Universitat de Lleida

KTH Energy and Environmental Technology

Ecostorage

COST Report
TUD Action COST-STSM-TU0802-05255
Next Generation Cost Effective Phase Change Materials

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TABLE OF CONTENTS

TABLE OF CONTENTS i
INDEX OF FIGURES ii
INDEX OF TABLES ii
NOMENCLATURE iii
1. Introduction 1
  Ecosaveit Cool by Ecostorage Sweden AB 1
  Description of Cubicle Setup at University of Lleida, Host of STSM 2
  Description of the KTH – Cold Storage Thesis Project 3
2. Experimental Setup 3
3. Testing Procedures 5
  TEST I 5
  TEST II 6
  TEST III 6
  TEST IV 6
4. Results 7
5. Future Work 10
6. Conclusion 10
7. Acknowledgement 10

INDEX OF FIGURES

Figure 1 Energy Flow Chart 2
Figure 2 Cubicles in Puigverd, Spain (Ecosaveit Cubicle: second from the right, Ref Cubicle: forth from the right) 3
Figure 3 Schematics of the Setup 4
Figure 4 Temperature Profiles (from left to right: fan on mode ; normal operating mode; 200W heat injection in Ecosaveit Cubicle; 400W heat injection in both cubicles; indoor air recirculation; normal operation.) 7
Figure 5 Measured Charging Power, Power Ratio and Power of Cooling Supplied to Room: Normal Operating Mode 8
Figure 6 Measured Extraction/Storage Power, Power Ratio and Power of Cooling Supplied to Room: Complete Discharge and Charge Cycle 9

INDEX OF TABLES

Table 1 Operation Modes for EcosaveIt Cool Prototype 1

NOMENCLATURE

Roman and Greek Letters

A	Area	m^2
Cp	Specific heat	J/kg/K
E	Energy capacity	Wh or kWh
$\dot{m}$	Mass flow rate	kg/s
P	Power	W
ρ	Density	kg/m^3
T	Temperature	K
U	Heat transfer coefficient	W/m^{2}K
$\dot{V}$	Volume flow rate	m^3/s
Valve	Valve opening	%

Subscripts

after	After PCM storage
ambient	Ambient air
in	Inlet
max	Maximum
PCM	Phase change material
out	Outlet
Room	Cubicle room
Cool	Cooling of Room
ref	Reference

1. Introduction

A Short Term Scientific Mission (STSM) exchange among Next Generation Cost Effective Phase Change Materials (NeCoE-PCM) delegates, Prof. Luisa Cabeza, Lleida University, Spain, Ass. Prof. Dr. Viktoria Martin, Royal Institute of Technology, (KTH), Sweden and CEO Fredrik Setterwall, Ecostorage Sweden AB was carried out within the framework of European Cooperation in Science and Technology (COST) in October 2009. Justin NingWei Chiu, PhD student from KTH, supervised by Dr. Martin, brought to Lleida a PCM-based storage, named "Ecosaveit Cool", developed by Ecostorage Sweden AB, to be integrated in buildings for free cooling purpose. The product is aimed at using nighttime cold for daytime cooling so as to increase energy use efficiency in buildings. Within the STSM proposed, KTH will evaluate Ecosaveit Cool by integrating it in the unique cubicle research facilities owned by Lleida University.

This Short Term Scientific Project as a collaboration between the industrial world and the two academic institutes boosted international networking in a multicultural research environment, furthermore this COST Action fostered cooperation between industrial know-how and academic expertise. The project also brought in economic perspective in a product development process, which has not yet been a concern in the academic research field. The STSM has truly promoted the possibility of bringing together research and product evaluation. This report will provide detailed description of the Ecosaveitcool prototype, the experimental setup, prototype evaluating procedures and a brief overview of the obtained performance results. In parallel, a strong bonding between the STSM and the PhD thesis studies entitled "Cold Thermal Energy Storage" coexisted throughout the project.

Ecosaveit Cool by Ecostorage Sweden AB

The prototype "Ecosaveit Cool" is an industry-designed active thermal energy storage for cooling of habitation zone in buildings. This is a PCM-based product for free-cooling of buildings using outdoor cold air. In this product, a phase change material (PCM) storage is charged, solidified, using ambient cold and then is later used for daytime cooling through melting by cooling of outdoor or indoor warm air judged on their temperature. The prototype weighs 60 kg, dimensioning 100 cm x 40 cm x 16 cm and has a storage volume of 40 kg corresponding to 1.6 kWh of latent heat storage capacity or 2 kWh with 8°C sensible heat storage. The storage is charged with free cooling from the ambient air through 18 l/s air ventilating device.

The control system consists of four possible operating modes, the modes and corresponding functions are described in Table 1.

