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Theoretical study of the application of Phase Change Materials (PCM) on the envelope of a typical dwelling in Cyprus

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Abstract--**In this work the application of Phase Change Materials (PCM) on the envelope of a dwelling in Cyprus is evaluated for the first time. The simulation process is carried out for a typical meteorological year using TRNSYS. Two types of simulations were carried out; the energy rate control and the temperature level control. The energy savings achieved by the addition of PCM compared to the base case (no insulation) ranged between 21.65-28.59%. When the PCM was combined with a common thermal insulation topology the maximum energy savings per year was 66.17%. In the second test the constructions containing PCM showed a better behaviour during summer conditions. Finally, the results of the optimum PCM case and the combined case were evaluated using Life Cycle Analysis. The results show that the PCM case is not yet considered to be very attractive due to the high initial cost.**

Index Terms--**Cyprus, energy savings, free floating temperature, macroencapsulated, Phase Change Materials.**

I. INTRODUCTION

THE use of thermal storage in building envelopes is of great importance since it can smooth out daily temperature fluctuations and as a result lower the energy demand for heating and cooling. A way to increase thermal inertia of buildings is by integrating or including PCM on the buildings envelope and thus store energy in the form of latent heat. The main advantage of latent heat storage is that it has high storage density in small temperature interval [1]. The general principle of operation of PCM is that they store heat using their chemical bonds when they change phase from liquid to solid and release heat in the opposite way. The PCM that can be used in building applications should have a melting temperature range between 20-32°C.

PCMs have been under study by many researchers around the world for over 30 years and thus many PCM are available in literature while some kinds are also commercially available by some companies such as BASF.

The main categories of PCM that can be used for this purpose are organic, inorganic and eutectics. In a very interesting and comprehensive work Cabeza et al. [1] reviewed all available PCM along with their classification, problems and possible solutions on their application in buildings. In their work Baetens et al. [2] also reviewed the state-of-the-art on the current knowledge of PCM applications in buildings.

In their work Tyagi and Buddhi [3] gave emphasis on the ways PCM can be applied in buildings such as PCM trombe wall, PCM wallboards, PCM shutters and PCM building blocks. Their results showed that there is a great potential on reducing the energy for covering heating and cooling demands.

A very promising application of microencapsulated PCM is their inclusion into construction materials such as concrete. This technology was studied in depth in the University of Lleida, Spain in 2004 but several drawbacks occurred. Consequently, Arce et al. [4] tried to overcome these problems. More specifically, the main drawback was the effect of the severe summer conditions (temperature and solar radiation) on the PCM that diminished their achievable potential benefits.

Although the inclusion of PCM into buildings materials such as concrete is considered to have numerous advantages it also has a very important drawback which lies to the fact that they can be used only in new buildings during the built up phase and not in existing buildings.

Additionally, in spite of the fact that a great number of studies have been performed for the incorporation of PCM in several construction materials only very few studies have been made for brick constructions. In his work, Alawadhi [5] numerically studied the application of PCM in bricks and obtained good results concerning the reduction of heat flow to the inner space during summer.

In a comprehensive work, Castell et al. [6] experimentally investigated the application of macroencapsulated PCM in two types of bricks namely conventional and alveolar brick. Their tests were performed under real conditions using five different cubicles located in Puigverd de Lleida. Two types of experiments were performed namely the free-floating temperature test and the controlled temperature test. The results showed good behavior, energy savings and technical viability. In spite of the promising results, a problem occurred during the experiments with the solidification of the PCM during night time. The authors suggested that this can be overcome by implementing a cooling strategy.

In this work the effect of the application of PCM in the thermal behavior of a typical dwelling in Cyprus will be theoretically investigated using several suitable models of the TRNSYS software library. Due to the complexity of the model used the simulations are carried out for a test cubicle and the results are then extrapolated for the typical dwelling.

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It should be noted that this is the first time the application of such materials is evaluated for Cyprus.

II. MODEL DESIGN

The model design process is carried out using TRaNsient SYstem Simulation software (TRNSYS). The main component that simulates the PCM layer located in a structural element of a dwelling is Type1270. This is obtained from Thermal Energy System Specialists (TESS) Company and is described below. The other main component of this model is Type56 which simulates the building (test cubicle).

