

RESEARCH ARTICLE

Investigation of phase-change materials for interior temperature regulation in public transport

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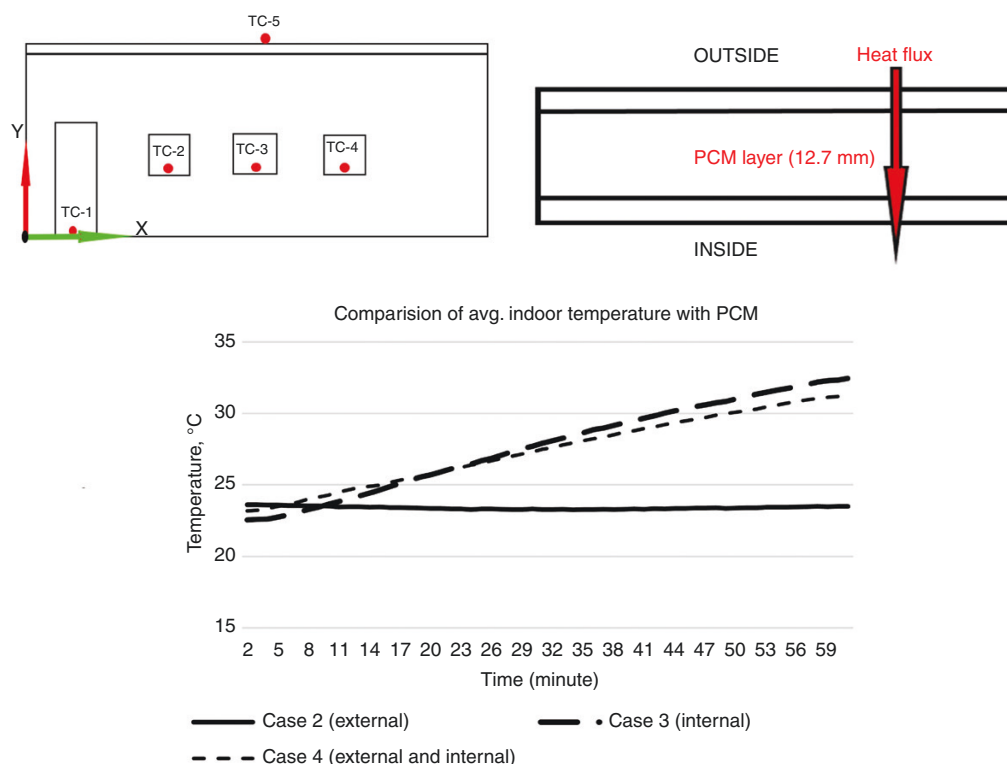
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Abstract

Regulating the indoor temperature of public transport on hot sunny days is a prime concern, as both the external and internal heat sources play an active role in heat gain. Experimental studies have been carried out on a bus model using sodium sulphate decahydrate as a phase-change material (PCM) that is placed in between the ceiling and the roof. Studies are conducted on a sunny day and also for different cases of external (300-W surface heater) and internal (25-W light bulb) heat sources. The results show that PCM, in the presence of an external heat source, can help to keep the indoor temperature lower and delay the time period for increasing the temperature by absorbing heat during the phase change. On the other hand, the presence of the internal heat source contributes to a detrimental effect on the indoor temperature, which gradually increases with the elapse of time. With the combination of the external and internal heat sources, it is found that the internal heat source plays a dominating factor to raise the indoor temperature. It is revealed from the experimental results that a 12.7-mm single layer and a single PCM are not enough to counter the internal heat of 25 W unless the thickness of the PCM layer is increased to delay the increase in the indoor temperature. An additional PCM layer with a lower melting temperature could be placed at the inner portion of the ceiling to have effective thermal-energy storage by absorbing the substantial heat gain from the internal heat sources.

Graphical Abstract



Keywords: latent heat; sodium sulphate decahydrate; phase-change material; transportation; thermal-energy storage

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Introduction

As the time that people spend in public transport such as buses has increased significantly, the thermal comfort of humans in public buses is becoming an important issue. Thermal comfort of the human body is a psychological state that expresses satisfaction with the surrounding environment [1]. The four physical environmental variables that influence human thermal comfort are air temperature, relative humidity, mean radiant temperature and relative air velocity. Also, the active level provided by the metabolism and the thermal-insulation value provided by clothing are two independent but related parameters that affect human thermal comfort. Among all of these, the air temperature is the most important environmental variable for human thermal comfort in vehicles. The thermal environment of the vehicle is sensitive to weather conditions; therefore, thermal discomfort is often evident in the interior of the vehicle. When passengers get on board in the summer, they may feel uncomfortable due to the higher temperature inside the vehicle rather than the ambient temperature. Experimental measurements in Fremont, California have concluded that an enclosed car can have a temperature rise of 22–27°C in 1 hour [2]. Furthermore, when a vehicle is parked in the sun, the temperature inside the passenger compartment can be >20°C higher than the ambient temperature [3]. From the numerical study, it was found that under summer conditions for a car parked in the sun, the inside air temperature and the temperature of materials can reach almost 100°C. Therefore, a large amount of air-conditioning power is essential to cool the automobile to a comfortable temperature value [4]. Obviously, this increases fuel consumption and, as a result, increases carbon-dioxide emissions. The USA alone consumes ~26 billion litres of fuel annually to cool vehicle interiors [5]. Therefore, a number of researchers and industries are giving emphasis to the design of the interior environment of vehicles.

Heat stroke is another problem caused by the residual heat experienced inside a vehicle. This mainly happens to young children and pets, leading to serious injury and even death. In fact, the temperature inside a car can reach deadly levels even on cloudy days when the ambient air temperature is low [2, 6]. In addition, pleasant vehicle climate control not only reduces a driver's stress, but also prevents fogging, ensures better visibility and contributes to a safer driving experience. Additionally, current demands for better vehicle energy utilization and more efficient performance attract researchers to analyse the design and system requirements for a better interior environment of a vehicle.

In addition to phase-change material (PCM), the use of thermal-energy storage is a possible solution to reduce the increase in air temperature inside a vehicle because it can keep the material within a limited temperature range by absorbing heat [7, 8]. Basically, PCM has been used as latent heat storage in the food, pharmaceutical and clothing industries. In addition, researchers have shown the effectiveness of PCM in reducing heat transfer through building walls [9–11]. It is also reported that by including PCM together with various building materials (gypsum, wood, straw) in the air cavity in the wall of a building, the indoor ambient temperature of direct solar heat gain can be reduced [12]. Placing a PCM layer near to the source of heat resists heat flow in the building, has a lower heat gain and also reduces temperature fluctuation in the room compared to other building materials [13]. In addition, the composite PCM can be a good choice as it has a wide range of melting points and can be used as building materials [14]. The heat source/heat sink orientation and cavity geometry have a significant influence on PCM melting and there-

fore the heat source with PCM at the desired melting point along with proper insulation can be useful in dissipating heat from electronic devices or other appliances [15].

Several researchers have studied the addition of PCM in different places in vehicles. An experimental investigation reported on the cold-storage characteristics and the heat-transfer regularity of liquefied natural gas (LNG)-refrigerated vehicles in order to provide design references for a cryogenic-energy-storage unit. Implementation of wave-like internal fins was able to enhance the heat transfer in both the radial and axial directions. It was reported that, with the proposed design aspects, PCM could be helpful for cold-energy recovery in LNG-refrigerated vehicles [16]. On the other hand, PCM can be used in automobiles for increasing fuel performance and removing cold-start problems in extreme climates [17–20]. It is also reported that various uses of PCM in automobiles such as thermal buffering in vehicles, thermal buffering of the cabin for passenger cooling, etc. all will improve passenger comfort along with reducing the amount of energy used [21].

PCM is also used to modify existing insulation methods for refrigerated trucks [22], specifically the use of paraffin-based PCM as a heat-transfer-reducing technology in conventional trailer walls. Moreover, it was found that adding PCM to the insulating foam of the trailer wall reduced the maximum heat transfer by an average of 29.1% and the total heat transfer by an average of 16.3%. It was found from another study that PCM-based container technology was able to stabilize the internal temperature and maintain internal temperature uniformity for up to 94.6 hours under a large change in the external ambient temperature between 13°C and 35°C. The results also demonstrated that the energy consumption, the operational cost and the emission were reduced by 86.7%, 91.6% and 78.5%, respectively [23]. Study of the indoor thermal conditions of a car parked in the sun revealed that by the addition of PCM, the surface temperature of the steering wheel was significantly reduced (from 5°C to 10°C) and the thermal comfort of the passengers could be increased [24]. In another study, a very thin layer of PCM with a melting point of 32°C was placed in the ceiling of a vehicle and showed that it was possible to maintain comfortable conditions in the cabin when 755 g of PCM was used. However, the calculations were based on the available data of the temperature rise inside a car [25].