Table 1 Operation Modes for EcosaveIt Cool Prototype

Inlet	Outlet	Purpose
Outdoor air	Outdoor	Charging of PCM
Outdoor air	Indoor	Cooling of room with outdoor cold air, while also charging the storage if not fully charged or discharging of the storage when outdoor air is warmer than the storage.
Indoor air	Indoor	Cooling of room from storage
Indoor air	Outdoor	N/A

Two types of power have been evaluated in the study, they are storage charging/discharging power and obtainable cooling power that can be delivered to the room. The emphases of the current report are placed on evaluation of PCM storage, nonetheless room cooling will also be briefly discussed in the results section.

Depending on the ambient air temperature, storage temperature and indoor room condition, six possible energy flows may be obtained with the four operating modes, referring to Figure 1. Flow patterns 1 and 3 correspond to air flow from outdoor to indoor, while discharging and charging the storage. Flow pattern 2 corresponds to an internal circulation, hence a discharge only of the storage. Flow patterns 4 and 5 correspond to charging of the storage by extracting cold outdoor air and releasing warm air to the outside. In the most unfavorable condition where ambient air and PCM are both at higher temperature than the room or when the room temperature reaches thermal comfort level, the fan is put to a halt.

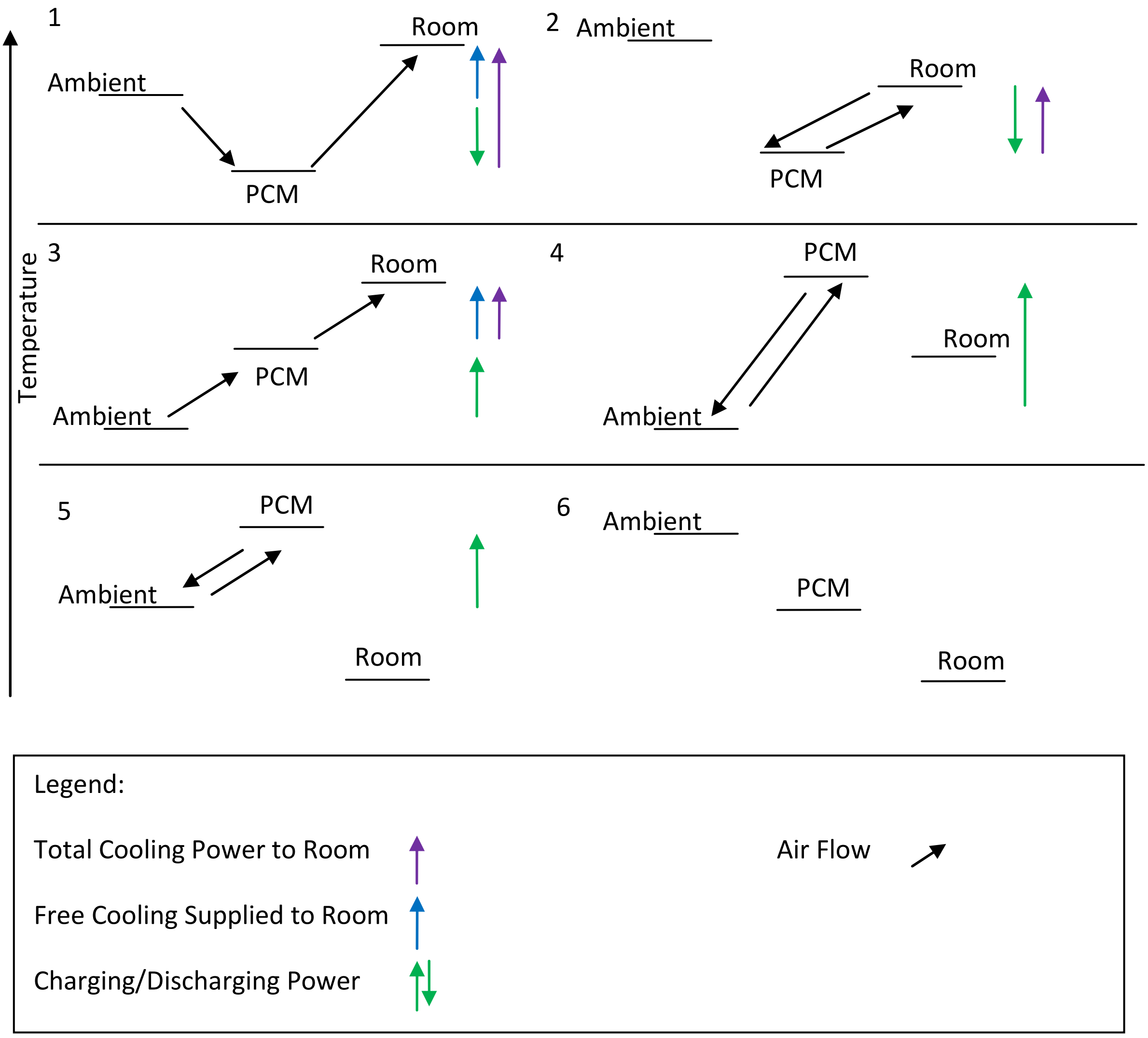

Figure 1 Energy Flow Chart

Description of Cubicle Setup at University of Lleida, Host of STSM

Energy Research Center (CREA) at University of Lleida, Spain has put in place, as of 2009, nine cubicles in a remote village, Puigverd aiming for energy efficiency evaluation and energy consumption studies. The prototype Ecosaveit Cool was installed in one of the cubicles which will be referred as Ecosaveit Cubicle, and the evaluation was carried out for a period of 14 days. Ecosaveit Cubicle was compared to a reference cubicle, which has similar insulation and thermal properties. The utilized cubicles are indicated in Figure 2.