Type1270 is designed to interact with Type56 and can model a PCM located in any position in the thickness of a Type56 wall. The complete TRNSYS model developed is shown in Fig. 1. There are two options for setting the physical properties of the PCM the manual option and the built-in option. More specifically, in the manual option the user can specify the physical properties such as density, specific heat, melting temperature, freezing temperature, and latent heat of fusion. In the second option the user can utilize the built-in values of this component which concern a specific brand of PCM and the user may select a model number directly by setting a single parameter. It should be noted that Type1270 models a pure PCM (as opposed to a mixture of a PCM with an inert material). From a physical point of view, this means that the PCM is assumed to go through its freeze/thaw process at constant temperature, to have a constant specific heat in the solid phase and to have a constant specific heat in the liquid phase. This is done in order to simplify the analysis of the PCM by treating the phase change layer in bulk; it does not account for the wave front of freeze/thaw propagating through the material over time.

The PCM layer can be applied in any structural element of a house such as external walls, internal walls and roof. The selection of the structural element on which the PCM layer will be applied is very important since it changes the procedure of utilizing the model. Due to the specific weather conditions of Cyprus (hot dry summer) the model will only be applied to the external walls and the roof since this is considered to be much more important than applying the PCM on internal walls.

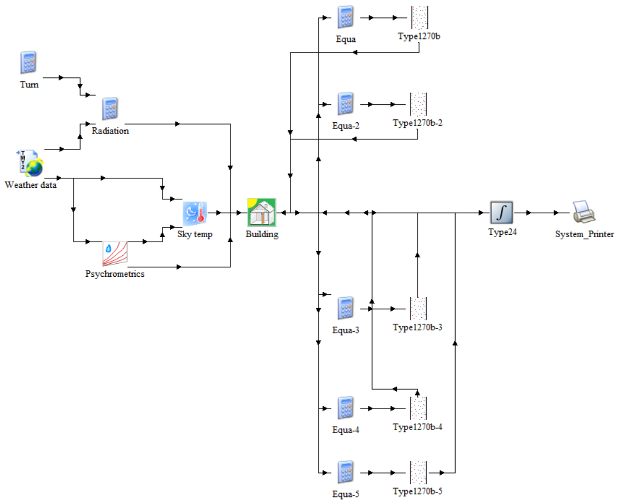

Fig. 1. Configuration of the complete TRNSYS model

III. INPUT DATA

The dimensions of the test cubicle are 3m x 2m x 3m and the orientation of the various walls is depicted in Figure 2. As mentioned above the introduction of a direct airnode is necessary for the utilisation of Type 1270, thus in every orientation a direct airnode is introduced with a width of 0.01m as is also shown in Figure 2.

A. Position of the PCM layer

For the purposes of this work, the PCM layer is installed in three different positions in order to cover both existing and new dwellings. In the first one the PCM layer is placed in the middle of a double brick wall, which can be applied only in a new dwelling. In the second and third one, it is placed in the inner and the outer side of the wall between the brick and the plaster layer respectively and these can be applied in both new and existing dwelling). In all cases examined, the PCM layer applied on the roof of the building is positioned in the inner side of the concrete slab just behind the plaster. This is due to practical issues such as the protection of the material from walking on it and the fact that it cannot be placed inside the concrete slab in the form of this product; this can be done by using microencapsulated PCM as described in many articles in the literature.

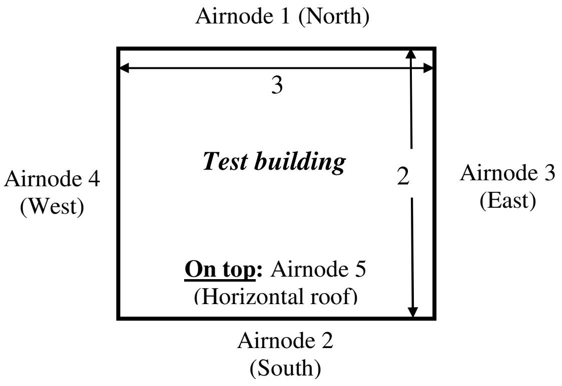

Fig. 2. Test building dimensions, orientation and adjacent airnodes

B. Physical properties and characteristics of the PCM used

During the simulation procedure the PCMs used were those of the built-in option. These PCMs concern specific commercial materials manufactured by Phase Change Energy Solutions Company and their series is BioPCmat™. These materials are the M27, M51 and M91 and their physical properties and characteristics are listed in Table I. These products are offered in four different melting temperatures namely 23, 25, 27 and 29°C.

