PAPER • OPEN ACCESS

Experimental and Numerical Investigation of Car Cabin Temperature under Solar Load Condition using Phase Change Materials

To cite this article: Bhargava Srusti *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **573** 012024

IOP Conf. Series: Earth and Environmental Science **573** (2020) 012024 doi:10.1088/1755-1315/573/1/012024

Experimental and Numerical Investigation of Car Cabin Temperature under Solar Load Condition using Phase Change Materials

Bhargava Srusti[1], Aravind S[2], Yadhu K[2], Aashish V[2], & M.B. Shyam Kumar[3,*]

[1]Research Scholar, School of Mechanical Engineering, VIT Chennai
[2]B.Tech Student, School of Mechanical Engineering, VIT Chennai
[3]Associate Professor, School of Mechanical Engineering, VIT Chennai

[*]Corresponding Author Email: shyamkumar.mb@vit.ac.in

Abstract. Cars kept in open have the tendency to attain temperatures far higher than the one prevailing in the surroundings. This condition is especially severe during summer months, and can cause a lot of discomfort to passengers, who re-occupy the car after parking it in the open for a while. Employing a Phase Change Material (PCM) can be a possible solution to control the car cabin temperature to a certain extent. This paper is focused on experimental and numerical study on employing a suitable PCM to control the car cabin temperature. Four different locations inside the car cabin namely roof, head, bottom and feet were selected for monitoring the temperature using temperature sensors. The effect of 90 minutes of exposure to the solar load is simulated by employing the Surface to Surface (S2S) radiation model available in ANSYS FLUENT 18.2. Experimental and numerical results conveyed the reduction in cabin average air temperature by ~ 8°C after Placing the phase change material inside the four wheeler cabin. Comparison of Numerical and experimental results was carried out and the absolute average deviation in temperature predicted by S2S model from the experimental data is 9.93 %.

1. Introduction

Subjective evaluation as checked that Thermal comfort is the impression in mind, which changes according to ambient conditions [1]. During hot summer months, parking cars in the open for a sufficiently long duration causes a large increase in the temperature inside its cabin. Various chemicals are used in the manufacture of car interiors (seats, carpets, dashboard etc) and they are at the highest levels when the car is freshly manufactured. When exposed to higher temperature these parts start releasing toxic fumes thus leading to off-gassing [2]. Around 30ºC increase in the car cabin temperature was reported for 90 min exposure of the car parked in open sunlight [3]. They observed the absolute average deviation in temperature predicted by Discrete Ordinance (DO) and Surface to Surface (S2S) radiation models from their experimental data were 10.08 % and 10.01 % respectively. It was also reported that the S2S radiation model was computationally less expensive than that of the DO radiation model. This undesirable increase in car cabin temperature thus leads to thermal discomfort of the passengers. Moreover, the load on the air conditioning system of the car also increases which leads to more fuel consumption. A possible solution for this problem is to employ a

IOP Conf. Series: Earth and Environmental Science **573** (2020) 012024 doi:10.1088/1755-1315/573/1/012024

Phase Change Material (PCM) in the car cabin to control the temperature to a greater extent by absorbing the cabin heat.

Phase change material which generally acts as a thermal storage device has already proven useful for many applications [4, 5, 6]. Phase change material stores the heat during conversion from solid state to liquid state. These types of materials have the capability to absorb heat and release heat in cycles according to the temperature. The phenomenon of absorbing heat and releasing heat is called as charging and discharging [7]. Energy systems like hydro and solar can store surplus energy using Phase change material [8, 9, 10] in order to meet the demand and supply gap [11, 12].

From the understanding obtained through literature study, there are no numerical studies related to the usage of PCM for controlling temperature in car cabin. Moreover, experimental studies on the usage of PCM for controlling temperature in car cabin are scarce. In the present study, attention is focused on carrying out experimental and numerical analysis to check the feasibility of employing PCM in controlling the car cabin temperature. This provides scope for reducing the rise in car cabin temperature due to solar load thereby decreasing off-gassing and preventing hyperthermia, which mostly affects children who are accidentally locked inside cars [13]. Even in cloudy days, with low ambient air temperatures, it is possible for the car cabin temperature to attain undesirable levels within a sufficient time [14].