Figure 2 Cubicles in Puigverd, Spain (Ecosaveit Cubicle: second from the right, Ref Cubicle: forth from the right)

Description of the KTH – Cold Storage Thesis Project

A four-year PhD project entitled "Cold Thermal Energy Storage" financed by Swedish Energy Agency is now being carried out by Justin NW Chiu at KTH-Royal Institute of Technology, Sweden. The project manager and PhD supervisor is Dr. Viktoria Martin. Thermal energy storage (TES) systems store thermal energy when it is available and provide thermal energy to the system in the aim of achieving better system regulation. Implementation of such system in a built environment reduces peak power demand and increases system stability. Latent heat based TES system using Phase Change Materials (PCMs) is the main focus of the cold storage thesis project. Latent heat based systems are used for them being capable of storing high thermal energy capacity and for them being able to provide constant and adequate storage temperature.

2. Experimental Setup

Cubicle built with mineral wool as insulation material and cubicle with polyurethane foam inside the walls have the most similar heat transfer U-value as judged through the relatively close indoor temperature profile of the two cubicles, 0.3°C difference. This was measured before the start of the Ecosaveit Cool evaluation, and is an average difference for a period of more than 2 months. Hence one cubicle was served as the reference (the one with polyurethane) and the prototype was installed in the other cubicle (the one with mineral wool).

The experimental setup is shown in Figure 3, the registered parameters shown below were acquired with onboard data acquisition device:

- indoor cubicle temperature GT1-Room (as measured by Ecosaveit Cool built-in sensor)
- PCM temperature estimate GT4 PCM (as measured from the outside of the casing)
- outdoor air temperature placed on the outside north wall GT3 Out
- outlet air temperature GT2-after PCM
- positioning of the inlet air valve
- positioning of the outlet air valve
- fan on/ fan off