However, selecting a PCM within the desired melting point is very important to maintain comfortable conditions in the cabin, as the indoor conditions will be benefited in two ways. First, the temperature will become more uniform and, second, the maximum temperature will drop, which eliminates the thermal discomfort of high temperatures. Relying on the purpose of the application, the melting temperature of PCM is likely to vary and, depending on the thermal properties of the PCM applicable for transport, the melting temperature ranges from 19°C to 29°C for organic PCM and 25°C to 35°C for inorganic PCM [25, 26]. There are many paraffinic and non-paraffin organic PCMs whose melting points are within the desired range, but there are some problems with specific PCMs used in certain applications. One is inflammability and the other is the special housing design required to use them, which requires additional production costs. On the other hand, inorganic compounds are non-flammable, have high latent heat per unit volume, have high thermal conductivity and are cheaper than organic compounds [27]. However, sodium sulphate decahydrate has excellent performance with high thermal-storage capacity and may be utilized as a PCM for thermal-storage systems [28]. The melting point of sodium sulphate decahydrate is 32.4°C. Although it has a low melting point, it has a reasonably high heat of fusion (251.6 kJ/kg),

which is a distinct benefit [29]. In addition, salt hydrates typically have a higher heat-storage density than paraffin, so salt hydrates can be used at temperatures of $>20^{\circ}\text{C}$. Additionally, salt hydrates are more cost-effective than organic products and, among them, sodium sulphate decahydrate is the most cost-effective [30, 31]. Sodium sulphate decahydrate was also used as a PCM for Trombe walls in building constructions to maintain thermal comfort by storing the heat energy [32]. In a recent study, it was found that the temperature fluctuation inside a building can be reduced by using PCM and the maximum average temperature could be lowered by 3°C by using a PCM layer inside building walls [33]. Concentrating on their work, this experiment has been extended to transportation and the thermal effect of sodium sulphate decahydrate as a PCM was studied in a bus model.

Therefore, the purpose of this paper is to use sodium sulphate decahydrate as a PCM to investigate the temperature distribution inside a bus model and reduce the peak temperature. Here, the research focused on the actual operating conditions. To carry out the experiment, a bus model with a dimension of $0.3048 \times 0.1524 \times 0.1524 \text{ m}$ ($12 \times 6 \times 6$ inches) was developed using mild steel and was placed in the sun to measure the temperature distribution with and without the PCM. In addition, the experiments are extended with external and internal heat sources and their combinations.

1 Experimental study

In order to investigate the influence of PCM in public transport, a bus model was considered to obtain the temperature distribution at different locations of the model for different conditions.

1.1 Experimental set-up

A bus model with a layer of PCM in the ceiling was designed for the purpose of studying the effect of PCM on the heat-transfer rate. The bus model was made of mild steel and the design of the model along with the different views and dimensions are illustrated in Fig. 1.

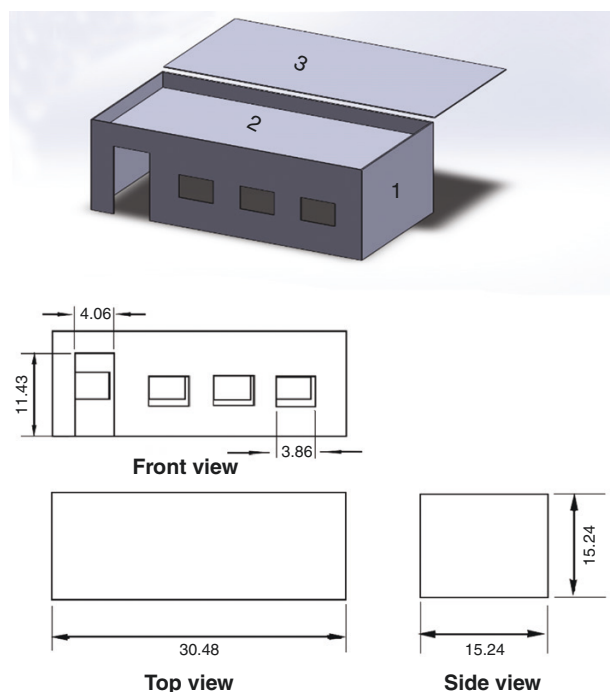


Fig. 1: Design and the different views (all dimensions are in centimetres) of the bus model.

Here, section 1 is the main frame, section 2 is the ceiling and section 3 is the roof of the bus model. In this constructed model of a bus, the ceiling (section 2) is fixed with the bus body (section 1) and the roof surface (section 3) is removable so that, after placing the PCM on the ceiling, it can be covered with a roof surface. As the ceiling is fixed to the bus body, there would be no leakage if the PCM is melted. Therefore, the PCM was placed in between sections 2 and 3 in order to study the effect of the PCM on the heat-transfer rate inside the bus. The bus body was designed having dimensions of $0.3048 \times 0.1524 \times 0.1524 \text{ m}$, which was 20× scaled down from a real mini bus in Bangladesh. The thickness of the mild-steel sheet that was used to build the model of the bus was 1.5 mm.

In Fig. 2a, the cross-sectional view of the ceiling and roof surface with the PCM layer is shown. The space between sections 2 and 3 is 0.5 inches (12.7 mm) where the PCM is placed. Here, heat flows from outside to inside when an external heat source is present, but when any internal heat source is present, the heat flux will flow in the reverse direction, provided no external heat source is considered. Here, during the experiments, a total of five thermocouples was used at different locations in the bus model (Fig. 2b). The positions of the thermocouples in the bus model are clearly detailed in Table 1. It should be mentioned here that three thermocouples were placed in the middle of the bus compartment to have a better prediction of the indoor temperature under different experimental conditions.

As the experiment has been performed in several cases with different external and internal heat-source placements, some changes have been made to the set-up depending on cases. In one case, solar heat was used as an external heat source; in another case, a surface heater was used as an external heat source. Also, in some cases, a light bulb (25 W) was used as an internal heat source. In Fig. 3, some actual experimental set-ups of the studies are shown.

1.2 Thermophysical properties of the PCM

In this experiment, sodium sulphate decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) is utilized as the PCM. Glauber's salt, commonly known as sodium sulphate decahydrate, is a salt hydrate. Sodium sulphate decahydrate is an inorganic PCM, according to PCM classifications, and its properties are shown in Table 2.

1.3 Experimental procedure

In this experiment, the situation was considered for a stationary bus especially when it is stuck in a traffic jam as, here in Dhaka city, when buses become immobilized due to traffic jams, most of them keep their windows and doors open. So, to replicate the original scenario, the door and windows were opened during the experiment. Then, the inside temperatures and roof-surface temperature of the bus model without using the PCM were measured on 2 November 2019. After that, the inside temperatures and roof-surface temperature of the bus model with the PCM on the ceiling were measured on 13 November 2019, as the weather conditions were almost the same as those on 2 November [34]. The temperature readings were taken from 7 AM to 6 PM for those particular days. During the daytime, the atmospheric temperature reached higher than that of the night-time due to the presence of solar heat; therefore, thermal comfort should be ensured for passengers during the daytime. That is why the thermal conditions of the bus model were measured during this time period (7 AM to 6 PM).

In the last week of November and in the month of December, the weather conditions were not appropriate for performing the

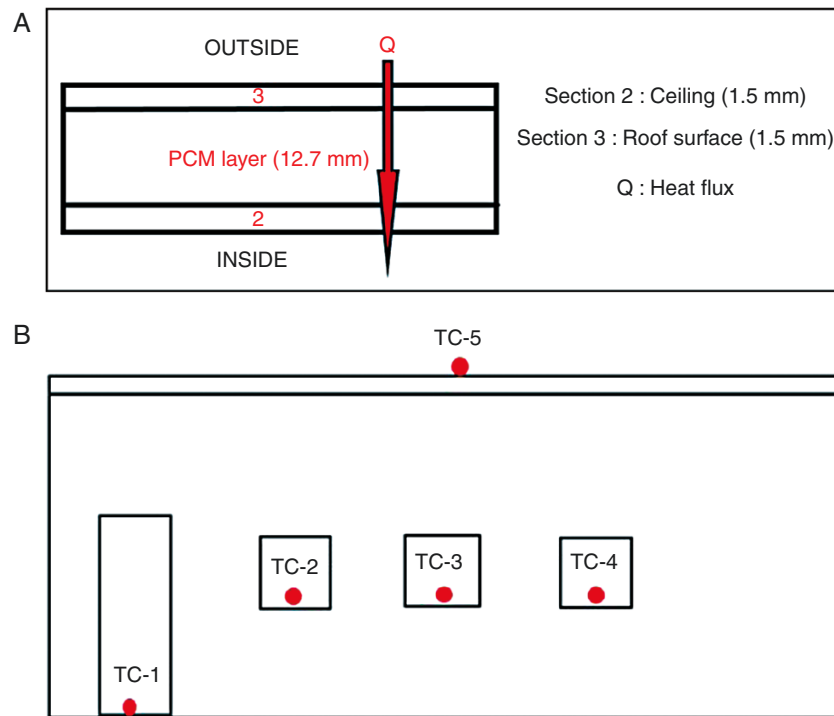


Fig. 2: (a) Cross-sectional view of the ceiling and roof surface with the PCM layer and (b) positions of the thermocouples (front view).

Table 1: Position of thermocouples in the experimental set-up

Thermocouples	Position
Thermocouple TC-1	Floor temperature
Thermocouple TC-2	Indoor temperature from first window
Thermocouple TC-3	Indoor temperature from second window
Thermocouple TC-4	Indoor temperature from third window
Thermocouple TC-5	Roof-surface temperature (outside)

experiment in outdoor conditions, as the temperature did not rise enough to melt the PCM. That is why a surface heater was used with a temperature controller on the roof surface on the bus model to attain sufficiently real conditions. Then, the inside and roof-surface temperatures were measured using thermocouples without using the PCM and with placing the PCM on the ceiling. After that, a case was considered in which the thermal conditions of the bus model were measured using an internal heat source (25-W bulb) without the PCM and with the PCM on the ceiling. Later, another case was considered in which both internal (25-W bulb) and external heat sources (surface heater) were used at the same time. By using two heat sources, the thermal conditions of the bus model were also measured without the PCM and with the PCM.

