Energy storage by eutectic materials for the air conditioning of an electrical vehicle

P. Trivero[1,2], W. Biamino[1], E. Borgo[1], I. M. Ottino[1], L. Pezzi[2] & G. Rosso[2]
[1]Università del Piemonte Orientale "Amedeo Avogadro" – DISIT, Italy
[2]RTP s.r.l.s., Italy

Abstract

Energy usage optimization is a crucial issue in electric vehicles, especially for energy consuming services such as air cooling, because vehicle autonomy is solely related to battery capacity. Positive phase change eutectic materials can be used to store thermal energy by exchanging latent heat; when phase change occurs around a "comfort zone" (i.e. about 20°C) those materials can be effectively used to control air temperature. Starting from components of natural origin, we exploited an eutectic material melting at about 22°C with high latent heat, to improve the performances of an electric cooling system, mounted on a fully electrical minibus. We measured time evolution of air temperatures inside the vehicle, as well as the electrical consumption of a cooler; tests have been carried out in a climatic chamber in order to simulate operational conditions in the summer season. Measures have been performed by installing into the vehicle 16 metal containers filled with the eutectic material, previously solidified; measures have been compared with available results from similar tests carried out without the material. The cooler alone was unable to maintain an inside temperature lower than 33°C, due to the standard insulation of the vehicle (e.g. windows made of standard glass, without any specially designed solution). By using the cooled eutectic material we obtained two main results: as first the temperature difference (outside/inside) $\Delta T = 13°C$ was reached and maintained for about 90 minutes without the need of active cooling; when turning on the electric cooling system, we maintained a $\Delta T = 13°C$ for about 6 hours.
Keywords: energy storage, eutectic, power saving, electric vehicle, air cooling, personal comfort.

WIT Transactions on Ecology and The Environment, Vol 199, © 2015 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/RAV150161

1 Introduction

Environmental pollution, increased levels of greenhouse gas emissions, imminent depletion of fossil fuels and the resulting increase in their cost, have been the focus of debate for a long time, prompting research into technological innovations in order to prevent the expected environmental problems.

A more efficient and responsible use of energy is today important as well as the energy supplying from renewable sources. Another problem to be addressed is the need for excess energy storage that otherwise would be wasted in bridging the gap between generation and consumption of energy [1]. One possibility to solve this problem is the development of systems of energy storage with an emphasis on techniques for preserving the thermal energy as latent heat. Phase change material (PCM), has been used in the last few years to store thermal energy. The PCM are exploited for their particular ability to store a large amount of energy in the form of latent heat, keeping constant its temperature. They are of natural or artificial origin, and their choice can be made on the basis of their melting points near to the desired temperatures. Today, these materials are widely used in various fields such as thermal storage of solar energy, thermal preservation of food, heat pumps, and spacecraft thermal systems. They also find large applications as passive storage in bioclimatic building or sustainable architecture especially for energy saving, in agro-alimentary industries and different medical applications [2]. One of the latest innovations concerns the use of PCM for air conditioning of buildings and vehicles, collecting great success in automotive [3].

The main role of heat storage systems is to decouple the phase of production of thermal energy from phase of its consumption and to ensure a more efficient use of energy in order to reduce pollutant emission. These materials can represent a reservoir of thermal energy (cold or hot) previously stored and later released.

To reduce environmental pollution, especially in urban centres, and to improve energy efficiency, electric and hybrid vehicles are nowadays considered. The use of electric vehicles, especially for mass transport, has the following advantages: a) reduction of smog concentration and pollutants produced by fuels combustion, which is a serious problem of big metropolitan cities; b) increase in the efficiency of electric energy consumption, only used when needed and not during stand-by (e.g. stop at traffic lights, traffic jams, passengers embarkation and disembarkation, etc.). These advantages are even more relevant for minibuses used in urban transport.

Our research was aimed to design and build an eco-friendly and environmentally sustainable system for the air conditioning plant optimization of an IVECO Daily Electric Minibus, in order to provide it a greater autonomy in traction, because the air conditioning system rests on electric consumption of the battery pack. In this way, the optimized system would allow to reduce energy consumption, contributing to improve the environmental impact.

