort by pre-cooling the structure [8-12].

The performance of a night ventilation system largely depends on the capability of the building inertia to conserve the night coolness, the relative difference between indoor and outdoor temperatures at night, and the air flow rate during the night [13, 14]. Therefore, the low mass and high energy storage capacity of PCMs, which augment the thermal inertia of buildings, make them a desirable thermal mass for night ventilation applications [15, 16]. Moreover, the heat stored in PCMs is based on latent heat, which is the most efficient way for conserving thermal energy with higher storage density and smaller temperature changes [17, 18]. Applying PCMs integrated into building elements such as walls [19-21], floors [22, 23], ceilings [24], facades [25, 26] is very prevalent in night ventilation systems, as they do not require a designated separate space. Furthermore, merely the deployment of PCMs in buildings can reduce the energy consumption for maintaining comfort conditions and decreasing air temperature fluctuations, as well as shifting the heating and cooling load from high-peak to off-peak periods [27, 28].

The efficiency of natural night ventilation in the urban environment depends on local climate characteristics derived from the effect of urban morphology [29], meteorological conditions and other microclimatic variables such as environmental albedo or the urban heat island effect [30]. Urban heat reduces the efficiency of night ventilation techniques since it causes the reduction of urban air quality and brings about changes in the urban area microclimate [31]; however, there are some techniques such as the application of cool coatings to mitigate this effect [32, 33]. The results of experiments in the London heat island and the rural reference site have shown that the energy demand for cooling a rural reference office is 16% lower than that of a similar urban office, and augmented urban temperatures at night (the peak of urban heat island effect) should be considered properly because they led to considerable deviations from utilizing standard meteorological weather data [34]. Applying

appropriate climatic data is also imperative since the use of undistributed climatic conditions overestimates the cooling efficiency of night ventilation and reduces the accuracy of investigations concerning the thermal behavior of buildings [35]. Moreover, in the urban environment an accurate assessment of the effectiveness of natural night ventilation depends on considering both the solar shading effect and the wind shielding of surrounding buildings which have a counteracting impact on the night ventilation productivity [36].

Since vast expanses of Iran have hot-arid climates, an extensive amount of energy must be consumed to cool buildings. The extent of research into the application of passive cooling techniques in these regions, however, has been scanty. In addition, owing to the growth in the number of high-rise buildings, the need for lightweight construction is increasing; thus, the use of PCMs with night ventilation can be a profitable method for these areas. While much research has been carried out on PCMs or night ventilation in this climate, few have focused on the simultaneous utilization of PCMs and night ventilation systems on the indoor thermal condition and structural elements in detail. This paper attempts to provide a more detailed investigation concerning the effects of incorporating night ventilation with PCMs on the temperature and stored/released energy for different structural elements, as well as the rooms individually.

2. Methodology

This study has been carried out with EnergyPlus software version 8.3, which enables users to simulate the parameters of night ventilation and PCMs. Thus, the “Conduction Finite Difference (CFD)” algorithm option of the software was utilized to simulate the impact of PCMs. The simulated model is a simple office space located in the city of Yazd, Iran, and is derived from an experimental model which studied the effect of PCMs on the energy consumption of buildings located in the hot-arid climate of Phoenix, Arizona [37]. The reasons behind selecting this model for simulation are the similarity between the climatic conditions of these two cities, as well as the similarity of the thermal mass used for energy storage application. The room studied in this paper has dimensions of $4.876 \times 3.675 \times 2.436$ m and a pitched roof with a slope of 4.12 degrees. The eastern wall of the model is supplied with a 0.762×0.4876 m window and a 1.98×0.762 m wooden door. Table 1 provides a full description of the structure of the envelope used in the experimental model and the order and arrangement of the building materials.