1.4 Data-acquisition system and calibration of thermocouples

A modern data-acquisition system has been developed to record the data without any interruption. An Arduino Uno, a DS3231 real-time clock and a 2000-mAh power bank for power supply have been used to develop the data-acquisition system. To measure the temperature of the experimental set-up in different positions for different cases, a total of five DS18B20 waterproof temperature sensors were used. The accuracy of these thermocouples (sensors) was $\pm 0.5^{\circ}\text{C}$ for a temperature range of -10°C to 85°C . In this study, a surface heater was also used as an external

heat source. The specifications of the heater and the thermocouples are given in Table 3.

Based on the experimental conditions, the temperature could vary within a wide range during the experiments; therefore, it was essential to calibrate the thermocouples. Also, the uncertainty and the repeatability of the data from the sensors were needed to be ensured. So, all the temperature sensors (i.e. five thermocouples) were calibrated to get more accurate data. The calibration of the sensor was carried out based on the melting and boiling points of water measured by the sensor. The detailed procedure of the calibration and repeatability of the thermocouples is considered from the literature [33]. Fig. 4 shows the calibrated data of Thermocouple 1 where TC-1 is the thermocouple reading and TC-1' is the original temperature.

Likewise, all other thermocouples were calibrated for proper values and repeatability before being used in the experimental set-up.

2 Results and discussions

In total, four different cases were considered in this experiment. In Case 1, the thermal conditions of a bus model were measured with and without the PCM in the presence of solar heat. In Case 2, the thermal conditions of the bus model were measured with and without the PCM using an external heat source (surface heater). To resemble the internal heat source in a bus, which is usually gained by the metabolic heat from the human body (i.e. passengers), engine heat, the heating, ventilation and air-conditioning system and also different electronic devices, a 25-W bulb was placed inside the bus model as an internal heat source. Therefore, in Case 3, the thermal conditions of the bus model were measured with and without the PCM by using an internal heat source (25-W bulb). In Case 4, the thermal conditions of the bus model were measured with and without the PCM in the presence of both an internal (25-W bulb) and an external (surface heater) heat source. All the cases are listed in Table 4.

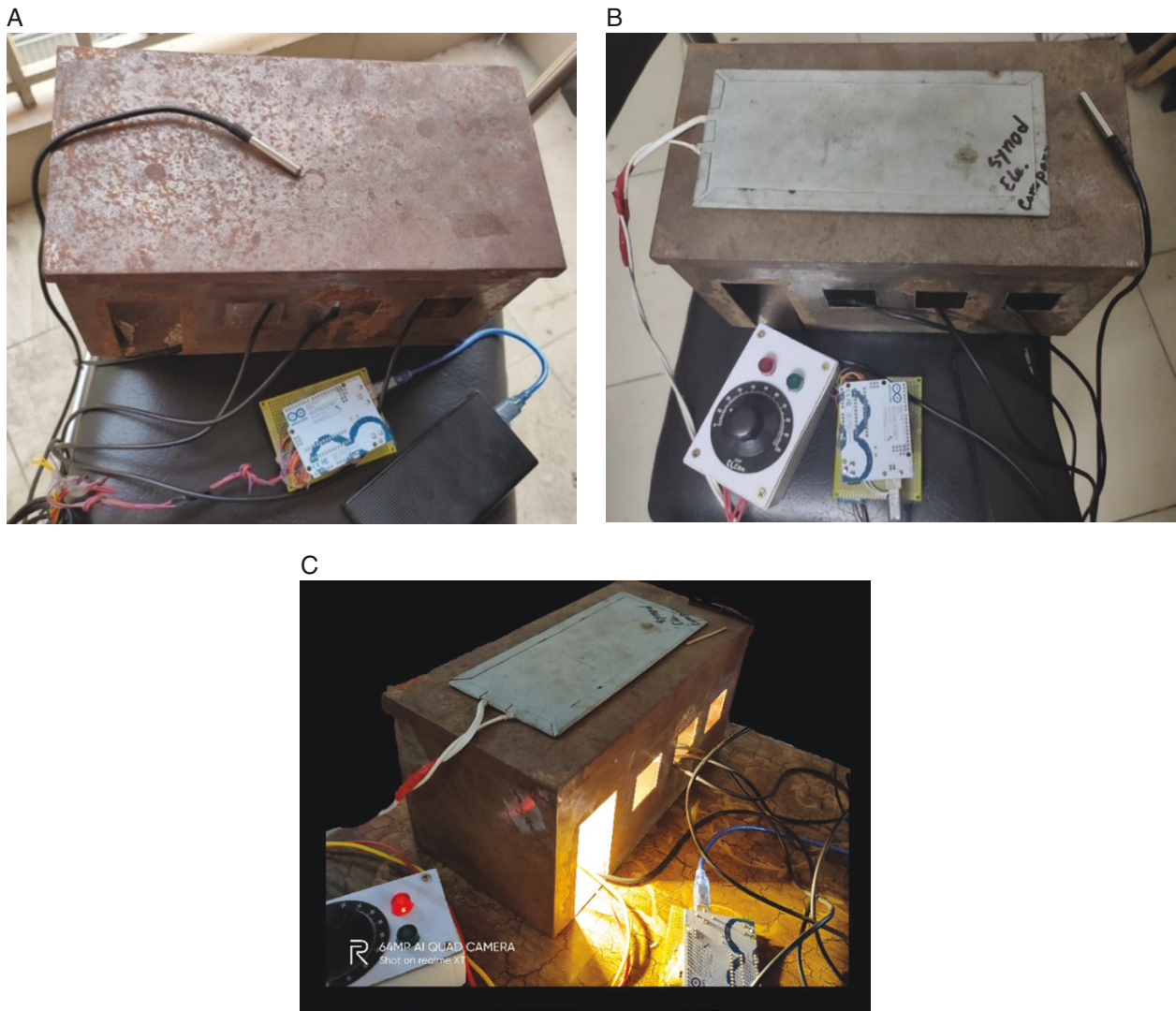


Fig. 3: Experimental set-ups of the bus model, (a) measuring the surface temperature due to solar heat, (b) measuring the temperature using a surface heater and (c) measuring the temperature using a surface heater and an internal heat source (25-W light bulb).

Table 2: Properties of the PCM (sodium sulphate decahydrate) [33]

Molecular formula	Na ₂ SO ₄ ·10H ₂ O
Density	1464 kg/m ³
Thermal conductivity	0.45 W/m·K
Specific heat	298.15 kJ/mol·K 2.09 kJ/kg·K (solid phase) 3.35 kJ/kg·K (liquid phase)
Molecular weight	322.20 g/mol
Melting point	32.4°C
Boiling point	1429°C
Heat of fusion	252 kJ/kg
Flash point	Non-flammable

In Case 1, the bus model was placed under in the sun at 7.00 AM on a sunny day and the temperatures of the bus model at different points were recorded using a digital data-acquisition system until 6.00 PM (on 2 November 2019) when no PCM was used on the ceiling. Then, the bus model was placed in the sun at 7.00 AM on another sunny day (13 November 2019) and the

Table 3: Specifications of the surface heater and thermocouples

Surface heater	
Name	RS PRO mica heating pads
Brand	RS Pro
Power rating	300 W
Peak temperature	+260°C
Supply voltage	230 V (AC)
Dimensions	200 × 100 mm
Country of origin	China
Thermocouples	
Manufacturer	Vktech
Model number	54170.01-DE1
Type	K-type
Power-supply range	3.0–5.5 V
Operating temperature range	–55°C to +125°C
Storage temperature range	–55°C to +125°C
Accuracy	±0.5°C
Cable length	100 cm

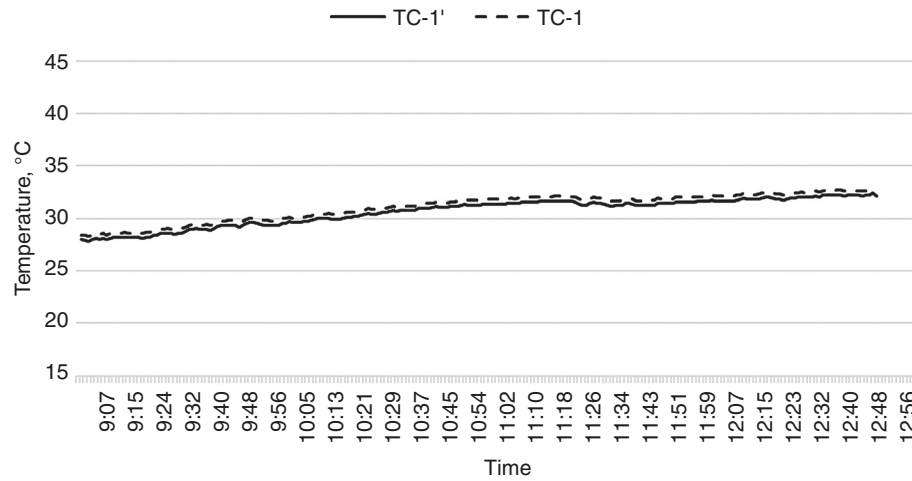


Fig. 4: Calibrated data for thermocouple TC-1.