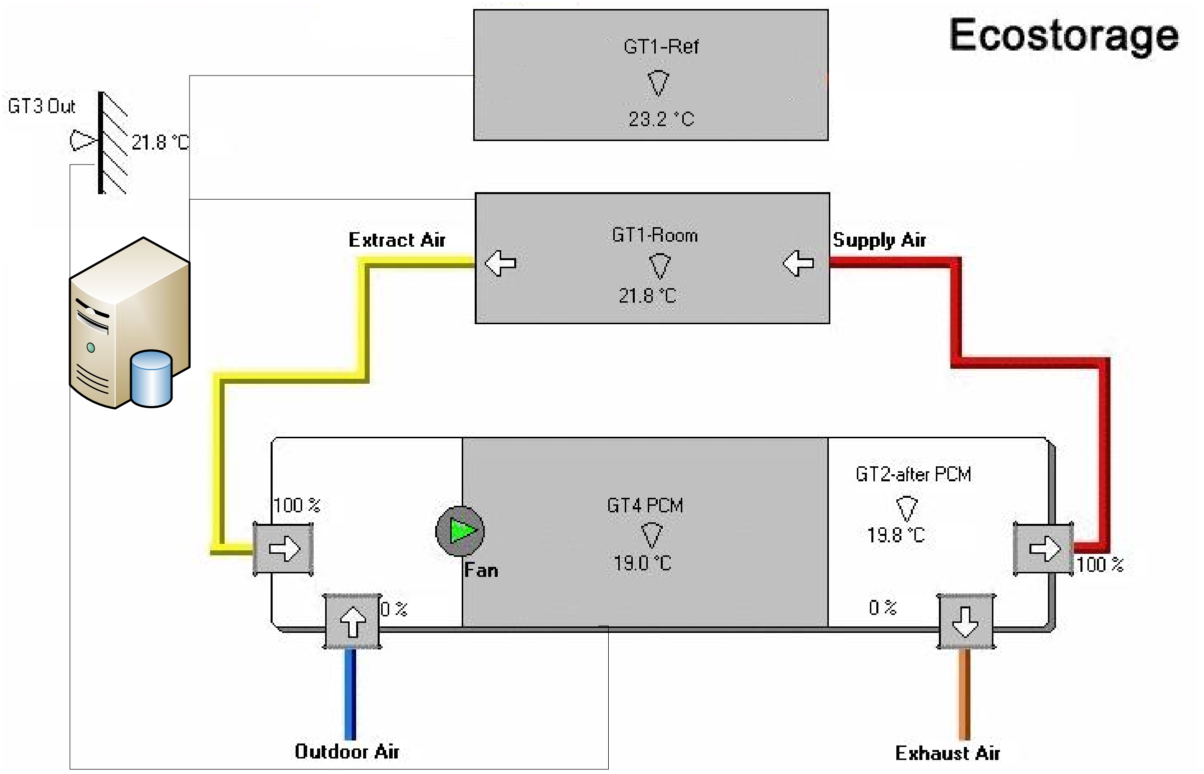

Figure 3 Schematics of the Setup

The data were measured at 10 seconds intervals and were averaged and stored after every 12 readings, tantamount to one registered value every two minutes interval. In parallel to the onboard data logger, additional data were also read from the existing cubicle measuring chain at averaged 5 min interval:

- indoor Ecosaveit cubicle temperature
- indoor Reference cubicle temperature
- floor temperature
- 4 walls temperatures
- ceiling temperature
- indoor humidity
- outdoor humidity
- wind speed
- solar irradiation
- heat flux through south wall

The storage/discharge power is obtained through analysis of inlet and outlet air enthalpies. The general equation for charging and discharging power is given in Eq. 1. However as the inlet to the Ecosaveit Cool was not measured directly, the inlet temperature was counted as a function of valve opening, as shown in Eq. 3

$$P_{PCM} = \dot{m}.Cp.(Tout - Tin) \qquad \text{Eq. 1}$$

Where Tout is the temperature of the air leaving the PCM section, and Tin the temperature of the air entering this section.

The mass flow is given from the knowledge of the volumetric flow and the density of air.

$$\dot{m} = \rho.\dot{V} \qquad \text{Eq. 2}$$

and

$$Tin = [(Tambient).\frac{Valve}{100} + (Troom).\frac{(100-Valve)}{100}] \qquad \text{Eq. 3}$$

hence the power results in

$$\mathbf{P_{PCM} = \rho.\dot{V}.Cp.\left[(Tout - Tambient).\frac{Valve}{100} + (Tout - Troom).\frac{(100-Valve)}{100}\right]} \qquad \textbf{Eq. 4}$$

The theoretical maximum storable/extractable power to the PCM may be obtained through substitution of outlet air temperature by PCM temperature in the charging and discharging mode, this gives Eq. 5.

$$\mathbf{P_{PCM\ max} = \rho.\dot{V}.Cp.\left[\left(T_{PCM} - Tambient\right).\frac{Valve}{100} + \left(T_{PCM} - Troom\right).\frac{(100-Valve)}{100}\right]} \qquad \textbf{Eq. 5}$$

In the performed calculation, air density and air specific heat are considered constant and are taken at 15°C.

The power ratio is then defined as the ratio of P_{PCM} and $P_{PCM\ Max}$.

$$\mathbf{Power\ Ratio = \frac{P_{PCM}}{P_{PCM\ max}}} \qquad \textbf{Eq. 6}$$

The stored/discharged energy capacity is then calculated through integration of power through time, as shown in Eq. 7.

$$\mathbf{E = \int P = \int \dot{m}.Cp.(Tout - Tin) = \int \rho.\dot{V}.Cp.[(Tout - Tambient).Valve/100 + (Tout - Troom).((100 - Valve))/100]} \qquad \textbf{Eq. 7}$$

In similar fashion, the total cooling power that is provided to the room by Ecosaveit Cool unit can be calculated through Eq. 8

$$\mathbf{P_{Cool} = \dot{m}.Cp.(Troom - Tout)} \qquad \textbf{Eq. 8}$$

It needs to be pointed out that this cooling power consists of either direct free-cooling and/or discharged cold from the storage. The part of the cooling power provided by Ecosaveit Cool that comes from discharging the storage is found from Eq 4 above.

3. Testing Procedures

The unit provides both free cooling from outdoor ambient air and direct cooling from discharging of the storage, the focus of the study is however mainly put on study of charging/discharging of the PCM. The experimental work carried out in Lleida, Spain was a dynamic evaluation of the prototype. During the evaluation period, acquired data were constantly monitored and modifications to the setup chain were done so as to improve the data quality. The experimental work and schedule are described as follows.

- Week 1: Oct 5-11. Installation of the Ecosaveit Cool, free cooling thermal energy storage prototype.