Table 1 [38]

Specifications of the building elements

	d (m)	(W/mK) λ	(kg/m ³) ρ	c (J/kg K)
<i>WALL</i>				
Plaster ext	0.013	0.1	500	1880
Composite wood stud & fiberglass	0.083	0.0445	119.63	1048
PCM	0.002	0.2	860	1620
Gypsum board	0.013	0.16	640	1150
<i>FLOOR</i>				
Concrete Floor	0.051	0.1	500	1880
PCM	0.010	0.2	860	1620
Flooring	0.051	0.1	500	1880
<i>CEILING</i>				
Plaster ext	0.013	0.1	500	1880
Composite wood stud & fiberglass	0.133	0.047	93.84	1006
PCM	0.010	0.2	860	1620
Gypsum board	0.013	0.16	640	1150
<i>FLOOR ATTIC</i>				
Gypsum board	0.013	0.16	640	1150
PCM	0.010	0.2	860	1620
Composite wood stud & fiberglass	0.133	0.047	93.84	1006
Plaster ext	0.013	0.1	500	1880
<i>ROOF</i>				
fiber glass desert tan shingles	0.013	0.15	600	1000
roofing felt	0.013	1.2	2250	1260
1/2 OSB roof sheathing	0.013	0.15	600	1000

OSB: Oriented Strand Board

PCM: phase change material

ext: exterior

A comparison between the simulation results and those reported by this experimental model shows that these results differ by less than 2%, and their correlation coefficient is roughly 0.93, which reinforces the validity of the conclusions hereinafter. Information concerning the experimental model and its validating process can be seen in [38]. The model studied in this paper is an office building with work hours of (8:00 - 18:00) oriented along a north-south direction in such a way that the glazing faces the south. This model is simulated for the city of Yazd, which has a hot and arid climate, and where low humidity brings about significant diurnal temperature fluctuations [39]. In this simulation, the comfort temperature is defined to be in the range 21 °C and 28 °C as stated by No.19 of the National Building Code of Iran [40]. The PCM used for the simulation is a paraffin/organic mixture with an optimal thickness of 1 cm [41]. To date, studies conducted on using this kind of PCM assisted night ventilation in office buildings in Yazd have reported the following results [38]:

- The most suitable fan thermostat temperature for the initiation of night ventilation is 30 °C.
- The PCM with a melting point of 27 °C is the optimal thermal mass for the described condition.
- The most desirable air change rate is 15 ACH.

Items mentioned above are the main parameters of night ventilation and applying these items to this model could reduce the annual cooling load around 47%, as a result improving the urban climatic conditions. Additionally, based on a full round analysis in the warm months, it is concluded that the priority of utilizing PCMs differs for different interior building elements so that the use of the PCM in the floor could increase the cooling load, while the deployment of PCMs on other building elements decreases the cooling load, thereby increasing the performance of night ventilation systems [38]. Hereafter to consider extreme conditions precisely, these parameters will be used as an optimal condition on July 22nd and September 3rd, namely the days during which Yazd experiences the highest daytime temperature and the lowest night-time temperature in the warm months of the year, respectively [41].

3. Duration of night ventilation

The commencement of night ventilation depends entirely on the outside temperature, i.e. it begins whenever the outside temperature drops to below 30 °C and will continue until 7:00. Fig. 1 shows the room temperature on July 22nd and September 3rd. It shows that on September 3rd, the daytime temperature is relatively low and consequently, night ventilation begins at 19:00. However, the very high daytime temperature of July 22nd delays the commencement of night ventilation until 20:57. The lower temperature on September 3rd causes its temperature reduction gradient to be steeper than on July 22nd, so that after night ventilation, the indoor air temperature for both days decreases by 8.4°C and 3.77 °C, respectively. In both figures, the duration of night ventilation is shown with dashed lines.

Fig. 1. Duration of night ventilation on a) September 3rd, b) July 22nd

4. The impact of night ventilation on the room temperature

In order to investigate the impact of night ventilation on the room temperature on both July 22nd and September 3rd, the indoor temperatures presented during the night (for different ventilation conditions) and during the day (without any air conditioners) are plotted. In these figures, the dashed lines signify the start and end of work hours (08:00 - 18:00).