Table 4: Different cases of the experiment

Case	Experimental study
1	Thermal conditions of the bus model with and without using PCM on the ceiling due to solar heat
2	Thermal conditions of the bus model with and without using PCM on the ceiling using an external surface heater in the upper surface of the bus model
3	Thermal conditions of the bus model with and without using PCM on the ceiling using a heat source (25-W bulb) inside the bus model
4	Thermal conditions of the bus model with and without using PCM on the ceiling using an external surface heater in the upper surface and a heat source (25-W bulb) inside the bus model

temperatures of the bus model at different points were recorded using the same data-acquisition system until 6.00 PM, but this time PCM was placed on the ceiling of the bus. Here, a total of five thermocouples was used to measure the temperature at five locations, i.e. the floor (TC-1), indoors (TC-2, TC-3, TC-4) and the roof surface (TC-5). However, the placements of the thermocouples in the bus model are shown in Fig. 2b and Table 1.

From Case 1, it was found that the temperature of the surroundings was not the same throughout the day due to the weather conditions on that particular day. From Fig. 5a, it can be seen that when the peak temperature of roof surface reached nearly 50°C, the floor temperature and indoor air temperatures were >38°C but, in Case 1, when the PCM was incorporated on the ceiling, the scenario was changed. From Fig. 5b, it can be seen that the floor temperature and indoor temperatures were <35°C even though the peak temperature of the roof surface was 50°C. In addition, the indoor temperature was <30°C for most of the time as compared to the conditions without the PCM. So, by adding a PCM layer, it was possible to reduce the indoor peak temperatures.

Now, in Case 1, the average indoor temperature of the bus (denoted by TC-2, TC-3, TC-4) without the PCM and with the PCM was analysed. From the comparison in Fig. 6, it can be clearly noticed that the average indoor temperature of the bus model with the PCM was always below that without the PCM. It was also observed that in Case 1, the recorded peak average indoor temperature was almost 37°C when the PCM was not placed, whereas with the PCM, the average indoor temperature reached a peak of 35°C. Also, from Fig. 6, it can be seen that the average indoor temperature with the PCM remained below that without the PCM, even though the roof-surface temperature was higher than that without the PCM. So, from Case 1, it can be concluded that by applying the PCM, it was possible to reduce the peak indoor temperature by almost 2°C, which would definitely reduce the energy consumption for air conditioning inside a vehicle.

In Case 2, the same bus model was used but this time, instead of solar heat, an external surface heater was used and the temperatures of the bus model at different points were recorded using a digital data-acquisition system at first when there was no PCM on the ceiling. Later, PCM was placed on the ceiling of the bus model and the temperatures of the bus model at different points were recorded. Here, a total of five thermocouples were also used as before to measure the temperature at five points, namely TC-1, TC-2, TC-3, TC-4 and TC-5.

As Case 2 was conducted without solar energy and to make the roof-surface temperature (TC-5) consistent with that in Case 1, a surface heater was used, set to 50°C, and ran for 1 hour (60 minutes) under both conditions (without the PCM and with the PCM). To control the temperature, a temperature controller was used. In this case, when the PCM was not present, the roof-surface temperature reached slightly over 54°C (Fig. 7a) at the end of the time period. But, in the presence of the PCM, after 60 minutes, that temperature reached nearly 50°C (Fig. 7b). It should be mentioned here that the difference in the surface temperature (TC-5) in the cases with the PCM and without the PCM might be due the variation in ambient conditions during the experiments, material properties and also the contact between the surface heater and the roof surface. It is also noticed from Fig. 7a and b that the roof-surface temperature increased more rapidly without the presence of the PCM than with the presence of the PCM in the ceiling. Thus, it can be said that the incorporation of the PCM delayed the increase in the roof-surface temperature as the PCM absorbed much of the heat as latent heat.

Now, in Case 2, the average indoor temperature of the bus model (denoted by TC-2, TC-3, TC-4) was also compared without the PCM and with the PCM as in Case 1. From Fig. 8a, it can be seen that in Case 2, the average indoor temperature started to increase linearly from 22.5°C after 20 minutes when there was no PCM placed on the ceiling. When the PCM was placed, the average

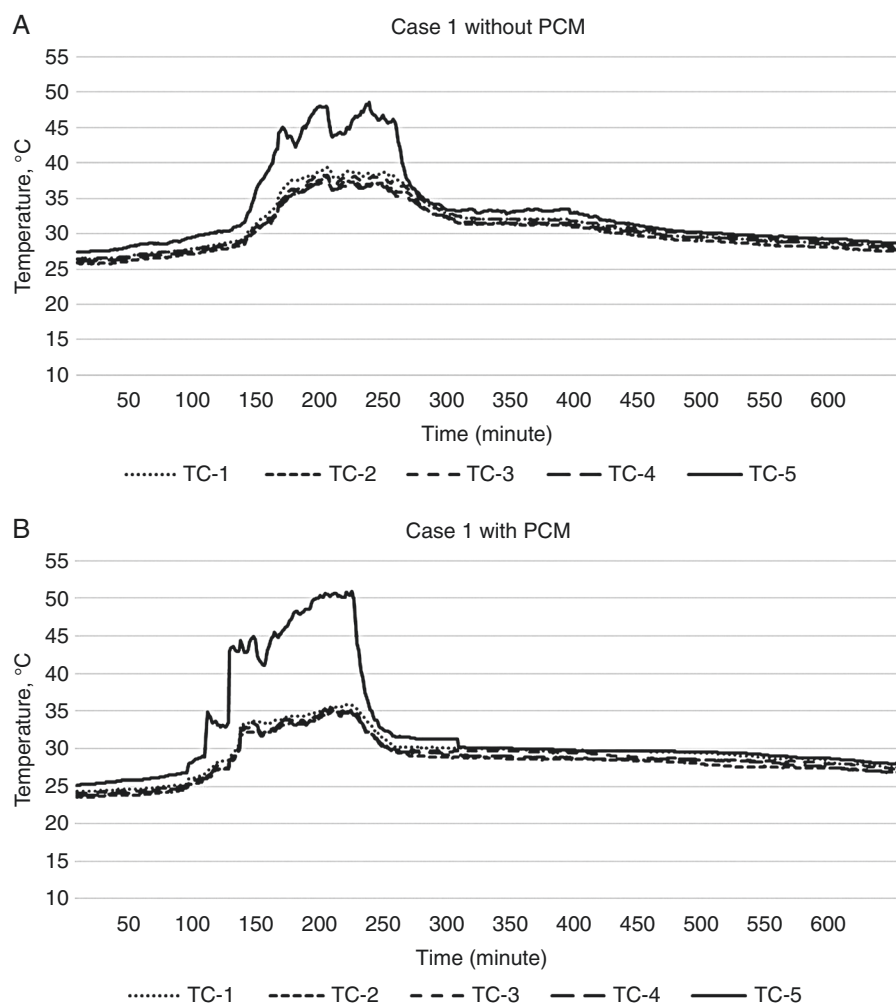


Fig. 5: Indoor and roof-surface temperatures of the bus due to solar heat, (a) without PCM and (b) with PCM.

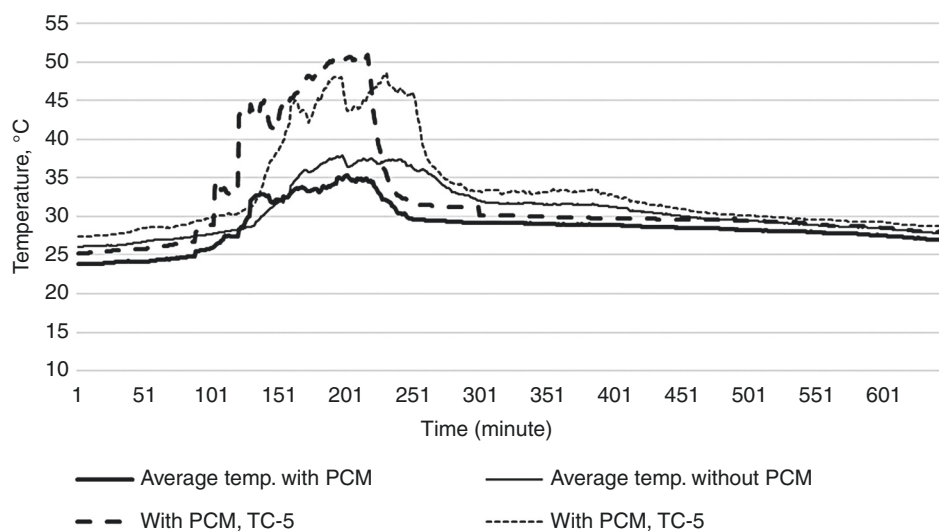


Fig. 6: Comparison of the average indoor temperature of the bus with the roof-surface temperature (TC-5) in Case 1.

indoor temperature at the beginning was higher than that without the PCM, but after 40 minutes, the average indoor temperature without the PCM outraced it. And, at the end of the time period, the average indoor temperature remained lower (with the PCM) than the average indoor temperature without the PCM. This

outcome reveals that the PCM absorbed a significant amount of heat (as latent heat) and delayed the propagation of heat to the interior.