TABLE I
PHYSICAL PROPERTIES AND CHARACTERISTICS OF THE PCM USED

Melting temperature*	29°C		
Product	M27	M51	M91
Thickness (mm)	14		
Weight per unit area (kg/m^2)	2.49	3.56	6.15
Total unit thickness (mm)	6.35 - 8.89	10.16 - 15.24	25.4
Dimensions/Width (mm)	419.1		
Latent heat storage capacity (J/g)**	165 - 200		

As it can be seen, the main differences between these products is their weight per unit area (kg/m^2), which indicates the mass of the PCM within the product, and the total unit thickness. According to literature, the most commonly used melting temperatures for the application of PCM in hot environments is between 26-29ºC. Thus, in our case since Cyprus is a predominant hot weather environment the product with a melting temperature of 29ºC is employed.

IV. METHODOLOGY

Once the detailed model of the test cubicle is setup the simulation is carried for the 'basic case' where the building is considered to have no insulation installed in any structural element. The simulation is carried out for a complete typical year (8,760 hours) lasting from the 1st of January until the 31st of December.

For the definition of the optimum PCM layer case the energy rate control test is conducted with which the total energy demand for heating and cooling are estimated. More specifically, the results of each case examined are compared to the results of the 'basic case' in order to calculate the consequent energy savings. In this test the set temperature for heating and cooling are fixed to be 20ºC and 26ºC respectively while the power of the heating and cooling system is set to be unlimited in order to maintain comfort conditions at all times. The results are in the form of energy consumption per square meter per year (kWh/m^2/yr). As part of this work, the three different PCM products shown in Table I are evaluated in three different positions through modeling and simulation.

When the optimum case is defined then a second simulation is carried out using the temperature level control, which is a test showing the effect of applying the optimum PCM layer on the fluctuation of the mean air temperature of the cubicle. In this simulation the cubicle is considered to be unconditioned and thus the heating and cooling systems are both switched off. The results of this test are presented for the hottest day of summer which is the 26th of July according to the TMY2 for Nicosia, Cyprus.

Additionally, the temperature fluctuation of the test cubicle when it is insulated using common insulation materials used in Cyprus is presented. More specifically the insulation used is 3.5cm of thermal insulation plaster applied on the outer surface of the envelope of the test cubicle and 4cm of extruded polystyrene applied on the outer surface of the roof.

Finally, the insulated cubicle is combined with the optimum PCM case and the temperature fluctuation is calculated.

V. RESULTS AND DISCUSSION

A. *Energy rate control simulation*

The results concerning the energy rate simulation are presented in Table II for all 9 PCM cases examined (3 types of materials times three positions examined). As it can be seen the optimum PCM case is that in position III with the 2991 material (29ºC melting temperature, material type 91) where the overall energy savings achieved is 28.59% (118.5 kWh/yr/m^2). Additionally, this case has the highest energy saving percentage in both heating and cooling which are 23.57% (62.585 kWh/yr/m^2) and 37.52% (55.925 kWh/yr/m^2) respectively. As expected, the energy savings in cooling are much higher than those of heating since essentially the PCM freezing/melting procedure is operating much better under the summer conditions. As aforementioned, the melting temperature of this PCM material is 29ºC and the only reason it is working in the winter is the fact that the space is conditioned and a part of the heat is absorbed by the PCM and released with a time lag and this is contributing to the decrease of the heating demand.

The reason for the superiority of this material against the others is that per unit area it has the higher weight and thus it contains a bigger amount of PCM material.

The results of the energy rate simulation concerning the insulated case and the combined case are presented in Table III where it can be observed that the combined (PCM and insulation) case achieves higher energy savings than the insulation case (66.17% instead of 60.95%) which is equal to 21.65 kWh/yr/m^2.