- Week 2: Oct 12-24. System performance evaluation, the goals and methods are described as below:

TEST I

Goal: Determine the power storage/extraction rate that can be reached with Ecosaveit Cool prototype.

Method: The storage/extraction power is studied through normal operating mode and maximum fan speed mode.

TEST II

Goal: Determine the energy capacity of the Ecosaveit Cool.
Method: Recycle the indoor air so as to discharge completely the storage followed by charging of the storage with outdoor ambient cold air.

TEST III

Goal: Determine the effectiveness of Ecosaveit Cool by studying the indoor temperature variation.
Method: Compare the indoor temperature profile of the reference cubicle and Ecosaveit Cool cubicle.

TEST IV

Goal: Perform parametric study of the effectiveness of Ecosaveit Cool with internal heat source variation.
Method: Compare the indoor temperature profile of the reference cubicle and Ecosaveit Cool cubicle while having an internal heat injection to both cubicles.

Each one of the performance tests is shown in Figure 4, the installation of the prototype to the cubicle was done on the 9th, the system was set to fan on mode until the 13th, control system was then set to normal operation mode from the 13th to the 15th. As the system started to idle (no discharge demand) due to attainment of comfort indoor temperature, 200W of internal heat input was injected from the 15th to the 16th in the EcosaveIt cubicle. Starting from the 16th, both cubicles were placed 400W (70W/m^2) heat input. In order to determine EcosaveIt maximum cold storage capacity, free cooling option was removed from the control system so as to discharge/melt completely the storage medium from 19th to the 21st. On the 21st, Ecosaveit was set again to normal operation mode so as to determine the maximum charging power and charging capacity.

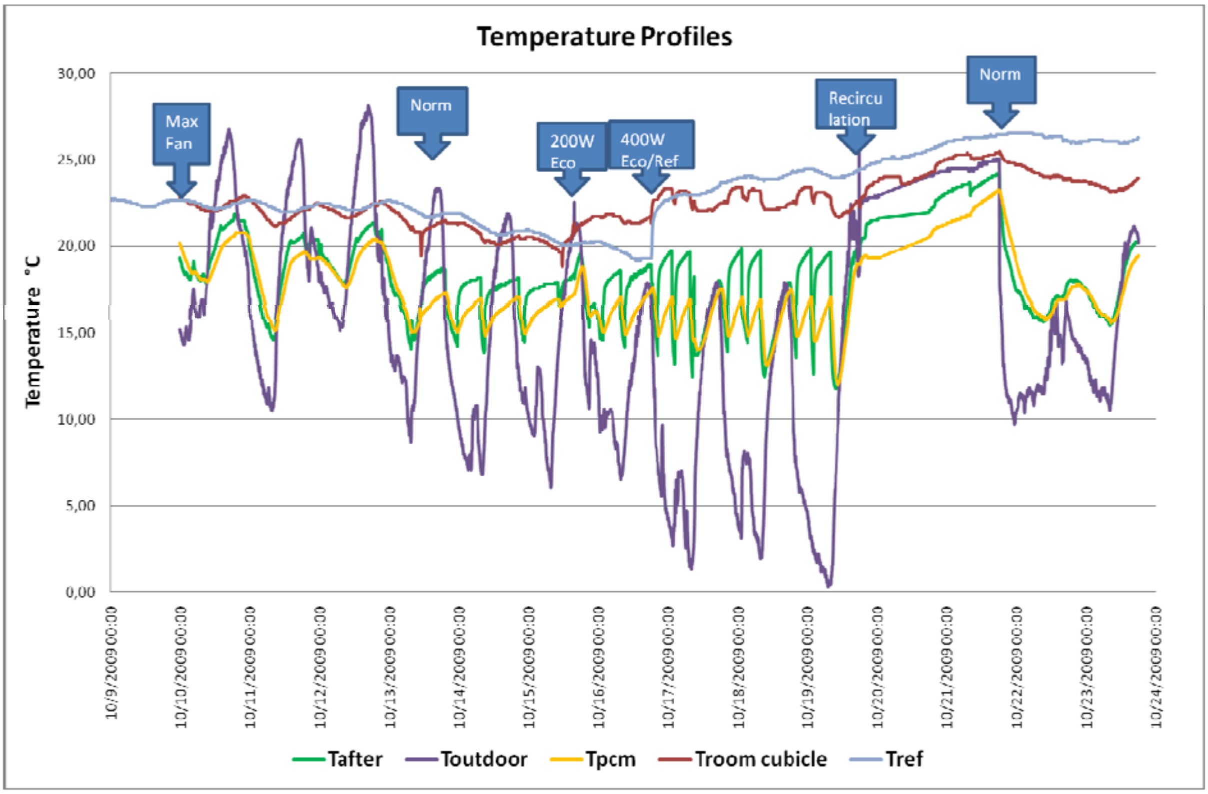

Figure 4 Temperature Profiles (from left to right: fan on mode ; normal operating mode; 200W heat injection in Ecosaveit Cubicle; 400W heat injection in both cubicles; indoor air recirculation; normal operation.)