More interestingly, there was a gradual drop in the surface temperature (TC-5) after ~40 minutes (with the PCM) while the

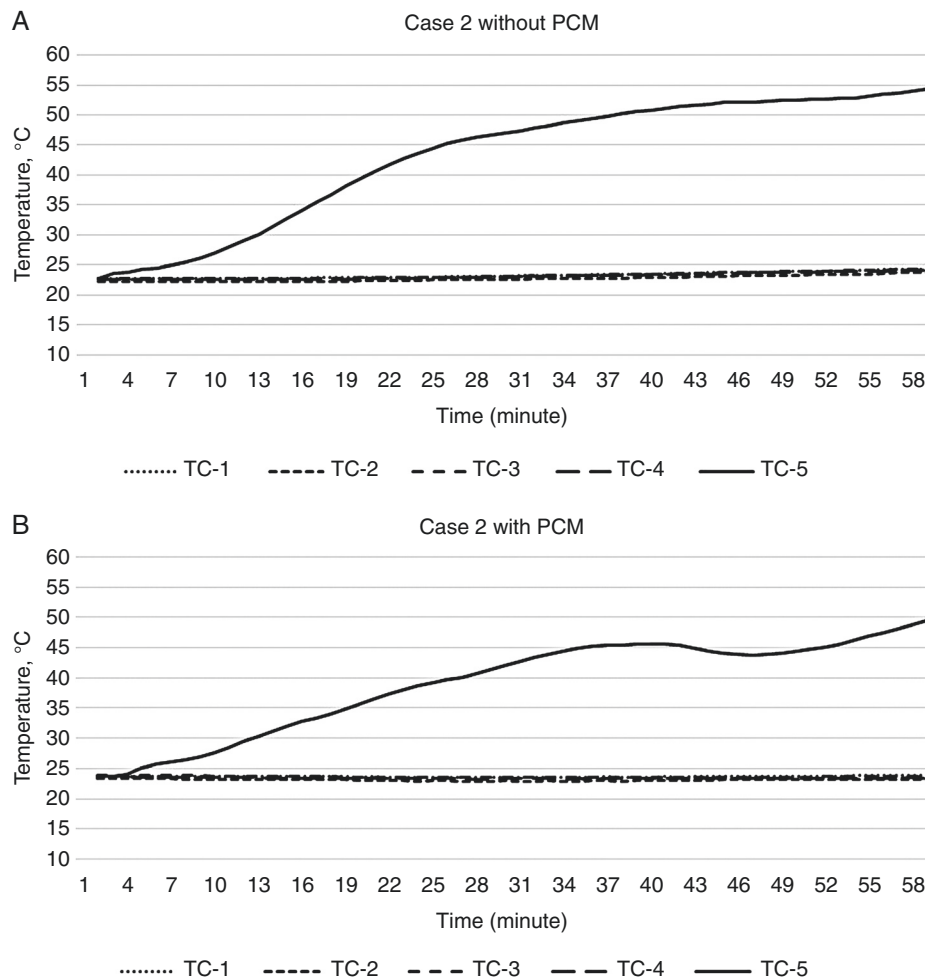


Fig. 7: Indoor and roof-surface temperatures of the bus for Case 2, (a) without PCM and (b) with PCM.

temperature of the surface reached $\sim 45^{\circ}\text{C}$. It is believed that for the first ~ 40 minutes, the PCM stored the heat until the melting process was completed. Therefore, for the first ~ 40 minutes, the heat flow from outside to the inside was restricted as the melting process was going on and led to a decrease in the indoor temperature, as shown in Fig. 8a. However, once the melting process was completed, the PCM layer transferred the heat in both the conductive and convective modes to the indoor part of the vehicle and the temperature gradually increased with the elapse of time, which can be observed in Fig. 8a also. On the other hand, for the case without the PCM, the indoor temperature gradually increased as the time elapsed. In the case without the PCM, air was present between the ceiling and the roof, and the air had a much lower thermal conductivity as compared with that of sodium sulphate decahydrate. However, the convective heat-transfer mode within the ceiling and roof played a major role in carrying the heat from the roof to the interior.

Now, having a closer look at Figs 7b and 8b, the time elapsed for the surface temperature to increase (with the PCM) from its melting point (32.4°C) to 45°C was ~ 26 minutes. This means that the amount of PCM should play a major role in holding up the heat transfer from the outer region to the interior of the vehicle. Now, considering Case 1, the duration of melting was found to be ~ 21 minutes. In Case 1, the time was shorter because the heat source, i.e. the sunlight, covered all the roof; however, for Case 2, the surface heater covered $\sim 43\%$ of the roof surface (surface-heater

dimensions were 200×100 mm). So, it is justified that the heat source and the covering area may play a role in the melting process, its duration and eventually the transfer of heat to the inside. Finally, the results indicate that placing PCM will help to resist heat flow from external heat sources and delay increases in the indoor temperature of vehicles under the condition that there is no internal heat source.

In Case 3, the same bus model was used and this time no solar heat and surface heater were used as external heaters. Instead of any external heater, in this case, a 25-W light bulb was used as an internal source and the temperatures of the bus model at different points were recorded using a digital data-acquisition system when there was no PCM on the ceiling. Later, the PCM was placed in between the ceiling and the roof of the bus model and the temperatures of the bus model at different points were recorded again. Here also, a total of five thermocouples were used as before to measure the temperature at five points, namely TC-1, TC-2, TC-3, TC-4 and TC-5, and the positions of the thermocouples were the same as in Cases 1 and 2. The internal heat source (light bulb) was turned on for 1 hour (60 minutes) under both conditions (with and without the PCM). In Case 3, it was found that the roof-surface temperature was lower than the floor-surface and indoor room temperatures. However, in previous cases (Cases 1 and 2), the roof-surface temperature was higher than the floor-surface and indoor room temperatures. In Case 3, the roof-surface temperature was lower because of the position of the heat source, i.e.

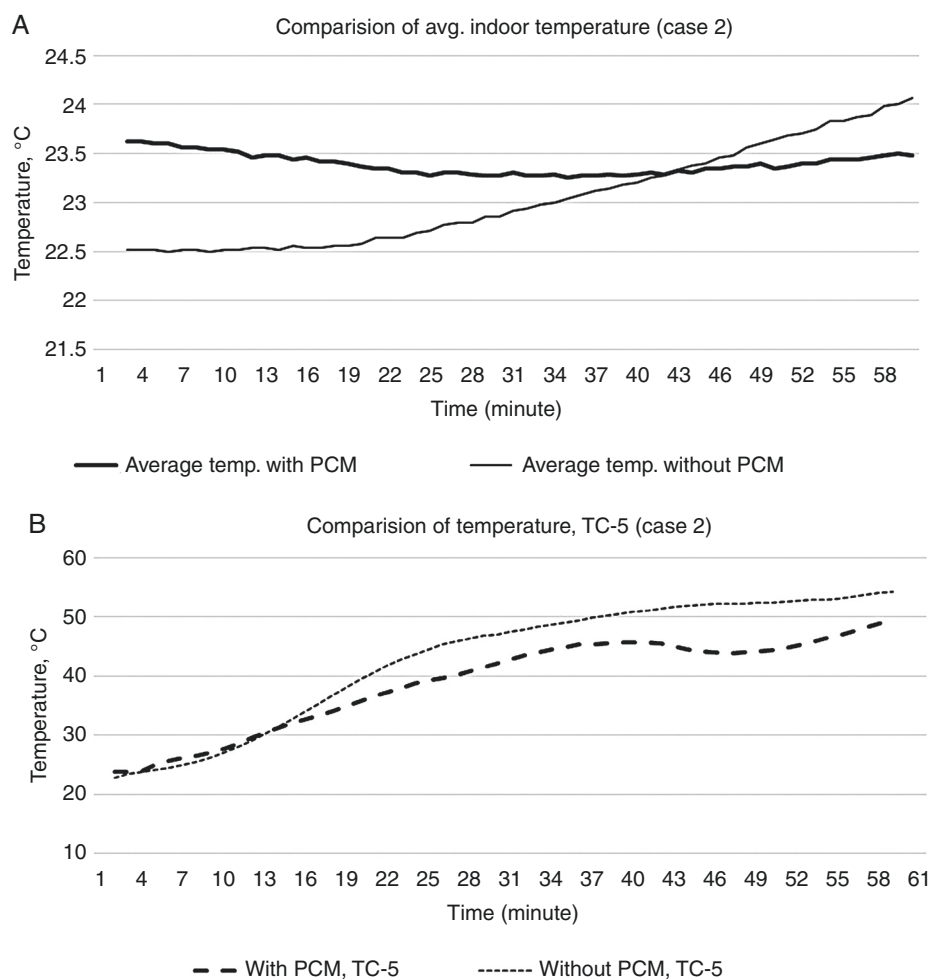


Fig. 8: Comparison of (a) average indoor temperature of the bus and (b) roof-surface temperature (TC-5) without PCM and with PCM on the ceiling in Case 2.

the heat source was used as an internal heat source. However, from Fig. 9a, when the PCM was absent, it was found that at the end of 60 minutes, the floor-surface temperature had reached slightly over 36°C. On other hand, when the PCM was placed on the ceiling, at the end of the time period, the floor-surface temperature reached almost 34°C (Fig. 9b), which was 2°C less than when the PCM was not used.