B. *Temperature level control simulation*

The results of the temperature level control simulation for the coldest day of winter (3-4th of February) and the hottest day of summer (26-27th of July) are depicted in Figures 3 and 4 respectively. In these figures the free-floating temperature for the base case (no insulation), the optimum PCM case, the insulation case and the combined case are plotted.

The optimum solution for the winter conditions is the insulation case followed by the combined case. The insulation case has a difference 2.5-3°C when compared with the base case. The combined case has a difference between 0.8-1°C when compared with the insulation case. When the combined case is compared with the base case shows a difference between 2-2.5°C. The optimum PCM only case has a difference between -0.2-1°C when compared to the base case. As can be seen between16:00-20:00 the mean air temperature of the PCM case is slightly lower (0.2°C) than that of the base case a fact that can be attributed to the low response time of the PCM layer to the sudden rise of the temperature.

During summer time the optimum solution is the combined one where the PCM is combined with the insulation. It should also be noted that the mean air temperature of the test cubicle is much smoother than in all other cases and it is also 3-5ºC lower than the base case (no insulation). A very interesting thing to observe is the fact that the mean air temperature of the insulation case between 02:00-14:00 is exceeding the mean air temperature for the base case due to the fact that the heat that entered the space is trapped into the cubicle and it cannot escape. However, when a PCM layer is installed on the walls and roof this is not happening while this case is also slightly better than both insulation cases with a difference between 0.1-1.1ºC.

According to the results of both simulations the most attractive solution to be applied in a dwelling in Cyprus is the combined one, where the PCM is used together with thermal insulation and thus the benefits of using both materials are combined.

C. *Life Cycle Analysis (LCA)*

The LCA is carried out for a complete typical dwelling of Cyprus by extrapolating the results of the energy rate control of the test cubicle. The typical dwelling used is that defined by Panayiotou [7] which is described below.

The typical dwelling is a single storey detached house located in Nicosia (Low mainland area) with a total area of 133 m^2. There are 4 occupants living in the dwelling and it does not have any kind of thermal insulation installed on its envelope. It consists of three bedrooms, a kitchen, a living room, a bathroom, and a dining room. For the production of DHW a solar water heating system is used while the heating and cooling energy demands are served by split type air-conditioning units. The windows of the dwelling are single-glazed with common aluminum frame; the main entrance door is made of wood while the kitchen door is made of aluminum frame and glass. Finally, the floor is in contact with the ground and is made of marble.

The cost of the optimum PCM case was estimated using the online calculator provided by the manufacturer [8] and was €22,490. According to the results of the LCA for the optimum PCM case (2991) the payback period of the investment is calculated to be 14 ½ years, the economic benefit at the end of the lifetime of the materials used, expressed as NPV, is €35,942 and the IRR is only 4%.

The cost of the combined case was calculated to be €23,259. The results of the LCA for the combined case showed that the payback period of the investment is calculated to be 7 ½ years, the economic benefit at the end of the lifetime of the materials used, expressed as NPV, is €110,416 and the IRR is 14%.

TABLE II
RESULTS OF THE ENERGY RATE CONTROL SIMULATION FOR THE PCMS EXAMINED

	PCM MATERIAL	**2927**		**2951**		**2991**	
		Q_{HEAT}	Q_{COOL}	Q_{HEAT}	Q_{COOL}	Q_{HEAT}	Q_{COOL}
POSITION I	Heating and cooling demand per m^2 (kWh/yr m^2)	224.88	99.89	224.82	99.57	224.73	99.28
	Total energy demand (kWh/yr m^2)	324.77		324.38		324.00	
	Heating and cooling energy savings per m^2 (kWh/yr m^2)	40.61	49.13	40.67	49.45	40.76	49.74
	Total energy savings (kWh/yr m^2)	89.74		90.13		90.51	
	Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	15.30%	32.97%	15.32%	33.19%	15.35%	33.38%
	Total energy savings percentage (% kWh/yr m^2)	21.65%		21.74%		21.83%	
POSITION II	Heating and cooling demand per m^2 (kWh/yr m^2)	225.85	99.84	225.78	99.59	225.65	99.19
	Total energy demand (kWh/yr m^2)	325.70		325.37		324.84	
	Heating and cooling energy savings per m^2 (kWh/yr m^2)	39.64	49.18	39.71	49.43	39.84	49.83
	Total energy savings (kWh/yr m^2)	88.81		89.14		89.67	
	Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	14.93%	33.00%	14.96%	33.17%	15.01%	33.44%
	Total energy savings percentage (% kWh/yr m^2)	21.43%		21.50%		21.63%	
POSITION III	Heating and cooling demand per m^2 (kWh/yr m^2)	203.01	93.42	202.97	93.26	202.91	93.10
	Total energy demand (kWh/yr m^2)	296.43		296.23		296.01	
	Heating and cooling energy savings per m^2 (kWh/yr m^2)	62.48	55.60	62.52	55.76	62.58	55.92
	Total energy savings (kWh/yr m^2)	118.08		118.28		118.50	
	Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	23.53%	37.31%	23.55%	37.42%	23.57%	37.52%
	Total energy savings percentage (% kWh/yr m^2)	28.49%		28.54%		28.59%	