4.1. September 3rd

Fig. 2. The effect of night ventilation on the room temperature on September 3rd

1 Fig. 2 demonstrates the temperature plot pertaining to the date September 3rd. As can be seen,
 2 in the scenario labeled simple (no night ventilation and no PCMs) the room temperature
 3 depends solely on the outside temperature. The use of PCMs without night ventilation (0
 4 ACH) reduces the mentioned dependence, as well as the average and peak room temperature,
 5 but has not made any use of cool night air. The graph also shows that applying night
 6 ventilation together with PCMs, owing to the use of cool night air to flush the heat stored in
 7 the thermal mass, contributes to a further reduction in average and peak room temperature
 8 during the day. In addition, increasing the air change rate leads to a further decrease in the
 9 temperature, especially in the early hours of the morning. Night ventilation with 15 ACH, for
 10 instance, keeps the work hours temperature below 26.79 °C (maximum temperature recorded
 11 at 15:09), and since the basic defined threshold for comfort temperature is 28 °C, this result
 12 indicates that the need for air conditioning in this scenario is eliminated during that day. The
 13 day September 3rd has the minimum diurnal temperature in the warm months, therefore
 14 naturally the room temperature during the day and at the onset of night ventilation (which
 15 starts when the outside temperature drops below 30 °C) will be lower than the rest of the hot
 16 days of the year. As Fig. 2 shows, there is a sudden jump at point A, which coincides with the
 17 outside temperature dropping below 30 °C (at 19:03) and the beginning of the ventilation
 18 process. This is because as night ventilation starts, it pushes warmer air (30 °C) into the
 19 room, which at that point has a lower temperature (27.35 °C for 15 ACH). However, this
 20 counterproductive process only lasts about 30 minutes, since at that time, the outside
 21 temperature tends to decline with a sharp gradient.

Fig. 3. The effect of ACH rate on the average indoor temperature and percentage of temperature reduction on September 3rd

The average temperature during the work hours of September 3rd in different scenarios is shown in Fig. 3. As is illustrated, the average room temperature during work hours obtained for various air change rates, 0 to 25 ACH, exhibits a 2.8% - 10.3% improvement as compared to the simple scenario. At the aforementioned optimal air change rate (15 ACH), this improvement is about 9%. This graph also shows that the room temperature improves at a phenomenal speed when the air change rate increases from 0 to 15 ACH, but this speed decreases for air change rates of above 15 ACH, pointing out the optimality of this rate.

Fig. 4. The effect of night ventilation with PCMs on the room peak temperature on September 3rd

Reducing and delaying the peak temperature are the most important features of night ventilation, which are studied along with the deployment of PCMs here. As shown in Fig. 4, on this day, the maximum exterior temperature, which occurs at 15:00, is 32.70 °C. The use of PCM without night ventilation results in a 5.06 °C reduction in peak temperature, decreasing it to 27.64 °C, which is below the threshold defined for the maximum comfort temperature (28°C); thus eliminating the need for air conditioning during that day. It should also be mentioned that in this scenario, room temperature reaches its peak value 78 minutes sooner than in the first scenario. Meanwhile, the simultaneous use of the PCM together with night ventilation (operating at 15 ACH) reduces the peak temperature by 4.38 °C, and, more importantly, delays it by 249 minutes, moving it past the end of work hours. Providing that work hours are considered, it decreases by 5.92 °C at 15:09, reducing to 26.79 °C, which again is lower than the threshold defined for the maximum comfort temperature.

1 4.2. July 22nd

Fig. 5. The effect of night ventilation on the room temperature on July 22nd

2 Fig. 5 shows the temperature plot pertaining to the date July 22nd. As is depicted, the
 3 behavior of this graph is approximately identical to that plotted for September 3rd, except that
 4 here, the high night time temperature fully eliminates the jump observed in the previous
 5 graph.