4. Results

The actual testing was carried out in Lleida for two weeks time in autumn, outdoor ambient air temperature ranged between 10°C and 25°C for the first few days of testing allowing thus evaluation of the latent heat store, but in a week time, outdoor temperature dropped to maximum 18°C. Due to the cold climate condition, latent heat thermal storage concept of the PCM storage was hardly ever used. The PCM temperature measurements indicated PCM remained for most of the time in solid state, except for the “forced” shut-off of free-cooling mode. In fact, most evaluated power extraction rate that was stored in the PCM only took into account the “sensible heat storage”.

The reference cubicle does not have the same insulation material as in the EcosaveIt cubicle, statistic analysis from data obtained in Sept (solar irradiation= 800W/m2) and in Oct (solar irradiation=700W/m2) shows as a matter of fact average 0.3 °C higher room temperature in the reference cubicle in free floating mode (without any heat supply/withdrawal). After the installation, under the normal operation without any internal heat supply, EcosaveIt cubicle room temperature dropped to 0.48°C lower than the reference temperature. While 400W (70W/m^2) heat was injected to the cubicle, EcosaveIt demonstrated the capability of maintaining the room temperature from 22°C to 23.5°C as compared to 26°C, steady state reference room temperature (refer to Figure 4).

Power storage and extraction rates are two of the key performance indicators for a free cooling based TES system. The charging and discharging power of the PCM store are indicated with positive and negative signs corresponding to respectively charging and discharging of the store. Measured powers are obtained from Eq. 4, and theoretical maximum attainable powers are based on Eq. 5. The power obtained for charging and discharging during maximum fan speed operation mode are respectively 90W and 80W, which correspond to 80% of the theoretical maximum power.

Figure 5 is a zoomed in representation of the days 13th to 15th. The broken lines correspond to fan off state. The PCM charging power, room cooling power and power ratio as defined in section 2 Experimental Setup are represented. In normal operating mode, as represented in Figure 5, due to the cold outdoor condition, no discharging was needed. This resulted in automatic shut off of the system through fan power off. Nonetheless during night time with ambient outdoor air temperature lower than PCM temperature, the prototype was set to charging mode. The charging power rate reached 40W to 90W the first and the third night, but had a soaring start off the second night reaching a charging power of 190W, the power ratio remained in all case constant at 80%. The system then shut off when PCM temperature reached 15°C, as shown in Figure 4. Finally, when an internal heat input of 200W (35W/m^2) and 400W (70W/m^2) were injected to the cubicles, the discharging power decreased to 40% of the theoretical maximum power. A detailed analysis of the test results with 400W input will be described later.