In this study we used two eutectic natural substances, a mixture of capric and lauric acid, which leverages its solid-liquid phase change [4]. This eutectic material is characterized by a melting point of 18°C, with a melting peak at 22°C and therefore accumulates latent heat in a temperature range comfortable to humans. Both fatty acids are extracted from coconuts. Because the mixture is not derived from petroleum, it is completely environmentally friendly and not toxic, reducing environmental impact in production and disposal phases. Furthermore, the fatty acids are readily available at accessible costs.

2 Materials and methods

For our purposes, 16 aluminium tube-shaped containers, to be inserted in the minibus, were filled of eutectic mixture of capric and lauric acid (called CALA). The containers (figure 1) have a specific section to maximize heat exchange, a length of 1.9 m each and contain a total of 88 kg of eutectic substance. Each tube weighs 8 kg for a total of 128 kg.

The goal of the tests was to maintain a constant temperature inside the Minibus in the range of the comfortable temperature for passengers, taking advantage of the latent heat storage of the eutectic mixture cooled in support of the air conditioning system that uses two coolers.

As the mixture completely solidifies below 18°C, the containers were cooled before use by means of ice inside a specially designed isothermal box for a few hours and subsequently inserted in the minibus on the overhead lockers and on the floor. Then we proceeded to carry out cooling tests.

Figure 1: Eutectic containers in isothermal box (left) and section profile (right).

Cooling tests on IVECO Daily Electric Minibus have been carried out at DIRNA BERGSTROM S.L. facilities in Alcalà de Henares (Madrid, Spain), with the use of the following instruments for temperature measuring:

a) 10 probes, 9 of which installed inside the minibus: driver's head, passenger's head, cooler exit (air outlet – front), cooler exit (air outlet – rear), inner space (aisle – central), external temperature, cooler air intake (front), cooler air intake (back), inner space (aisle – back) and headrest last row (figure 2). Temperatures and a relative humidity probes were directly connected to a computer, allowing real-time temperature monitoring and recording by means of a suitable software;

b) Escort iMiniPlus temperature loggers and Escort iMini MX RH hygrometer (temperature and relative humidity logger). These probes were installed inside and outside the Minibus. Escort iMiniPlus and Escort iMini MX RH hygrometer dataloggers measure the temperature of the object with which they are in contact, but are partly influenced by air temperature; they reach 67% of actual value in ~15 minutes.

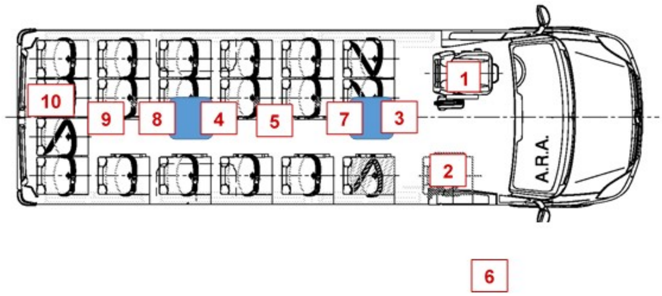

Figure 2: Plan of the minibus and available probes.

Other parameters measured were power supply voltage (~24 V dc link) and power supply current A.

The temperatures have also been evaluated using a Flir E5 thermographic camera.

2.1 Characteristics of the "Bycool Compact" cooler and IVECO Daily Electric Minibus

DIRNA Bycool Compact 3.0 technical specifications:

- Thermal power: 3.0 kW max
- Current: 11–38 A/h
- Voltage: 24 V
- Peak electric power: 912 W
- COP = 3.29 (evaluated on maximum current)
- Weight: 39.3 kg
- Dimensions: 826 mm x 726 mm x 203 mm

IVECO Daily Electric Minibus main specifications:

- Inner volume: 18 m^3
- Internal surface (cabin): 46 m^2
- External surface (vehicle body): 56 m^2
- Mass: 4038 kg without driver and passengers; ~5 ton with 3 battery packs (195 kg each) + 2 Bycools Compact 3.0 installed on the roof.

3 Measurements

The cooling tests were performed during two days: the first one using only the coolers and the second using coolers and eutectic system.

3.1 "Cool-Down" test: first day

The aim of the first test was to reproduce the "Cool-Down" condition, simulating the minibus parked in the morning, away from direct sunlight, before service start.

Environmental conditions during the test were set as follows: a) Average temperature at heads level at the beginning of the test (about 40°C); b) Relative humidity at heads level at the beginning of the test (about 40%); c) Outside temperature (about 40°C); d) Outside relative humidity (about 40%); e) Coolers operating with air recirculation at maximum speed and maximum power.