TABLE III
RESULTS OF THE ENERGY RATE CONTROL SIMULATION FOR THE INSULATION CASE AND THE COMBINED CASE

Examined case	**Insulation case**		**Combined case**	
	Q_{HEAT}	Q_{COOL}	Q_{HEAT}	Q_{COOL}
Heating and cooling demand per m^2 (kWh/yr m^2)	64.29	97.58	89.93	50.29
Total energy demand (kWh/yr m^2)	161.87		140.22	
Heating and cooling energy savings per m^2 (kWh/yr m^2)	201.20	51.44	175.56	98.73
Total energy savings (kWh/yr m^2)	252.64		274.29	
Heating and cooling energy savings percentage per m^2 (% kWh/yr m^2)	75.78%	34.52%	66.13%	66.26%
Total energy savings percentage (% kWh/yr m^2)	60.95%		66.17%	

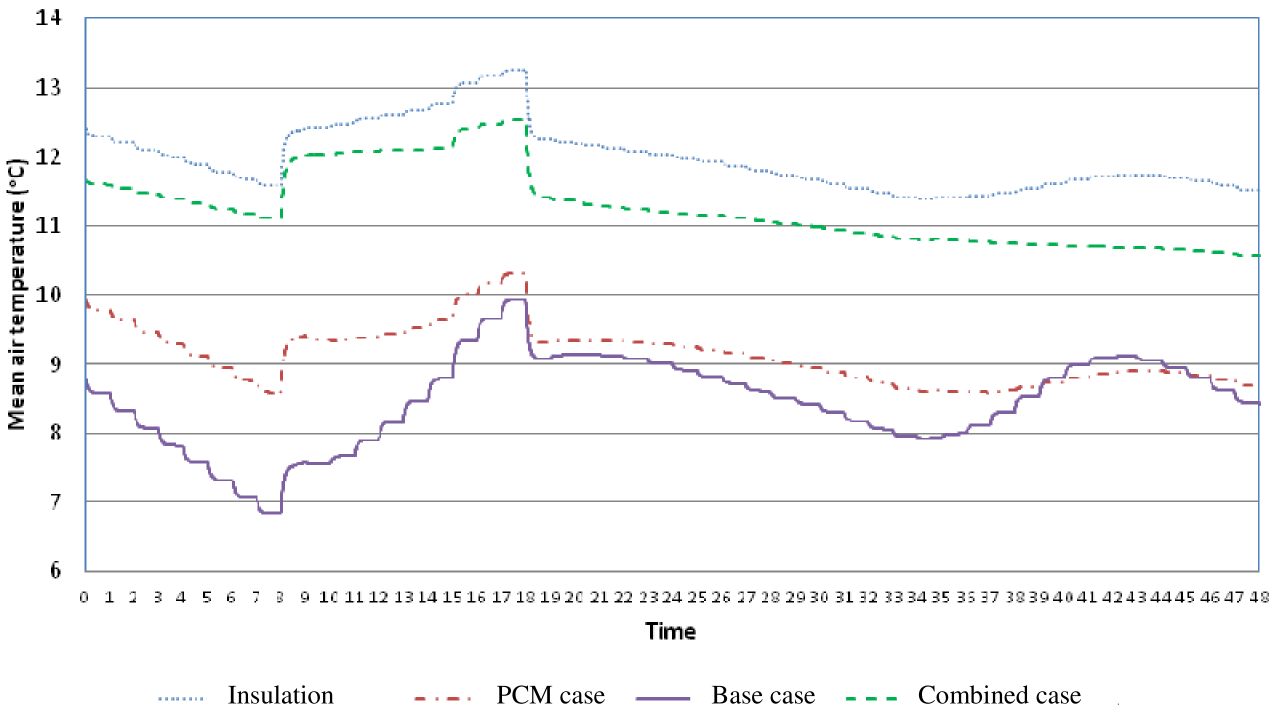

Fig. 3. Mean air temperature for all cases examined during the 3-4th of February

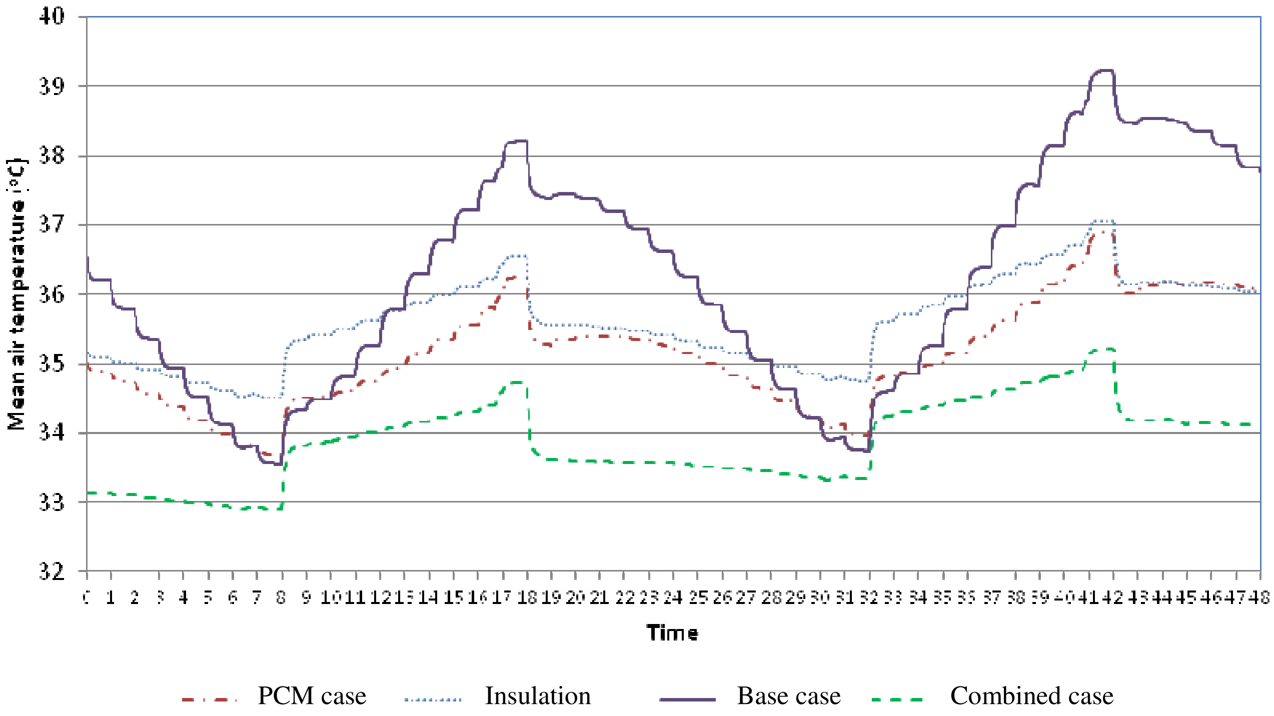

Fig.4. Mean air temperature for all cases examined during the 26-27th of July

VI. CONCLUSIONS

In this work the effect of the application of macroencapsulated PCM in the thermal behaviour of a test cubicle in Cyprus was theoretically investigated for the first time using a suitable model of TRNSYS software.

The results indicate that the application of such material in Cyprus is very attractive and advantageous since they operate very well in the specific weather conditions of Cyprus. More specifically, the optimum energy savings achieved by applying a PCM material with a melting temperature of 29ºC on the outer surface of a wall and inner side of the concrete slab just behind the plaster is 28.59% (118.5 kWh/yr/m^2). A very interesting option is when the PCM layer is used in combination with thermal insulation where the results showed that an energy saving of 66.17%

(274.29 kWh/yr/m^2) could be achieved while the energy savings achieved by the insulation alone is 60.95% (252.64 kWh/yr/m^2).