6 In addition, in comparison to the simple scenario, the average room temperature during work
 7 hours decided upon for various ACH rates, 0 to 25 declines between 1.3% and 7.8%, see Fig.
 8 6. As can be seen, due to the higher diurnal temperature, the temperature improvement
 9 achieved here is less than what was accomplished for September 3rd.

Fig. 6. The effect of ACH rate on the average indoor temperature and percentage of temperature reduction on July 22nd

According to Fig.7, on this day, the maximum exterior temperature, which occurs at 16:00, is 37.20 °C. The application of PCMs without night ventilation results in a 3.88 °C reduction in the peak temperature, also delaying it by 114 minutes. Meanwhile, the simultaneous use of PCMs and night ventilation (operating at 15 ACH) reduces the peak temperature by 6.54 °C and delays it by 189 minutes, again moving it past the end of work hours. As a consequence, in such days with high diurnal temperature, night ventilation can diminish the peak temperature and shift it to the end of work hours, therefore decreasing the use of HVAC systems; however, this system cannot thoroughly replace conventional air conditioning systems.

Fig. 7. The effect of night ventilation on the room peak temperature on July 22nd

5. The energy released during the night

To assess the relationship between the night ventilation start time and the consequent reduction in the cooling load, the total amount of heat flushed out during the night is evaluated. The hourly change in the amount of heat flushed through night ventilation during July 22nd and September 3rd is shown in Fig. 8. This figure reveals that the amount of heat flushed out of the room is directly proportional to the air change rate and is inversely related to the outside temperature. On July 22nd, the start and end of the heat flushing process both match the start and end of night ventilation at 20:57 and 07:00 ; see Fig. 1b, but on September 3rd, heat flushing, which should start at 19:00; see Fig. 1a, has 78 minutes delay, thereby starting at 20:18. The reason behind this delay is the relatively lower temperature of the room until 20:18; however, after that point, ventilation and heat flushing proceed as normal. The amount of heat flushing in the optimal conditions (15 ACH) on September 3rd is 1.36 times that of July 22nd because the former experiences a lower outside temperature.

Fig. 8. The amount of heat loss energy in different air change rates during the night on a) September 3rd, b) July 22nd

Details of heat gain storage and heat loss for each element in optimal conditions are indicated in Fig. 9. It shows that on 3rd September owing to low outdoor air temperature, all of the stored heat is released; whereas, on the other day, around 86% of the heat stored in the elements is released. On this day, for the north, south, east and west walls, respectively, 76%, 84%, 91% and 93% of heat stored is flushed out. It is significant to note that due to the changing outdoor conditions, the amount of heat storage for different elements varies on different days; nevertheless, the west and north walls store the highest and lowest amount of the heat stored, respectively.

Fig. 9. Amount of heat storage gain and loss rate on a) September 3rd, b) July 22nd

6. The impact of night ventilation on the temperature of inner surfaces

In order to investigate the impact of incorporation of PCMs in night ventilation on the temperature of inner surfaces, the temperature of the southern and northern walls during these days is compared with the zone mean air temperature. The results of this comparison are shown in Fig. 10. As this figure shows, on both days, the night ventilation keeps the room temperature lower than the wall surface temperature until 07:00, when this ventilation ceases. Thereafter, for instance the southern wall, on September 3rd the room temperature begins to rise, surpasses the wall temperature at approximately 8:50, and remains higher until around 20:40, see Fig. 10 a; however, on July 22nd the room temperature surpasses the wall temperature at around 9:30, and remains higher until around 21:40, see Fig. 10 b. On average, the temperature of the inner surface of the northern wall during the work hours of September 3rd and July 22nd, accounts for 0.57 °C and 0.49 °C, respectively lower than the room air temperature, and for the southern wall on both days it amounts to 0.48 °C. In other words, apart from the day or element, during the significant part of work hours, the inside element faces are cooler than the room temperature. As a result, heat radiation is toward the surfaces and this will have a positive impact on comfort conditions. However, in the early morning, on average before around 9:00, the surface temperature is more than room temperature; interestingly it can prevent the coldness felt during the early morning, which is one of the noticeable problems of night ventilation systems.