Escort iMiniPlus temperature loggers were installed on first and fourth row, while Escort iMini MX RH hygrometer on central seats.

The test started when the outside temperature was 40°C and the internal air temperature was in equilibrium (minibus doors were left open during air heating). The average temperature of blown cold air was 19.9°C from Cooler 1 and 21.8°C from Cooler 2. Measurements of the battery voltage and current were respectively 27.3 V and 60 A and remain constants during the period of the test.

A second test had the purpose of controlling the temperature replicating the operational use of the vehicle under direct sunlight, simulated with high-power lamps (1000 W/m^2).

Test conditions: a) Temperature, reached before, at heads level at the beginning of the test; b) Outside temperature (about 40°C); c) Outside relative humidity (about 40%); d) Radiation (1000W/m^2); e) Roof cooling with air recirculation at maximum speed and maximum power.

Due to radiation, outside air temperature reached 42.5°C.

A third test had the purpose of cooling down the temperature after doors opening, to replicate minibus actual conditions after a 10 minute stop with opened doors at the previous test conditions.

Figure 3 shows the graph of temperatures detected with the Escort iMiniPlus probes. From the figure one can derive that the temperature decreases from a higher starting value (38°C–37.5°C) to a minimum of 32°C, in about half an hour; the final average value is ~33.4°C.

3.2 "Cool-Down" test: second day

Eutectic containers, stored in the isothermal box, were cooled with ice for more than 12 hours to be sure the eutectic material was solidified.

To record temperatures, Escort iMiniPlus and Escort iMini MX-RH dataloggers were placed on: A: luggage rack (rear, right); B: luggage rack (front, right); C: luggage rack (front, left); D luggage rack (rear, left); E: roof; F: floor; II: headrest (centre, aisle seat); III: headrest (rear, aisle seat); V: headrest (front); Ex: outside; thermohygrometer: aisle seat (centre left);

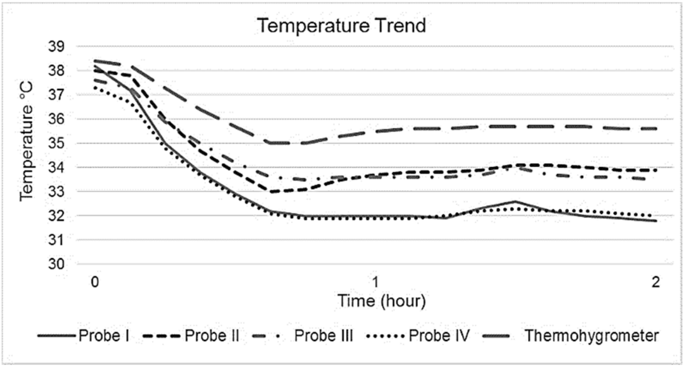

Figure 3: Temperature trend with the probes Escort iMiniPlus. I: aisle seat (front, right); II: aisle seat (front, left); III: aisle seat (rear, right); IV aisle seat (rear, left); Thermohygrometer: aisle seat (centre left).

The 16 containers were removed from the box and placed on the minibus; 6 were placed in each head locker (3 on the front, 3 on the rear), 4 on the aisle floor (2 on the front, 2 on the rear). Containers temperature was ~11°C.

At the start of the test, internal temperature was 21°C, external temperature 25°C.

Doors were closed and test started, according to the following steps: a) Turn on probes; b) Turn on room heating, to reach an external air temperature of 40°C with closed doors; c) Switch on the 1000 W/m^2 lights, to reach 40°C.

The duration time of the test was 9 hours approximately.

The rationale behind the "eutectic strategy" is different from the standard cooling approach. During operational use, with eutectic material installed in the minibus, the cold must be accumulated during the night when batteries are also charging. After service start in the morning, the temperature is kept low by the cold stored in the containers (latent heat adsorption). When using conventional cooling instead, the whole minibus mass (~5 ton) can be hypothesized at higher temperature, needing therefore high cooling power. The different procedure, used for eutectic tests, comes from this consideration.

After 50 minutes, outside air temperature reached 40°C. Outside temperatures, as measured by probe "Ex", appear lower than those measured by DIRNA sensors because it was placed on the floor. Internal air temperature reached 33°C 2 hours after. The coolers were then turned on. Starting from that moment, voltage and current were measured every 5 minutes.