In the temperature rate control test the constructions containing PCM showed a better behaviour during the summer conditions, as expected, while during the winter conditions did not work very well. More specifically, during the winter conditions the optimum solution is the insulation only case followed by the combined case. The insulation case has a difference of 2.5-3°C. When the combined case is compared with the base case the former show a difference between 2-2.5°C. On the contrary during summer time the optimum solution is the combined case where the mean air temperature is 3-5°C lower than the base case.

Finally, the results of the optimum PCM layer case and the combined case were economically evaluated using Life Cycle analysis (LCA) in order to define the IRR and the payback period of each investment. This is done by extrapolating the results of the test cubicle to a typical dwelling in Cyprus which as an area of 133 m^2. The results show that the PCM only case is not considered to be a very attractive solution, in monetary terms, due to the combination of the high initial cost and the annual money saving which result to a very long payback time which is estimated to be 14 ½ years and a rather low IRR (4%). This is changing when the PCM is used together with insulation where the payback period is reduced to 7 ½ years and the IRR is 13-14% respectively.

From the results of this work it can be concluded that the application of macroencapsulated PCM on the envelope of dwellings in Cyprus is considered to be a very attractive solution in terms of energy saving and comfort conditions while in monetary terms is not yet so attractive due to their high initial cost. Of course, this could change if the cost of PCM is decreased in the near future. It would be very interesting if in the near future an experimental unit is setup so as to validate experimentally the results of this work.

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VIII. BIOGRAPHIES

Soteris A. Kalogirou was born in Trachonas, Nicosia, Cyprus on November 11, 1959. He is a Senior Lecturer at the Department of Mechanical Engineering and Materials Sciences and Engineering of the Cyprus University of Technology, Limassol, Cyprus. He received his HTI Degree in Mechanical Engineering in 1982, his M.Phil. in Mechanical Engineering from the Polytechnic of Wales in 1991 and his Ph.D. in Mechanical Engineering from the University of Glamorgan in 1995. In June 2011 he received from the University of Glamorgan the title of D.Sc. He is Visiting Professor at Brunel University, UK and Adjunct Professor at the Dublin Institute of Technology (DIT), Ireland. For more than 25 years, he is actively involved in research in the area of solar energy and particularly in flat plate and concentrating collectors, solar water heating, solar steam generating systems, desalination and absorption cooling.

He has 41 books and book contributions and published 264 papers; 109 in international scientific journals and 155 in refereed conference proceedings. Until now, he received more than 4000 citations on this work and his h-index is 35. He is Deputy Editor-in-Chief of Energy, Associate Editor of Renewable Energy and Editorial Board Member of another eleven journals. He is the editor of the book Artificial Intelligence in Energy and Renewable Energy Systems, published by Nova Science Inc., co-editor of the book Soft Computing in Green and Renewable Energy Systems, published by Springer and author of the book Solar Energy Engineering: Processes and Systems, published by Academic Press of Elsevier.

Gregoris P. Panayiotou was born in Limassol, Cyprus on February 18, 1983. He graduated from the Technological Educational Institute of Athens first of his class as an Energy Technology Engineer in 2007. He had his MSc in Energy in Heriot-Watt University, Edinburgh where he graduated in 2008 with Distinction.

He is currently employed at Cyprus University of Technology as a Research Associate in a nationally funded project concerning the study and the deeper understanding of the thermosiphonic phenomenon that occurs in solar water heating systems that operate thermosiphonically.

In the past he had also worked in two research projects. The first project was funded by the Research Promotion Foundation of Cyprus and concerned the categorization of buildings in Cyprus according to their energy performance. The second project concerned the application and evaluation of advanced absorber coatings for parabolic trough collectors.

The main simulation tool he had used in most of his work is TRaNsient SYstem Simulation (TRNSYS) while he had also worked with HOMER and PVSyst.

He currently has 9 Journal publications and 12 Conference publications and his special fields of interest include wide range applications of Renewable Energy Sources systems and Energy Efficiency in buildings.