Fig. 10. Comparison of surface inside face temperature of the southern and northern walls with zone air temperature on a) September 3rd, b) July 22nd

7. The thermal profile of the walls

To evaluate the thermal performance of the modeled wall shown in Fig. 11, all the walls in the optimal night ventilation condition at three time instances of 08:00, 16:00, and 00:00 on September 3rd, are assessed. These walls exhibit generally analogous thermal behavior during July 22nd, with the only exception being that the higher temperature of July causes the inside and outside temperature to be naturally higher. It should be noted that air conditioners are assumed to not be used during the day.

As Fig. 12a shows, at 08:00 the external surface of the eastern wall is exposed to sunlight; hence the temperature difference between the internal and external surfaces is 28.74 °C. However, on the southern wall, which at this time is partly exposed to sunlight, this temperature difference reaches 7.98 °C. Meanwhile, due to only the natural change in outdoor temperature on the western and northern walls, the temperature difference accounts for approximately 3.3 °C.

Fig. 11. Cross-section of walls

Fig. 12. The thermal profile of the walls at a) 8:00, b) 16:00, c) 00:00

At 16:00, the western wall is fully exposed to sunlight and the outside temperature is near its peak, so its external surface exhibits a sharply increased temperature, resulting in an internal-external temperature difference of 33.7 °C. Meanwhile, the eastern and northern walls which have been in shadow, despite the significantly higher temperature of this hour (as compared to 8:00), exhibit a much lower temperature difference, i.e., approximately 13 °C; see Fig. 12b.

According to the results obtained for 08:00 and 16:00, during this time the outdoor ambient temperature increases by 14.21 °C, but the average inside face temperature and room temperature rise by 4.07 °C and 7.68 °C, respectively, which indicates the importance of the insulation and cooled PCMs in maintaining the indoor air conditions.

At 00:00, owing to lack of radiation during the night, the heat transfer of all the walls is approximately the same. At this time, the temperature of the outside air is relatively lower than that of the internal surfaces, which are kept warm by the daytime heat stored in the PCMs, and this phenomenon leads to a reversed heat transfer trend. At this hour, the

1 difference between the internal and external wall surface temperatures is roughly 6.4 °C.
2 However, as illustrated in [Fig. 12c](#), the temperature of the PCM is higher than other layers,
3 even the interior surfaces, as a consequence of discharging and solidification. The heat
4 flushing process also continues as planned (until 07:00) to cool the room, as well as cool the
5 PCMs.

6 **8. Conclusion**

7 This study set out to determine the effect of PCMs used in conjunction with night ventilation
8 on the indoor thermal conditions of office buildings for the highest daytime and the lowest
9 night-time temperatures in the warm months of the hot-arid climate of Yazd. This research
10 has shown that this combination has a large impact on improving room temperature
11 conditions, i.e. combining PCMs with night ventilation not only reduces the average room
12 temperature considerably but also reduces the peak temperature and shifts it away from the
13 hours of peak electricity demand. This combination can also decrease the cooling load of air
14 conditioners on the hottest days, or even completely eliminate the need for air conditioners on
15 moderate days. Studying the amount of heat released through night ventilation showed that
16 this parameter rises with an increase in air change rate or a decrease in outside temperature.
17 On hot days, this operation would not be fully completed and also the amount of heat
18 flushing or storing differs for different wall directions; nonetheless, the west and north walls
19 store the highest and lowest amount of the heat stored, respectively. Subsequently, the
20 influence of night ventilation on the inner surface temperature of the walls demonstrated that
21 in most occupancy hours the wall surface temperature is approximately 0.5°C lower than the
22 room temperature; thereby leading to improvement of the thermal comfort conditions.
23 Moreover, the presence of insulation, as well as cooled PCMs between the wall layers have a
24 significant impact on reducing the penetration of the outside heat and stabilizing the daytime
25 room temperature.

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