Now, in Case 3, the average indoor temperature of the bus model (denoted by TC-2, TC-3, TC-4) was also compared without the PCM and with the PCM as in Cases 1 and 2, as shown in Fig. 10. It can be seen that the average indoor temperature with the PCM was below that without the PCM up to 60 minutes and started to catch up at the end of the time period. In this particular issue, air was filled within the ceiling and the roof, and it had a lower thermal conductivity than the PCM ($K_{\text{air}} = 0.02 \text{ W/mK}$ and $K_{\text{PCM}} = 0.45 \text{ W/mK}$). Therefore, air behaved like an insulating material and ultimately led to a higher temperature inside the vehicle. However, the heat was passed through the air or the PCM eventually reached the outer surface and caused an increase in the outer-surface temperature, i.e. TC-5. Now considering Fig. 10, it can be seen that TC-5 without the PCM exhibited a higher temperature than with the PCM. Comparing the specific heats of air and the PCM, the PCM had a higher specific heat (2.09 kJ/kg.K) as compared with air (1.005 kJ/kg.K), which means that a larger amount of heat was stored by the PCM as compared with the air. This thermal property of the two substances created a tempera-

ture difference at TC-5. This observation is true until the melting point of the PCM is reached as the temperature gradually decreased for the first 40 minutes (see Fig. 8a in Case 2). This scenario was not observed in Case 1 and it might be that the heat from the sunlight passed through not only the roof, but also the west face of the bus model (as the bus model was facing south during the experiments). Therefore, one of the findings that can be drawn here is that PCM will not be effective to resist heat flow once the temperature exceeds its melting point. Benefit from PCM cannot be gained unless the thermal conductivity of the PCM is lower than those of the compared materials, especially when the external heat source is active. In addition, the present study also indicates that the application of PCM will help to resist an increase in the indoor temperature of vehicles when the PCM is incorporated with an internal heat source (as shown in Fig. 10) and ultimately delay an increase in the indoor temperature. Therefore, the placement of PCM in between the ceiling and the roof gives advantages with a lower indoor temperature for the internal heat source (as compared to the without-PCM case) and, on other hand, the PCM is able to keep the indoor temperature lower until it reaches the melting point for the external heat source.

It has been seen that placing the PCM layer within the roof and ceiling was able to keep the indoor temperature lower for the internal heat source and the external heat source (until the melting point). Therefore, the study was extended while both the internal and external heat sources were used (i.e. Case 4) on the same

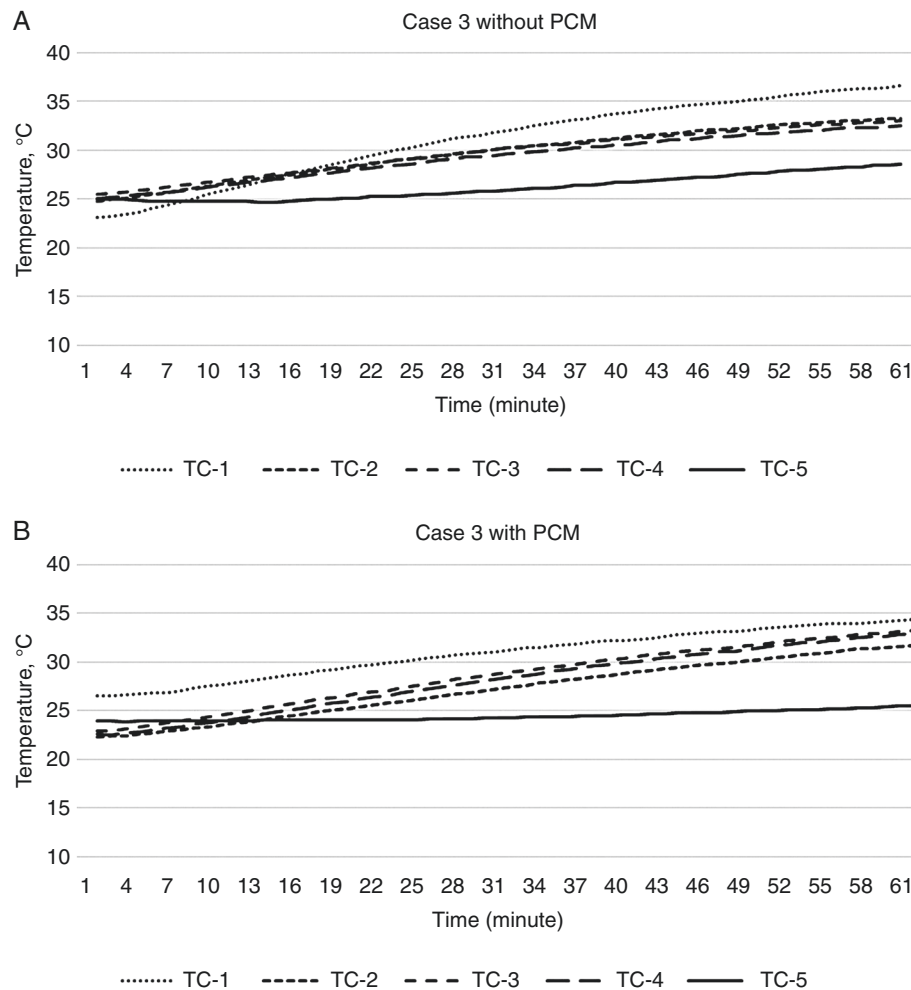


Fig. 9: Indoor and roof-surface temperatures of the bus for Case 3, (a) without the PCM and (b) with PCM.

bus model. Here, in this case, a 25-W bulb as an internal heat source and surface heater as an external heat source were used. At first, data were taken in presence of both the internal and external heater without using any PCM on the ceiling. Later, PCM was placed on the ceiling of the bus model in the presence of both the heaters and the temperatures of the bus model for different points were recorded again. Here, also, a total of five thermocouples were used as before to measure the temperature at five points, namely TC-1, TC-2, TC-3, TC-4 and TC-5, and the positions of the thermocouples were the same as before in Cases 1, 2 and 3.

In Case 4, the heat sources (internal and external) were run for almost 1 hour (60 minutes) under both conditions (with and without PCM) and it was found that the roof-surface temperature and floor-surface temperature were higher than the indoor room temperatures, which was different from previous cases. It was previously mentioned that in Cases 1 and 2, the roof-surface temperature was higher, and in Case 3, the inside temperatures of the vehicle (floor-surface and indoor room temperatures) were higher than the roof-surface temperature. From Fig. 11a, it was found that at the end of the time period, the roof-surface temperature reached slightly over 56°C and the floor-surface temperature reached 34.7°C when no PCM was incorporated. But when the PCM was placed in ceiling, from Fig. 11b, it was found that at the end of time period, the roof-surface temperature reached slightly over 53°C, which was almost 3°C lower than without the presence of the PCM; on other hand, the floor-surface temperature

reached nearly 34°C (Fig. 11b), which was almost same as without the presence of the PCM. That is because the PCM resisted heat transfer, which is a negative outcome for internal heat sources. However, the observation comes from Fig. 12 and it is noticed that in Case 4, at the initial time period, the average indoor temperature with the PCM was slightly higher than that of the case of without the PCM and this was also found in Case 2. However, as time went on, the indoor temperature without the PCM increased and exceeded the case with the PCM. And at the end of the time period, the temperature with the PCM was around 1.5°C lower than the temperature without the PCM.

Now, having a close look at Fig. 11b, the temperature profile of the outer-surface temperature (TC-5) started to become flattened around the temperature of 50°C, which was ~25 minutes from the melting point of the PCM. A similar observation was also found in Case 2 when only the external heat source was used. However, in Case 2, at first, the indoor temperature gradually decreased and later it started to increase slowly once the outer-surface temperature was slightly reduced after completion of the melting process. However, in Case 4, it was not observed because of the presence of the internal heat source. As a result, the indoor temperature continued to increase, which was also evident in Case 3 with the internal heat source.

Here, in Case 2, only the external heat source was applied and no internal heat was applied, which replicates the scenario of a bus that is parked in the sun. In Case 3, only an internal heat

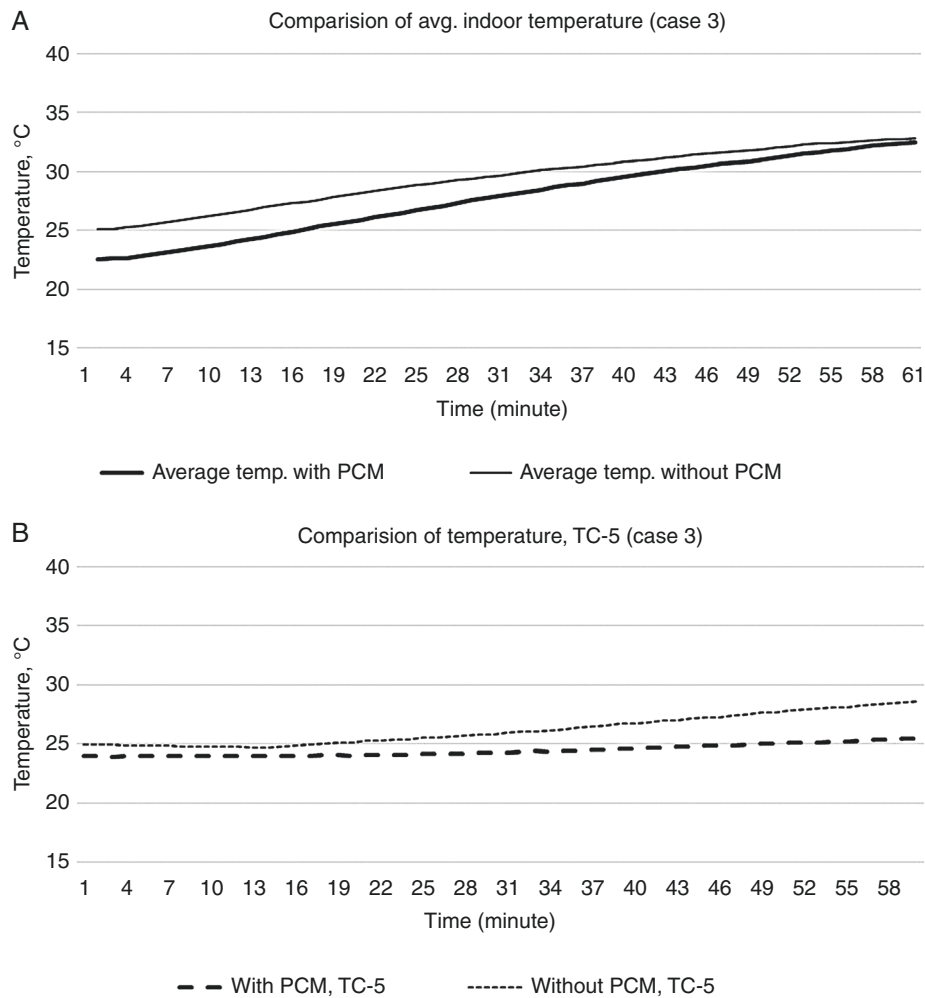


Fig. 10: Comparison of (a) average indoor temperature of the bus and (b) roof-surface temperature (TC-5) without PCM and with PCM on the ceiling in Case 3.