On the basis of the desirable car cabin air temperature to be maintained, OM29 PCM with a liquidus temperature of 29^0C was employed in experiments. Any PCM can maintain the temperature for only a specific time period which is based on the time it takes to completely melt by absorbing the latent heat. After this time period, the PCM would no longer be able to absorb latent heat thereby its temperature increases. Common materials like solidified coconut oil can also be used as PCM. Although it can maintain a low temperature, since its melting point is much lower, this cannot be utilized for maintaining temperature for a longer duration [4]. The phase change material (OM29) has been chosen keeping its operating range in mind with that of the temperature rise and range of the car cabin temperature. This has been done using temperature sensors placed at different locations of the car, by taking temperature readings in fixed intervals using data logger, so that a steady state temperature is obtained. Care has been taken to prevent exposure of the temperature sensors to direct solar radiation.

2. Experimental investigation

2.1. Car Description

The car used to perform the experiment was a Ford Figo (Fig 1). The car is length of 3600mm, height 1560mm, internal useful volume 1.5 X 109mm3. To ensure the same environmental conditions, the same location was used to perform the experiment each time. The ambient temperature at the beginning of each cycle of the experiment was approximately the same. In the process of capturing the temperature at different locations, measurements were done at 4 regions in the front and back of the car, at the roof, head, bottom/seat and ground/feet levels.

Instruments: Pt – 100 (1/5 DIN class B) Temperature sensors were calibrated in MICROCAL T100 equipment, from a temperature range of 10 to 80°C, with an accuracy of 0.1°C. Sensors are connected with 16 channels data logger for recording purpose. Solar radiation is measured using Standard Pyranometer, which is manufactured by TENMARS ELECTRONICS CO., LTD. and has an accuracy of $\pm 10 W/m^2$.

2.2. PCM Description

The PCM was obtained in an encapsulated form. Table 2 shows the physical properties of OM29 PCM. The pouches were placed on the roof of the car (Fig. 2). There are multiple reasons for this. Most importantly, since hot air is lighter than cold air, it rises. Hence, the roof must be the hottest region in the car. Placing the PCM on the roof would provide the most optimum temperature control.

Additionally, the roof is the most convenient location to place the PCM, both in terms of installation and passenger comfort. Also, the roof provides the largest area inside the car for placing the PCM. A total of 6 kg of PCM is used.

Figure 1. Car used for Experiment

Figure 2. PCM at the Roof of the Car

3. Numerical Simulation

Modelling of the car is done in CATIA. To reduce complexity, seat and IP panel features are neglected. This CAD geometry is imported to Hypermesh for meshing and geometry clean up. First the simulation is performed with a coarser mesh structure and then the mesh relevance is gradually changed to fine. Table 2 shows the mesh independence study carried for the present work.

Table 1. Physical Properties of OM29 PCM.

Physical Properties	Values
Density at 20°C	1830 kg/m3
Density at 40°C	1530 kg/m3
Fusion Temperature range	29°C -30°C
Latent Heat	190kJ/kg
Specific Heat capacity	2.3 kJ/kg-°C
Thermal Conductivity	0.382 W/mK

Table 2. Grid Independency Study

Mesh Type	**Coarse**	**Medium**	**Fine**
No of Elements.	3310988	10505292	16203222
No of Nodes	517342	1641452	2613423
Roof Temp (Simulation).	39.37°C	42.98. °C	44.11°C
Roof Temp	49.12°C	49.12°C	49.12°C

(Experiment)			
% Error	19.84%	12.5%	10.19%

3.1. Governing Equations

Governing equations like Continuity, Momentum, Energy & Transport equations like turbulent kinetic energy (k) & turbulent dissipation rate (ε) were solved using the finite volume method.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho \overline{u_i})}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho \overline{u_i})}{\partial t} + \frac{\partial(\rho \overline{u_i}\,\overline{u_j})}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial u_l}{\partial x_l}(-\rho\overline{u_i^l u_j^l}) \tag{2}$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla\vec{u}(\rho E + P) = -\nabla(k_e \nabla T) + Se \tag{3}$$