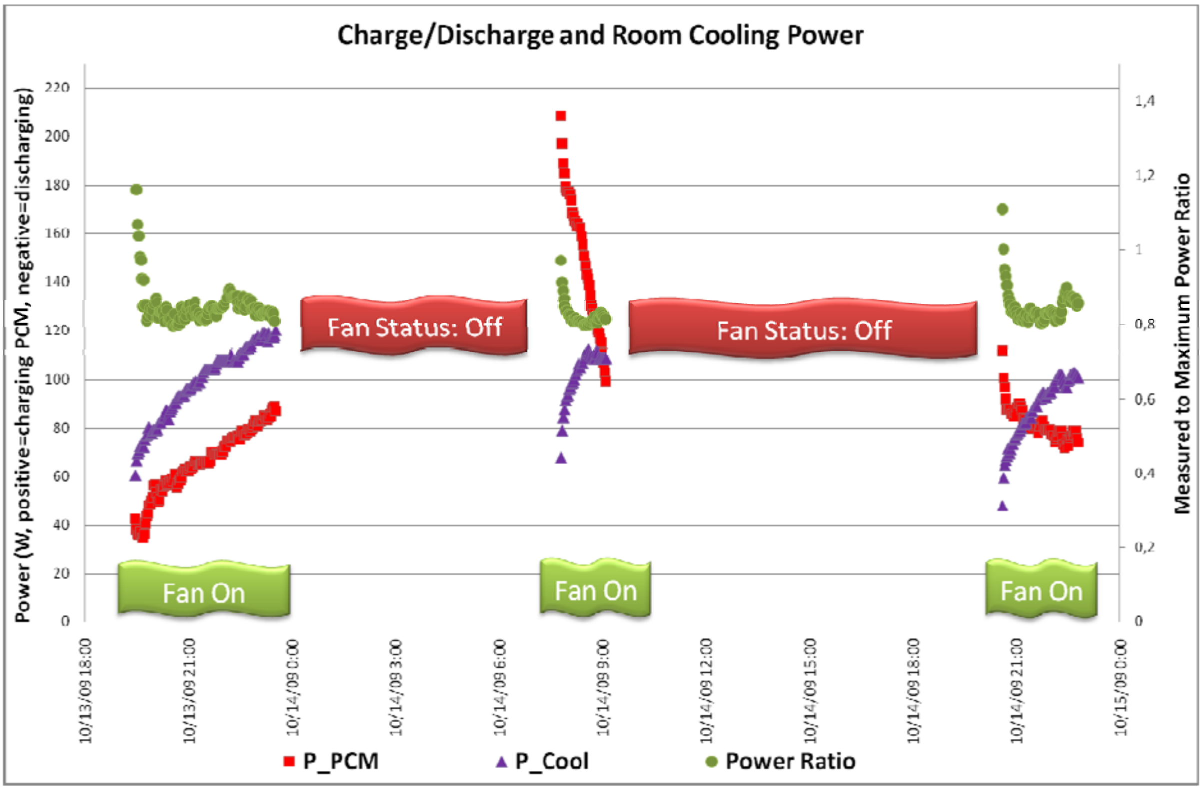

Figure 5 Measured Charging Power, Power Ratio and Power of Cooling Supplied to Room: Normal Operating Mode

The storage capacity was obtained through integration of charging power to time as depicted in Eq. 7. TES was first discharged through recirculation of indoor hot air until depletion as indicated in Figure 6, period A, then the prototype was reconnected to outdoor cold air for charging, period B. The timeframe chosen for capacity evaluation corresponds to the charging period when PCM temperature is higher than the outlet air temperature. PCM temperature at the start of the charging was at 23.2°C, and it decreased to 15.8°C at the end of the charging. The obtained capacity equals to 2.1 kWh, which matches with 5% difference to the designed storage capacity of 2kWh with 8°C temperature swing.

The charging of the storage started on the 22^{nd} as shown in Figure 6, the charging power reached 170W at a power ratio of 80% to 95% then dropped to 90W after approximate 12 hours of charge time. It can be seen from the curve that high charging power was obtained at the beginning of the process but decreased proportional to charging time.

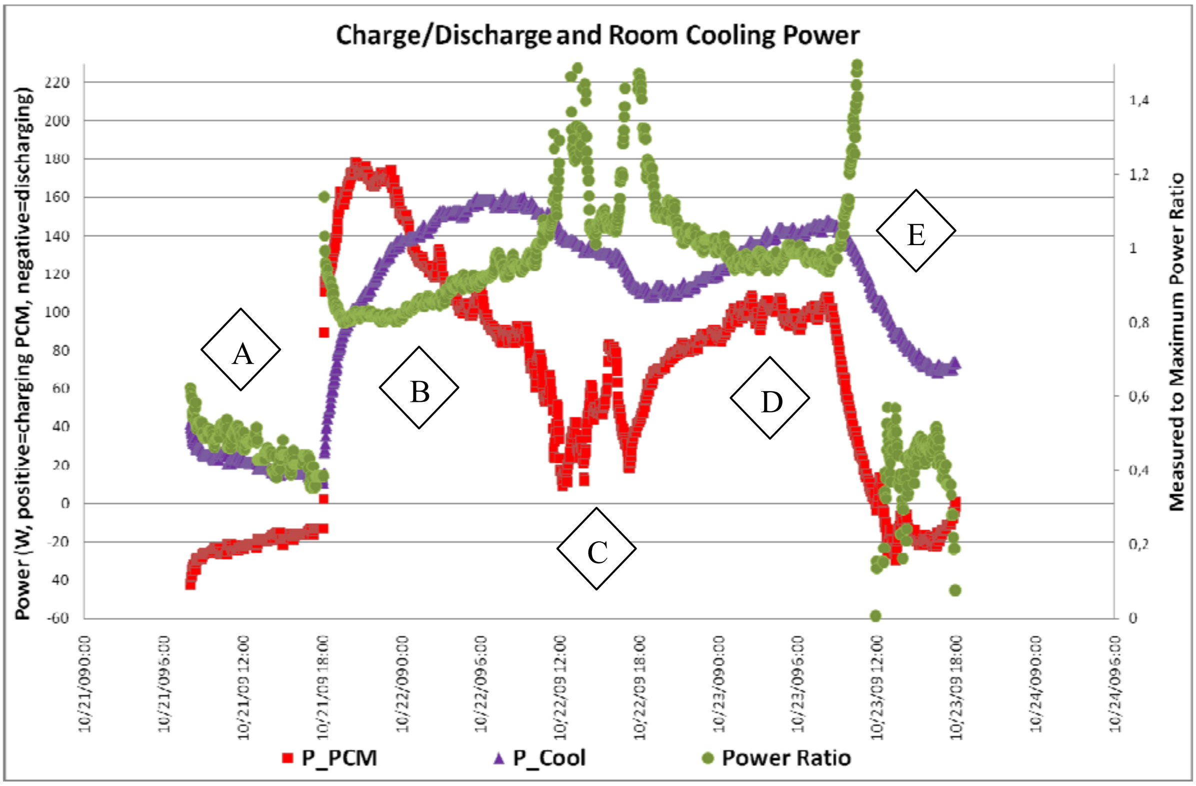

Figure 6 Measured Extraction/Storage Power, Power Ratio and Power of Cooling Supplied to Room: Complete Discharge and Charge Cycle