At the end of the measurements the door were opened for 10 minutes and the internal temperature grew. Figure 4 shows the trends of temperatures detected by the Escort iMiniPlus probes.

The development of humidity during the test is shown in figure 5. As expected, relative humidity decreased with increasing temperature, reaching very low values.

The current demand for the feeding of cooler has evidenced an increase during two first hours remaining almost constant until the end of the test.

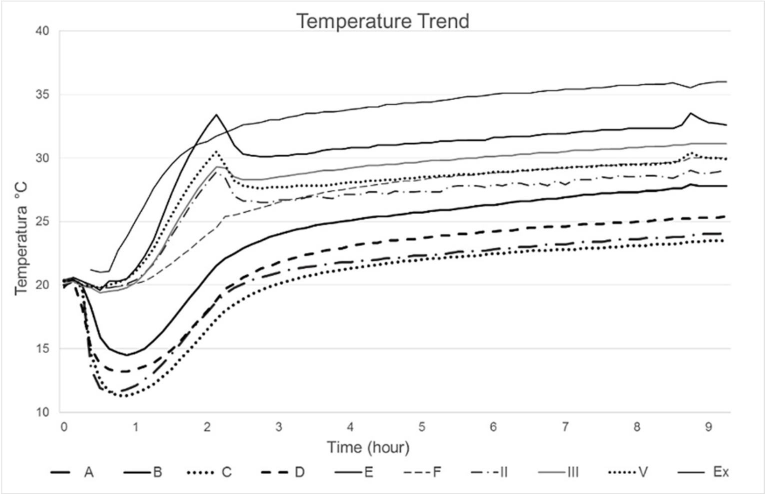

Figure 4: Temperature trend with the probes Escort iMiniPlus. A: luggage rack (rear, right); B: luggage rack (front, right); C: luggage rack (front, left); D luggage rack (rear, left); E: ceiling; F: floor; II: headrest (centre, aisle seat); III: headrest (rear, aisle seat); V: headrest (front); Ex: outside.

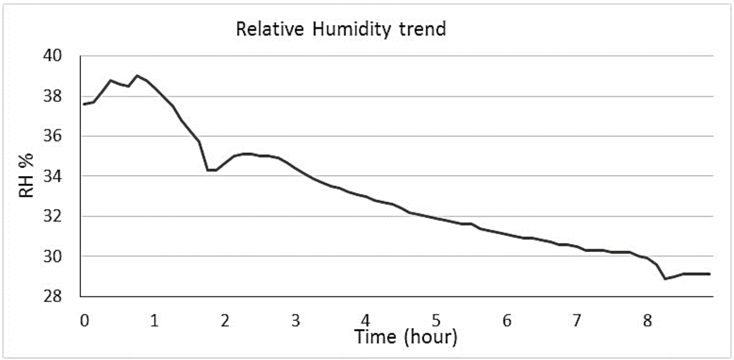

Figure 5: Relative humidity trend with the Escort iMini MX-RH hygrometer.

3.3 Two days tests: "Cool-Down" and transmittance evaluation of IVECO Daily Electric Minibus

Figure 6 gathers the results from the two measurements days; different measurements of inside air temperature have been averaged.

Figure 6 links tests carried out on the first day (coolers only) and during the second (with eutectic material); it is possible to note how the "cooling only" approach cannot cool the inner air below 33°C (temperature difference $\Delta T = \sim 9°C$ between inside and outside air temperature), while the use of eutectic material allows a temperature decrease of ~28°C (temperature difference ΔT= ~13°C between inside and outside air temperature), with an equilibrium reached after 6 hours at 30,8°C (ΔT= ~11.2°C).