Here ρ - density, μ - dynamic viscosity, $\bar{u}$ - mean velocity, u' - fluctuating velocity component, $\bar{p}$ - mean pressure, T - temperature, t - time. Subscripts i, j are the x, y, z position tensor, Se is the source term for energy, α - thermal diffusivity, υt - turbulent eddy viscosity and σt - turbulent Prandtl number.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_K \tag{4}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{K + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}p_b + S_\varepsilon \tag{5}$$

where $C_1 = \max[.43, \frac{\eta}{\eta+5}]$, $\eta = S\frac{k}{\varepsilon}$, $S = \sqrt{2S_{ij}S_{ij}}$

$$S_{ij} = \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}$$

Where $\mu_t = -\rho C_\mu \frac{k^2}{\epsilon}$, $P_k = -\rho\overline{u^l{}_i u^l{}_j}\frac{du_j}{dx_i}$, $P_b = \beta g_i \frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i}$

$C_\mu(\text{varying according to boundary layer}) = 0.05 - 0.09$

$Pr_t = \text{turbulent prandtle number} = 0.85$

$\beta = -\frac{1}{\rho}(\frac{\partial \rho}{\partial T})$, where β is coefficient of thermal expansion

The default model constants as given in ANSYS FLUENT are μ_t = turbulent kinectic viscosity, $C_{3\epsilon} = 1.44$, $C_2 = 1.9$, $\sigma_k = 1$, $\sigma_\varepsilon = 1.2$

S_K = user defined soure terms, S_ε = user defined soure terms

4. Results and Discussions

The present study mainly focuses on the feasibility of employing PCM in decreasing the car cabin air temperature. Table 3 shows the details of the methods used in present simulation. The temperature data obtained from the earlier experimental work without PCM [3] will be utilized for comparing the temperature of air inside the car with PCM. Figure 3 shows the position of thermocouple and phase change material inside the car. The thermocouples have been placed at the same location as were placed in the earlier work [3]. Temperature of air inside the car (without PCM) cabin at various intervals of time is shown in Figure 4(left pic). Temperature of air inside the car (incorporating phase change material) at various intervals of time is shown in Figure 4(right pic). It is thus evident that incorporating phase change material inside the car can decrease the cabin air temperature. The roof temperature of car with PCM at 90 min is 8.63°C lesser than that of the car without PCM at 90 min. The maximum reduction in the air temperature is observed at the roof. This may be because of placing phase change material near the roof. Moreover, the reduction in temperature is minimum near to the feet as it is far away from PCM.

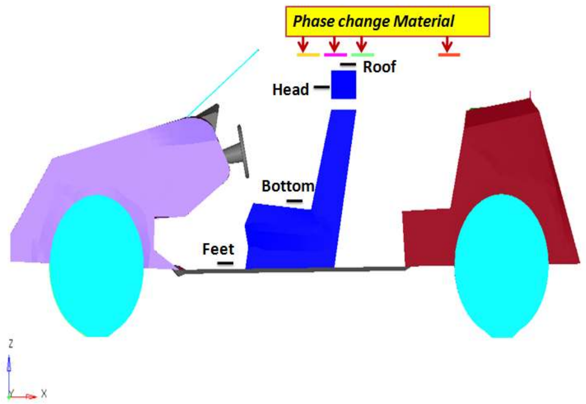

Figure 3. Positioning of Thermocouple at various locations.

Table 3. Simulation Methods.

Physics	Models
Radiation Model	S2S Model
Phase Change Model	Solidification and Melting Mushy Zone - 10000
Turbulence Model	k-ε Realizable
Simulation Type	Transient (90 min)
Discretization Method	Solver – SIMPLE Algorithm Pressure – Body Weighted Average Velocity – Second Order Energy – Second order DO radiation – First order
Gravity	-ze direction
Convergence Criteria	Continuity /Momentum/Velocity – 1e-04 Energy – 1e-06

Figure 5 shows the air temperature obtained for roof, head, bottom and feet temperature of car predicted by simulation. The roof temperature predicted at 90 min is 44.12°C which less than the air temperature predicted by S2S model for car without phase change material [3]. The same trend is observed at locations near to feet, bottom and head. The maximum reduction in temperature is obtained at roof because it is situated near to phase change material. Thus numerical simulation results show the same trend as experimental results. Figure 6 shows contour of air Temperature at middle plane of car cabin. Figure 7 shows the mass fraction of PCM at different intervals of time. The contour shows an increasing liquid mass fraction at different intervals of time. The melting point of PCM used in present work is 29°C, so there is no phase change observed in PCM for the initial couple of minutes. The melting fraction of PCM at 10 minutes is zero. As the time passes PCM absorbs the heat inside the cabin which results in reduction in cabin air temperature. Table 4 shows the comparison in the results obtained from experiment and simulation. The average deviation obtained in the result is below 9.93% which suggests that the above method can be used for simulating phase change material inside the car.