A closer analysis of the power delivered to the Ecosaveit Cubicle shows during discharge period A, Figure 6, discharged power (redline) was taken entirely by the cubicle (purple line). Such observation is justified by the fact that the prototype was on a forced indoor air recirculation mode for complete discharge of the PCM, the corresponding energy flow is represented in Figure 1, diagram 2. In period B, partial cold thermal energy was used for charging of PCM and partial thermal energy was used as free cooling for indoor cooling, the energy flow corresponds to Figure 1, energy flow type 3. It can be seen that room cooling power gained in proportion and reached 160W as PCM charging power decreased to 90W. Period C corresponds to an elevation of daytime ambient temperature approaching the PCM temperature, hence the charging power was reduced to almost zero, yet outdoor ambient air was still able to provide free cooling at 130W power as indoor cubicle temperature remained higher than outdoor air temperature. Period D corresponds to the second night charging of the store, the charging power was reduced to half of the charging power obtained the first night, an hypothesis is that the increasing solid state PCM increased the thermal resistance around the heat exchanger, further study should however be carried out for confirmation. Period E shows the first discharge of PCM in the afternoon of the second day, the corresponding energy flow is type 1 as shown in Figure 1, the discharge power was relatively low as the temperature driving force between outdoor air and PCM store was small. Total cooling provided to the room amounted to 70W.

Regarding the power ratio for charging the PCM, defined as measured power to the theoretical maximum power, the obtained results lead to a preliminary conclusion that charging is in general more efficient than discharging when there is an internal heat source. Further experimental work needs yet to be done in order to confirm this finding.

5. Future Work

A handful of useful results were obtained during the two-week testing, allowing thus a preliminary characterization of the prototype, Ecosaveit Cool. Free floating mode, fan on mode, indoor air recirculation mode, 200W/400W internal heat generation mode, full charging and full discharging were tested and overall performance of the equipment was evaluated.

The ever decreasing outdoor ambient temperature put halt to the free floating performance evaluation due to impossibility of extracting full amount of stored cold thermal energy. Although solutions were found through adding of internal heat source of respective 200W and 400W input, for an in depth evaluation of the storage system, the prototype has to be continuously evaluated under distinct environmental and climate conditions. One cost effective evaluation method would be to perform evaluation inside a well controlled climate chamber with artificial solar irradiation.

6. Conclusion

The Ecosaveit Cool prototype was partially, but successfully, evaluated within the two-week experimental testing timeframe. The partial evaluation was a result of unfavorable outdoor climate which impeded thorough testing of latent heat storage. Nonetheless, means of extracting and charging latent heat storage were implemented and an overview of the prototype's performance was obtained. The storage was eventually capable of 170W of PCM charging power when performing a new charging cycle after complete discharge. During normal operating mode, 40W-90W of charging may be reached. While running the system at fan on mode, the discharging was forced and the discharging power mounted to maximum 80W. Ecosaveit Cool has shown to provide 2.1 kWh of storage capacity with 8°C temperature swing, this figure lies well in the 5% error range with the design value.

A successful short term scientific mission has been carried out in the scope of developing and studying Next Generation Cost Effective Phase Change Materials (NeCoE-PCM). International collaboration between two academic entities, University of Lleida, UdL, Royal Institute and Technology, KTH and an industrial partner, Ecostorage Sweden AB was attained. European Cooperation in Science and Technology (COST) has by all means royally established and paved the way in providing opportunities of creating joint projects and short term cooperation work in the aim of consolidating and uniting European top research managers and leading industries. It is believed that such opportunities should be kept and be promoted for the sake of shaping a cutting edge inter-united European research platform.

7. Acknowledgement

The evaluation team that has carried out this Short Term Scientific Mission would like to acknowledge Energy Research Group (GREA) of University of Lleida, UdL for hosting this project. The team also expresses gratitude to European Cooperation in Science and Technology (COST) for initiating the inter university and industry collaboration. Vesam AB is kindly acknowledged with special thanks to Mikael Hansson and Ove Karlsson for setting up the parallel logic control and data acquisition system. Finally, the team would like to thank especially Swedish Energy Agency for its financial support, without which the project would not have been possible.