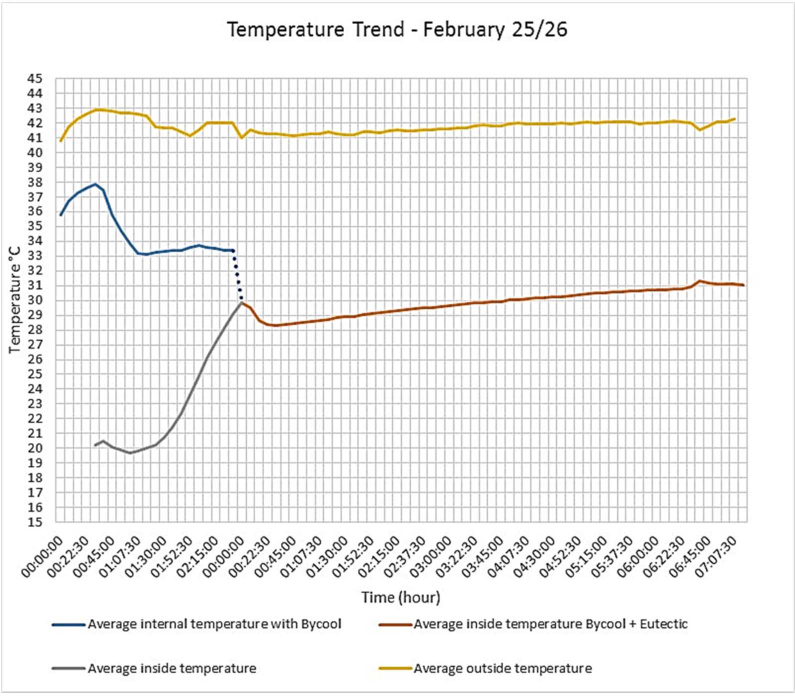

Figure 6: Measurements performed during the two days of tests.

The main reason for these results can be found in the high transmittance of the minibus that can be roughly estimated by considering the thermal equilibrium reached during first test, after turning on the two coolers. The total adsorbed current was I = 60 A, and voltage V = 27.3 V; this gives an electrical power of 1,638 kW, corresponding to a thermal power W = 5,346 kW (evaluated by taking into account Bycool technical specifications for maximum thermal ad electric power values). Transmittance can be evaluated with the formula:

$$U=WS^{-1}\Delta T^{-1} \tag{1}$$

where W is the thermal power, S is the minibus surface and ΔT is the difference of internal and external temperature.

Considering ΔT=9°C the maximum transmittance is U = 11.7 W/m^{2}K. However, it is necessary to take into account the heat stored into the whole minibus mass, initially heated up to 40°C, and the blackbody radiation emitted by the internal surface; the thermal energy, that the two coolers must supply to pump the heat outside, is equivalent to the sum of two contributions: the outside-to-inside heat flux and the radiation from inner surface to the inside air (at a lower temperature).

A more realistic transmittance estimation can be deducted from measurements carried out with eutectic material coupled with coolers. We take into account the thermal equilibrium reached on the second day, six hours after turning on the two coolers; in that moment the energy contribution from eutectic containers was almost depleted, and internal minibus surfaces were in equilibrium with inner air; therefore the thermal power W = 5,246 kW was compensating the outside-to-inside heat flux; transmittance can be computed as U = 9.2 W/m^{2}K (with ΔT=11.2°C).

With the minibus mass fully heated, the thermal energy flux from blackbody radiation can be estimated as 1.14 kW by using U= 9.2 W/m^{2}K and ΔT =9°C. This value is validated by considering the difference between blackbody radiations, from minibus inner surface, evaluated at 36.5°C (estimated surface temperature) and 33°C (inner air temperature).

The heat flux has also been evaluated on the basis of temperatures measured with a Flir E5 thermographic camera, evidencing the windows as the most critical areas; a huge thermal dispersion is observed through roof windows that are made of standard glass without any anti-reflective coating (figure 7).

Figure 7: Minibus interiors: picture (left) and thermographic image (right).

4 Results and discussion

In order to summarize and evaluate the obtained results, figure 8 gathers all the measurements carried out during two days; values of inside air temperature have been averaged and all temperatures have been normalized to external temperature of 40°C to better evidence, with respect to figure 6, the differences between the two approaches.

The little temperature increase (~1°C) in the last phase of the tests, due to passenger door opening for 10 minutes, is not a critical issue: only 17 kJ of thermal energy are needed to cool down the 18 m^3 of inner air to the previous temperature.

A number of advantages come from the "eutectic approach":

a) The whole minibus mass is cooled to a low temperature, acting as a cold storage (sensible heat, while eutectic material accumulates latent heat);
b) The eutectic material changes its phase, becoming solid, accumulating a big amount of frigories with respect to its small weight; the solid phase can be preserved or regenerated during the use by turning on the coolers and forcing the air flux through the eutectic containers installed in the head lockers;
c) In operational use (daytime) the inner air temperature is kept low without battery consumption, up to exhaustion of cold stored in eutectic material, with standard cooling needed only in the warmest months; this compensates minibus the weight increase (~100 kg);
d) coolers are turned on only at hottest temperatures, or when the cold storage runs out;
e) The same approach will be used in future also for winter heating.