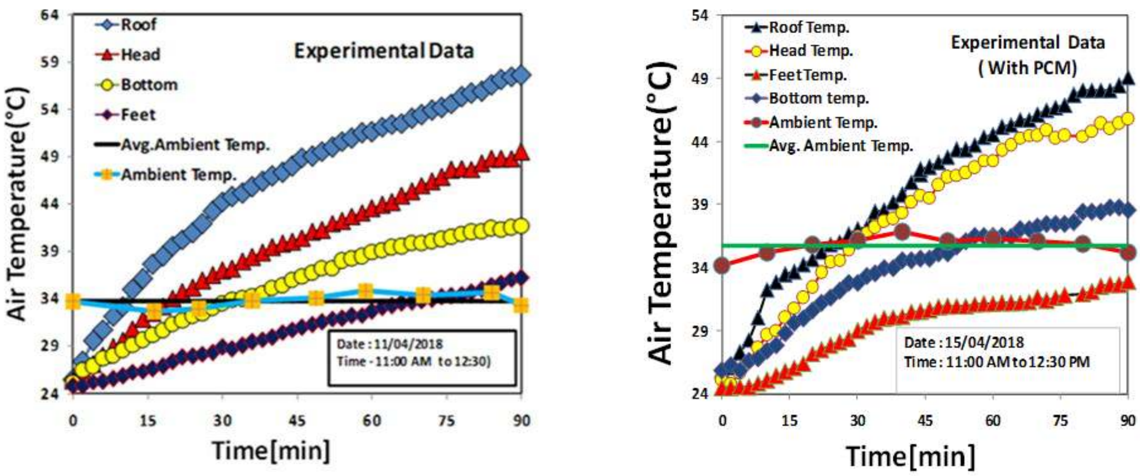

Figure 4. Air Temperature at different intervals of time (without PCM & With PCM).

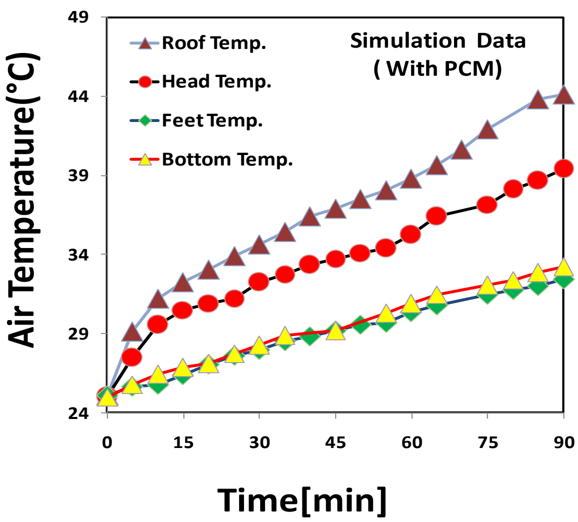

Figure 5. Air Temperature at intervals of time.

Table 4. Deviation from Experimental Result.

Location	Experimental Data	CFD Data	% Deviation
Roof	49.12°C	44..11°C	10.2%
Head	45.76°C	39.38°C	13.94%
Seat	38.60°C	33.20°C	13.98%
Feet	32.95°C	32.41°C	1.63%
	Average		9.93%