source was supplied and no external heat was supplied, which reflects the scenario of a bus that is stuck in a traffic jam at night. And, in Case 4, both the internal and external heat were supplied, which represents the conditions when a bus is stuck in a traffic jam on a hot sunny day. From the investigation of this paper, it was found that in all cases in which a bus is parked or stuck in traffic (day or night), PCM can reduce the inside temperature of the bus and also help to delay an increase in the inside temperature. From the literature, it is found that applying a 0.5-inch (0.0127-m) thick layer of PCM inside the building wall could decrease and delay an increase in the inside room temperature [33]. So, sodium sulphate decahydrate can be used as the PCM to resist an increase in the inside temperature of buses and buildings. Fig. 13 shows the comparison of the average indoor temperature for Cases 2, 3 and 4. Once the external heat source is used (Case 2), PCM can easily keep the indoor temperature within the comfort-zone temperature; however, the presence of an internal heat source has a significant influence on the indoor temperature and, in fact, it increases linearly over the time. One observation is that in the presence of both internal and external heat sources (i.e. Case 4), the indoor temperature is ~1.5°C lower than in Case 3. This is a good sign for the use of PCM and it is believed that the temperature gradient is lower for Case 4 to transfer the heat from outside to the inside, which leads to an increase in the indoor temperature at a slower rate as compared with Case 3.

In public transportation like buses, in the rush hour, the number of passengers used to be higher, so the metabolism heat generated by the human body was sufficiently high and should be considered a major contributor to internal heat sources. The amount of heat gain or the cooling load of public transport could be 26 kW on a hot sunny day in the summer [35]. Therefore, this significant amount of heat should be absorbed. In the above experimental studies, it was found that both external and internal heat sources play a significant role in increasing the indoor temperature. The placement of PCM could easily help to delay an increase in the indoor temperature from an external heat source. However, it was observed that the indoor temperature has a trend to increase with time; therefore, the day-long service of a bus with passengers with both external and internal heat sources should be considered seriously.

For the external heat sources, the outer-surface temperature is usually higher and PCM could melt easily. From the analytical analysis, the heat gained in the PCM from its melting point to a certain temperature can be calculated as

$$Q = mL + mC_p\Delta T \quad (1)$$

where Q is the amount of heat gain, m is the mass of PCM, L is the heat of fusion, C_p is the specific heat and ΔT is the temperature difference. The heat gain for a certain period of time Δt is given by $\dot{Q} = \frac{Q}{\Delta t}$.

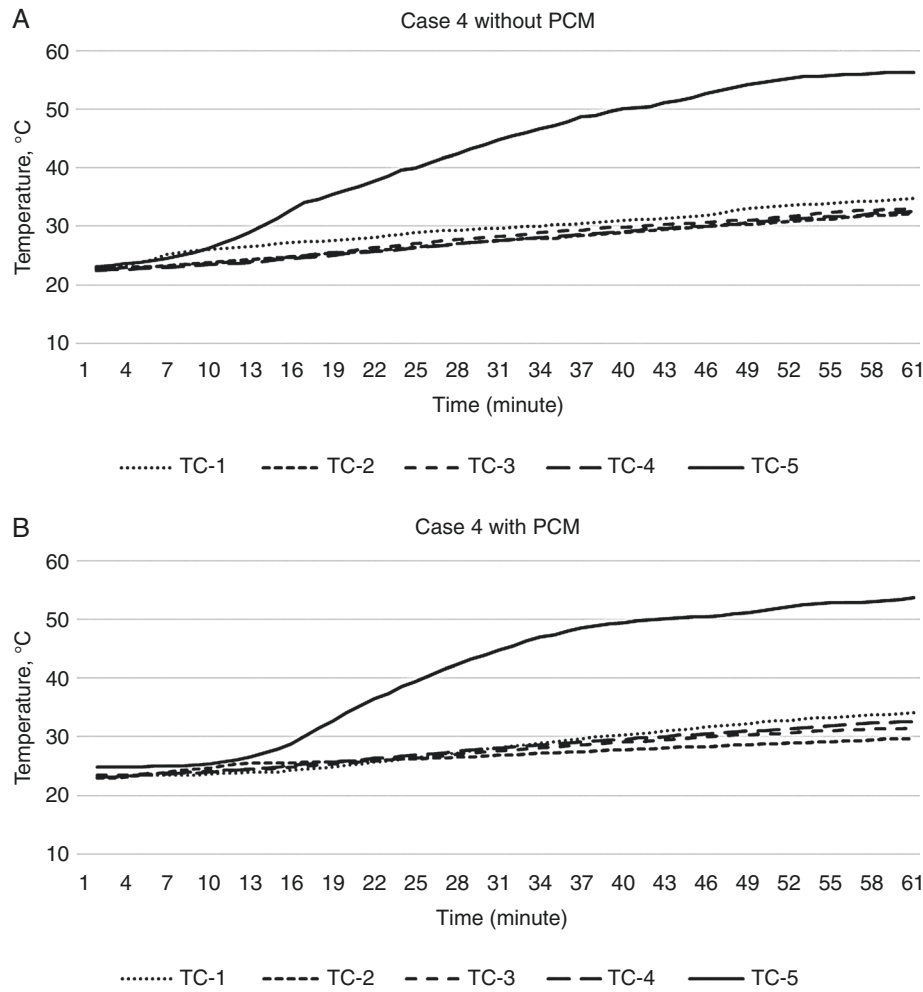


Fig. 11: Indoor and roof-surface temperature of the bus for Case 4, (a) without PCM and (b) with PCM.

In the present experimental set-up, the external heat source is relatively closer to the PCM layer. Therefore, the PCM adjacent to the outer surface will melt first and gradually propagate within the PCM slab. At the same time, the temperature of the PCM adjacent to the outer surface will gradually increase. The propagation of the solid-liquid interface is quite unpredictable and is usually termed as a Stefan problem. The Stefan number is defined as the ratio of the sensible heat to the latent heat: $St = \frac{C_p(T - T_m)}{L}$. It was observed that for all the cases with external heat sources, the surface temperature (TC-5) gradually increased and after completion of the melting of the PCM it slightly reduced. The temperature (T) at which the surface temperature started to drop was found to be ~45–46°C for Cases 1 and 2; on the other hand, it was a little higher for Case 4, at ~50°C (as explained earlier). Therefore, in principle, it can be said that under the presented experimental conditions, T is nearly constant.

In order to delay heat transfer to the inside of the vehicle or to delay an increase in the indoor temperature, the melting time could be increased, which can be done with a decrease in the time constant b where $b = \frac{hA}{\rho VC_p}$. Therefore, on increasing the amount of PCM, b will be decreased and this could possibly increase the melting time. On other hand, increasing the melting time will lead to an increase in the Fourier number, τ , which is defined as $\tau = \frac{\alpha t}{z^2}$, where α is the thermal diffusivity, z is the thickness of the PCM layer and t is the time. This means that in order to attain a certain temperature (e.g. 45°C), it will take more time for a certain Biot number, Bi .

Therefore, the increase in the amount of PCM between the ceiling and the roof will lead to an increase in the time constant b , which means that it will take more time to reach a certain temperature. So, with the same time frame or duration t , the temperature T will be lower for a higher b . That will ultimately lead to having a lower Stefan number. In fact, the lower Stefan number means that latent heat will dominate over the sensible heat. So, the heat transfer from the outside to the inside will be delayed and it will be possible to maintain the lower temperature, as the duration for the melting will increase [36]. Therefore, to increase the time constant, the thickness of the PCM layer can be increased to lower the indoor temperature. Fig. 14 shows the analytical results of the time to reach a certain temperature under the present experimental conditions for different PCM-layer thicknesses by using the following equations:

$$b = \frac{hA}{\rho VC_p} \quad (2)$$

$$\theta = e^{-bt} \quad (3)$$

Fig. 14 shows the required time to attain a certain temperature at the PCM layer with an increase in the thickness of the PCM layer. The graph shows the typical transient curve of the temperature with time and indicates that with an increase in the thickness of the PCM layer by 3 times (z/z_{setup}), it would be possible to delay reaching the certain temperature by ~2.5 times (t/t_{exp}). In the present study, the PCM layer thickness (say z_{setup}) was 0.5 inches (0.0127 m) and the time required (t_{exp}) to attain ~45°C, at which