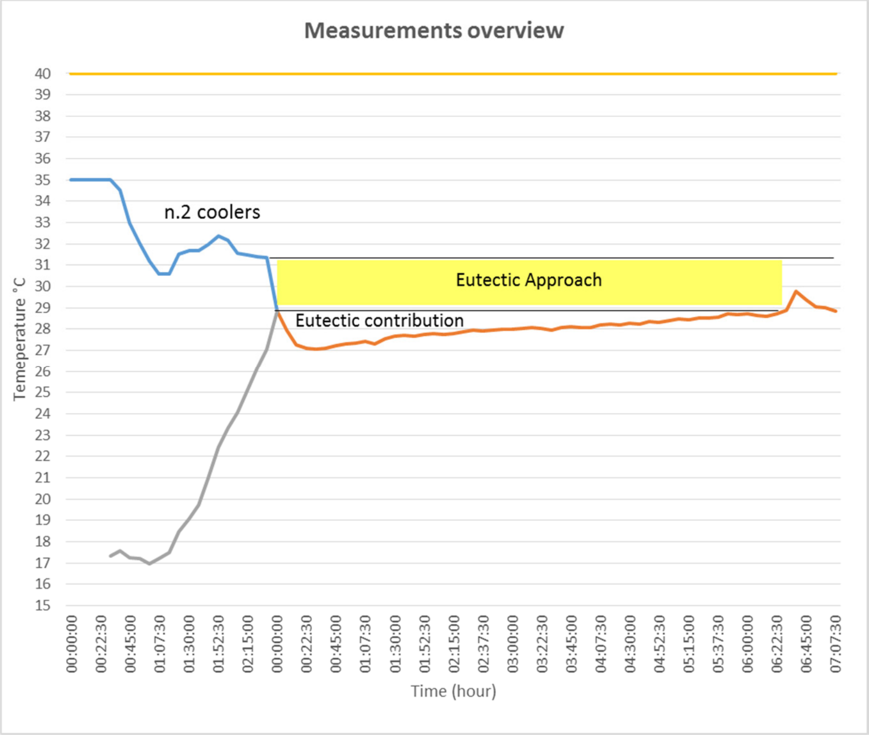

Figure 8: Results of the two measurements days.

We are building a prototype of a new cooling system, to be integrated with the existing one. The new cooling plant will be realised by removing air outlets from the coolers and installing new pipes to force the cool air into the head lockers, where eutectic material will be placed; also air outlets will be installed in head lockers. The eutectic material containers, thanks to a new design respect to the ones we used in these tests, will allow a better efficiency in heat transfer. The eutectic material will be cooled at night during battery charge, and shall be cooled also in the daytime when needed.

Acknowledgements

The described activities have been carried out during PIE_VERDE project activities, financed by Regione Piemonte (Italy) in the framework of POR FESR 2007/2013 with the financial aid of European Regional Development Fund, Italian Republic and Piemonte region.

The cooling system based on PCM (100% ecologic, positive phase change), exploited in PIE_VERDE grant, comes from an original idea protected by Italian patent n° 1413684 (January 30, 2015) by Rosso Giovanni, Pezzi Lorenzo and Trivero Paolo (firm: RTP s.r.l.s.).

The authors want to thank DIRNA Bergstrom S.L. for allowing us to use their facilities in Alcalà de Henares (Madrid, Spain), and IVECO SpA for letting us use the Daily Electric Minibus.

References

[1] Agyenim, F., Hewitt, N., Eames, P. & Smyth, M., A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). *Renewable and Sustainable Energy Reviews*, **14**, pp 615–628, 2010.

[2] Sharma, A., Tyagi, V.V., Chen, C.R. & Buddhi, D., Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews,* **13**, pp. 318–345, 2009.

[3] Li, G., Hwang, Y. & Radermacher, R, Review of cold storage materials for air conditioning application. *International Journal of Refrigeration*, **35**, pp. 2053–2077, 2012.

[4] Dimaano M.N.R. &Watanabe T., Performance investigation of the capric and lauric acid mixture as latent heat energy storage for a cooling system. *Solar Energy*, **72**, pp. 205–215, 2001.