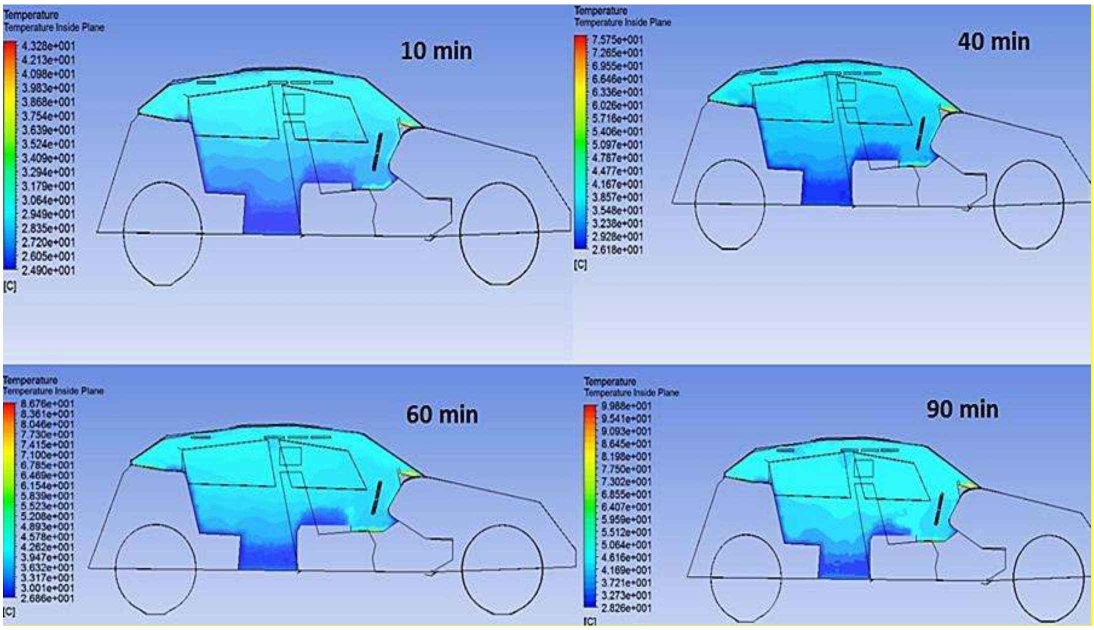

Figure 6 Contours of Air Temperature distribution along a plane at intervals of time