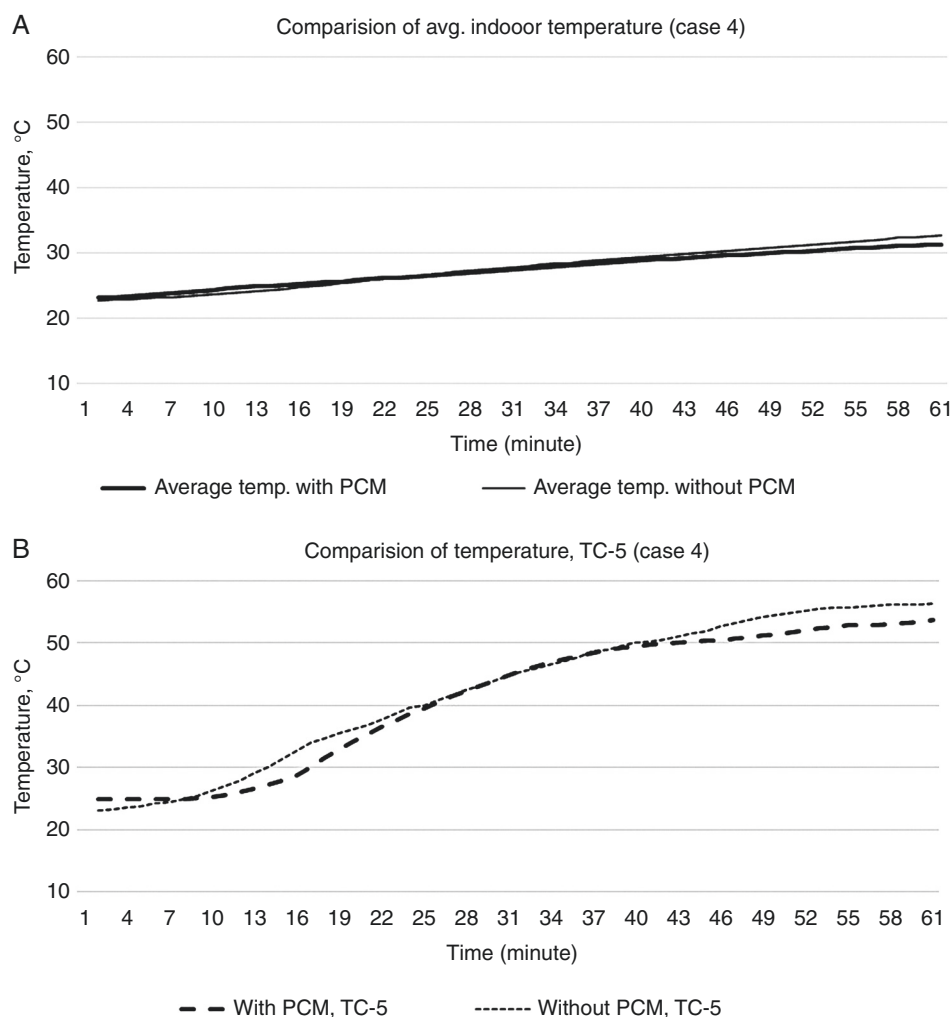


Fig. 12: Comparison of (a) average indoor temperature of the bus and (b) roof-surface temperature (TC-5) without PCM and with PCM on the ceiling in Case 4.

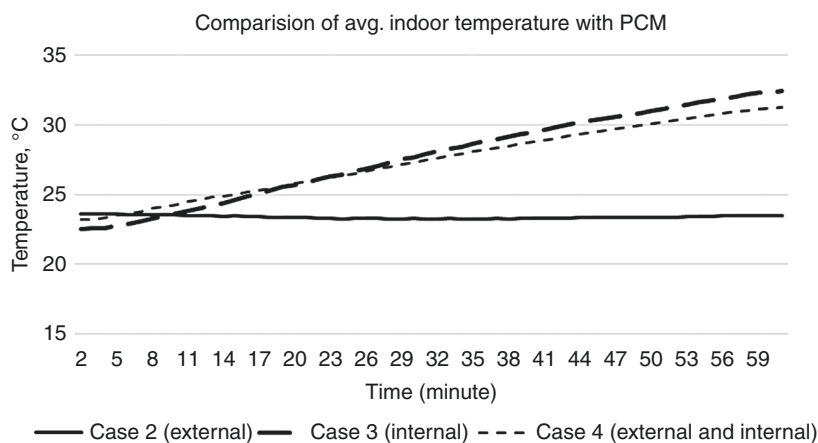


Fig. 13: Comparison of average indoor temperature of the bus for Cases 2, 3 and 4.

the entire PCM would melt (explained earlier), was ~21 minutes. Therefore, by increasing the layer thickness by three times (z/z_{setup}), it might take ~53 minutes to reach 45°C and help to delay a temperature rise inside the vehicle. Therefore, for day-long operation of a vehicle on a hot sunny day, increasing the thickness of the PCM layer should give better results by delaying an increase

in the indoor temperature for the external heat source conditions. Now, again, go back to Case 1 (Fig. 6) in which the experiment was conducted on a sunny day and the roof-surface temperature was above the melting point of the PCM for ~100 minutes. Therefore, increasing the thickness of the PCM layer by five to six times would probably restrict the temperature increase. However, in

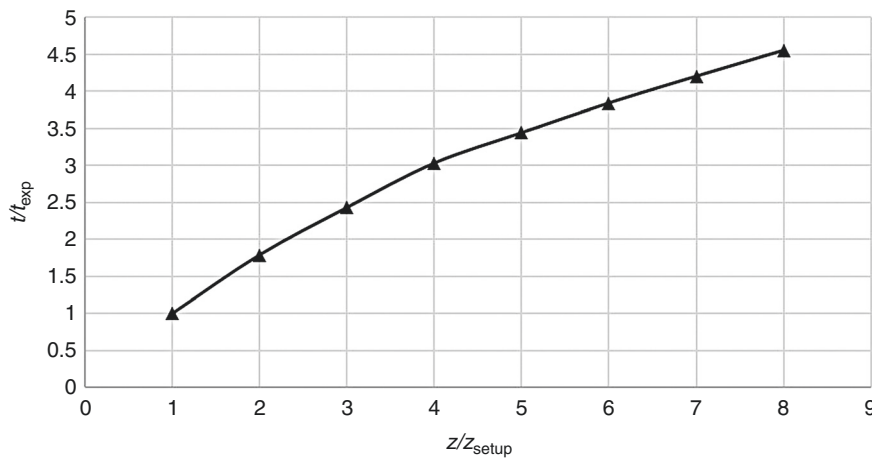


Fig. 14: Time required to attain certain temperatures of the PCM layer with an increase in the PCM-layer thickness.

the present experimental study, the metal thickness was 1.5 mm but in a real bus, the roof is constructed with foam, leather or resin etc., and also there is paint. Therefore, optimization of the thickness of the PCM layer can be done and it is possible to keep a lower temperature in a hot sunny day and make it comfortable inside the vehicle.

Now, for internal heat sources like the metabolic heat generated from the human body and other internal heat sources, a few alternative options can be considered. First, a PCM with a lower fusion point, e.g. 25–30°C, and a high volumetric heat capacity can be used on the inner side of the ceiling. Second, a good thermal mass can be considered to absorb the heat of the internal heat sources. However, optimization of the cost, amount of additional materials, parasitic loads, compactness and aesthetic issues need to be studied further. $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (manganese (II) nitrate hexahydrate) can be a good choice, as its melting temperature is ~25°C and it has moderate energy-storage density (65 kWh/m³) [37, 38]. Alternatively, calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$) has a melting point within the range of 24–30°C and has higher energy-storage density (80 kWh/m³) [37, 39, 40]. However, $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ is rather expensive compared with $\text{Mn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ [30]. Therefore, the heat generated from different internal sources can be absorbed by the PCM layer that might be placed on the inner side of the ceiling. As a single layer of PCM is unable to control the indoor temperature, as an alternative, two different PCMs with different melting points with high heat capacity can be considered. In such a case, the PCM with the higher melting point (30–35°C) can be placed on the outer surface of the roof and the PCM with the lower melting point (20–30°C) can be placed on the inner surface of the ceiling based on the usual climatic conditions.

3 Conclusion

Experimental studies have been carried out on a bus model in which sodium sulphate decahydrate was used as a PCM and placed in between the ceiling and the roof. Four different cases were considered to replicate the different scenarios of the bus during a day-long trip. When sunlight was considered as an external heat source and PCM was not used, the indoor temperature of the bus model increased up to 37°C for ~100 minutes while the roof-surface temperature was ~54°C. However, with the presence of the PCM, it was possible to reduce the temperature by ≤2°C as compared to the conditions without the PCM. Later, three different cases were considered when a surface heater and light bulb were used as external and internal heat sources, respectively.

When only the external heat source was used, the results indicate that the presence of the PCM could maintain a low temperature in the interior and delay the time period of increasing the temperature. However, the presence of an internal heat source does not reflect such an outcome; rather, it gradually increases with the elapse of time. On the other hand, when both internal and external heat sources were used, the indoor temperature did not drop in the presence of the PCM layer; in fact, the temperature gradually increased as time went on. The present experimental results also indicate that the PCM required ~21 minutes to melt and these findings are justified as the indoor temperature gradually decreased for ~21 minutes and then started to increase. Therefore, single-layer PCM struggles to counter internal heat gain from internal heat sources. In such a case, increasing the PCM-layer thickness would increase the delay period of the indoor temperature rising. On the other hand, to reduce the effect of the internal heat source, an inner layer of PCM with a moderate melting temperature (15–25°C) along with high volumetric heat capacity could be used to absorb a substantial amount of the internal heat. Manganese (II) nitrate hexahydrate may be a good choice to counter the increase in the indoor temperature due to the presence of internal heat sources. So, two different PCMs with higher and lower melting-point temperatures could be placed on the outer surface of the roof and inner surface of the ceiling, respectively, to encounter external and internal heat sources.

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Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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