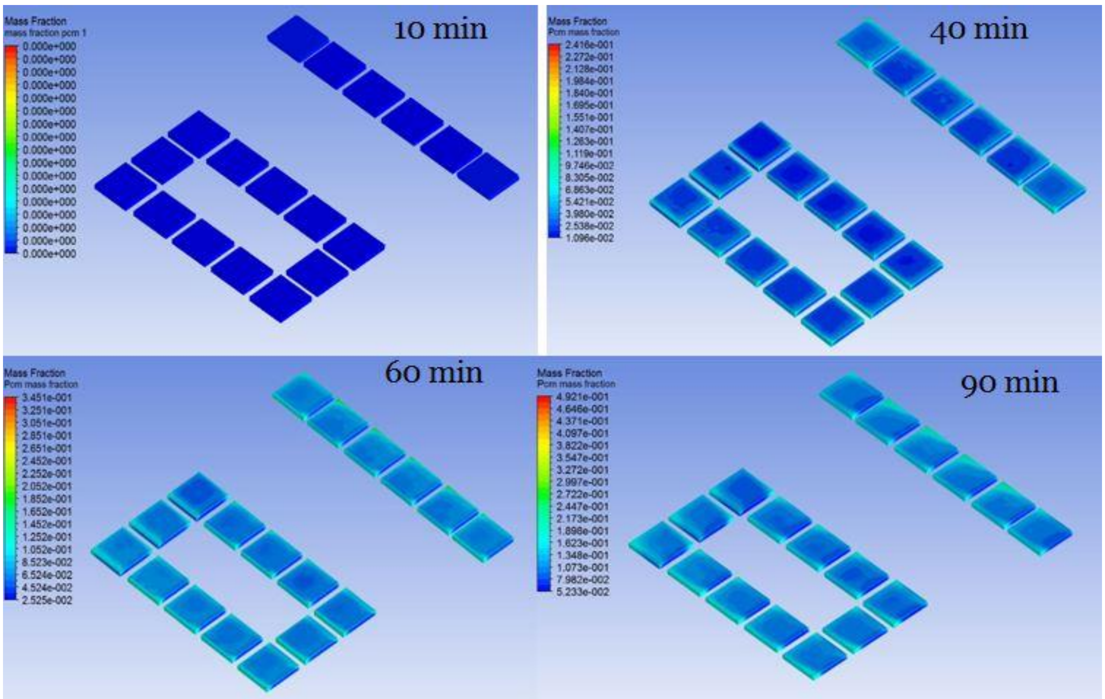

Figure 7 Liquid mass fraction of PCM

5. Conclusion

A high ambient temperature will lead to higher cabin temperatures in the parked cars, to verify this an Experimental & Numerical analysis is carried out by parking the car in the sun light, during the peak summer. It is observed that the cabin temperature will be ~22ºC more than the outside temperature. To reduce the cabin temperature an 6kg PCM is placed near the roof, then experimental & Numerical analysis is carried out. By this the cabin temperature is reduced by an average of 8ºC, also observed that average variation between experimental & Numerical results is 9.93%. By this a benchmarking between Numerical & experimental is established, so many no of Numerical analysis can be carried out by changing Location and mass of PCM.

References

[1] ANSI/ASHRAE Standard 55, 2013, “Thermal environmental conditions for human occupancy”, https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

This reference has two entries but the second one is not numbered (it uses the ‘Reference (no number)’ style.

[2] Hingane, A. S., “Temperature Variation in Parked Vehicle during summer and Its Threats and Prevention”- International Research Journal of Engineering and Technology, Vol. 05, No. 05 (2018), 271-274.

[3] B. Srusti, M. B. Shyam Kumar., “Experimental and Numerical Investigation of Air Temperature Distribution Inside a Car Under Solar Load Condition” – International Journal of Engineering, Vol. 32, No.7(2019), 1031 to 1039.

[4] Saleel, C. A., Mujeebu, M. A., Algarni, S., “Coconut oil as phase change material to maintain thermal comfort in passenger vehicles”, Journal of Thermal Analysis and Calorimetry, Vol. 136, No. 02 (2019), 629-636

[5] Jadidi, A. M., Jadidi, M., “An algorithm based on predicting the interface in phase change materials”, International Journal of Engineering - Transactions B : Applications, Vol. 31, No. 5 (2018), 799-804.

[6] Ebrahimi, M., Farhadi, M., Sedighi, K., Akbarzade, S., “Experimental investigation of force convection heat transfer in a car radiator filled with SIO2-water nanofluid”. International Journal of Engineering – Transaction B : Application, Vol. 27, No. 2 (2014), 333-340.

[7] Cabeza, L.F., Gutierrez, A., Barreneche, C., Ushak S., Fernández Á.G., Fernádez A.I., Grágeda, M., “Lithium in thermal energy storage: A state-of-the-art review”. Renewable and Sustainable Energy Reviews, Vol. 42, (2015), 1106–1112.

[8] Aydin, D., Casey, S.P., Riffat, S., “The latest advancements on thermochemical heat storage systems”, Renewable and Sustainable Energy Reviews, Vol. 41, (2015), 356–367.

[9] Shalaby, S.M., Bek, M.A., El-Sebaii, A.A., “Solar dryers with PCM as energy storage medium: a review”, Renewable and Sustainable Energy Reviews, Vol. 33, (2014), 110-116.

[10] Ma, T., Yang, H., Zhang, Y., Lu, L., Wang, X., “Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: a review and outlook”, Renewable and Sustainable Energy Reviews, Vol. 43, (2015), 1273-1284.

[11] Karimpour, P.F., Behesthi, H., "Performance Enhancement and Environmental Impact Analysis of a Solar Chimney Power Plant: Twenty-four-hour Simulation in Climate Condition of Isfahan Province, Iran" International Journal of Engineering – Transaction B : Application, Vol. 30, No. 8 (2017), 1260-1269.

[12] Fang, G., Tang, F., Cao, L., “Preparation, thermal properties and applications of shape-stabilized thermal energy storage materials”, Renewable and Sustainable Energy Reviews, Vol. 40 (2014), 237-259.

[13] McLaren, C., Null, J., Quinn, J., “Heat stress from enclosed vehicles: moderate ambient temperatures causes significant temperature rise in enclosed vehicles”, Pediatrics, Vol. 116, No. 1 (2005), 109–112.

[14] Grundstein, A., Meentemeyer, V., Dowd, J., “Maximum vehicle cabin temperatures under different meteorological conditions”, International Journal of Biometeorology, Vol. 53, No. 3 (2009), 255–261.