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Use of phase change materials (PCM) for the improvement of energy storage in solar water heating systems

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Abstract

In this paper the use of Phase Change Materials (PCM) in solar storage tanks is considered in an attempt to improve the solar system operation without changing the production line of solar water heater manufacturers. Hot water storage tank is one of the main components of any solar water heating system. It is important to increase the storage capacity and to keep the stratification in these systems, as this affects the effectiveness of the solar system operation. In general, PCMs present high latent heat of evaporation and they offer more storage capacity than water. The experimental investigations of the operation of the storage tank were carried out both during heating up and draw off. In all experiments carried at different initial storage temperatures, number of PCM canisters (1-3) and draw-off rates (1, 3 and 6 l/min), the tanks with PCM show superior performance than the same tank operating in similar conditions without PCM. For the 50 l tank used, two PCM canisters showed the best performance and a draw off profile up to 3 l/min. The flow of 6 l/min seems to be excessive for small storage volume as the high flow rate does not allow the PCM to give its heat to the flowing water. Another experiment performed is the intermitted withdrawal of water from the storage tank so as to simulate the actual use. The results were also positive. Therefore, from this work it is concluded that the use of PCM gives improved storage capacity of the system and improved system behavior during draw-off.

1. Introduction

Hot water storage tank is the «heart» of any solar water heating system. For such systems it is important to keep the stratification, as this affects the effectiveness of the solar system operation. It is also true that the storage tank is not usually considered in the required detail during the system design. In this paper the use of Phase Change Materials (PCM) in solar storage tanks is considered in an attempt to improve the solar system operation. This should be done in such a way so as it will not change the production line of solar water heater manufacturers.

It is well known that PCMs have high latent heat of fusion and thus they are able to absorb energy during melting and release this energy during solidification. Therefore, the objective of this work is not only to improve the stratification characteristics of the storage tanks but also to reduce their volume by storing more energy in smaller volume.

For these tanks it is very important to create and keep the stratification both during heating up and during usage when there is a draw of water from the tank which is replaced by city mains cold water. This affects directly the effectiveness the solar system operation. With stratification it is possible to allow the hot water to "concentrate" at the top of the tank and the cold water at the bottom. As the water that returns to the solar collectors is from the bottom part of the storage tank, by keeping the stratification, relatively cold water is directed to the collectors and this increases their efficiency.

Many scientists have carried out research in this area. Cabeza et al. [1] used PCM to improve the stratification of a storage tank. In this work they investigated the choice of the right PCM for this application based on its thermodynamic and corrosive properties. They also studied the best configuration of the heat transfer vessel. Based on their experiments they found that the inclusion of a vessel with PCM at the top of the stratified storage tank there is an increase of the storage density at that area. The PCM used in this work had a melting temperature of 45°C and was contained in four small vessels.

Mazman et al. [2] in their work concluded that storage systems, separating the hot from the cold water through stratification, are very popular in applications of low and medium temperature. This happens because of the simplicity and low cost of these systems. With the inclusion of a PCM vessel at the top part of a stratified hot water storage tank, the storage density can be increased at this level, as well as the replacement of heat loss through the latent heat of solidification of the PCM. In this work the authors carried out experiments with a storage cylinder of 150 l capacity and a PCM vessel which has a diameter of 0.176 m and height of 0.315 m. They have also proved that a PCM with a mixture of paraffin and stearic acid (PS) gives the best results concerning the improvement of the thermal performance of the system.

Shmueli et al. [3] dealt with the numerical investigation of melting the PCM in a vertical cylindrical tube. The analysis aimed at an investigation of local flow and thermal phenomena by means of a numerical simulation which is compared to the previous experimental results. The numerical analysis is realized using an enthalpy–porosity formulation. The effect of various parameters of the numerical solution on the results is examined; in particular, the term describing the mushy zone in the momentum equation and the influence of the pressure–velocity coupling and pressure discretization schemes. Image processing of experimental results from the previous studies is performed, yielding quantitative information about the local melt fractions and heat transfer rates. The results showed quantitatively that at the beginning of the process, the heat transfer is by conduction from the tube wall to the solid phase through a relatively thin liquid layer. As the melting progresses, natural convection in the liquid becomes dominant, changing the solid shape to a conical one, which shrinks in size from the top to the bottom.

Menon et al. [4] also studied the melting of commercial paraffin in vertical pipes using various values of the height of the PCM vessel. They have used copper pipes and the analysis was carried out using the Fourier, Stefan and Rayleigh numbers. A demonstration of melting was also carried out separately in a glass tube. They concluded that due to differences in density, the flow near the hot wall of the pipe was upward whereas the flow at near the cold interface of solid-liquid was downward.

Kousksou et al. [5] presented a numerical study for the use of phase change materials (PCMs) in solar-based domestic hot water (DHW) systems. The goal of the authors was to analyze the conditions under which there is no advantage of using PCMs in a DHW system and to propose improvements. The mathematical model considered describes the heat storage tank with PCM, collector, pump, controller and auxiliary heater. Realistic environmental conditions and typical end-user requirements were imposed. The authors concluded that the high sensitivity of the DHW system to the choice of first order design parameters, such as the PCM melting temperature, can lead to successful designs of PCM based DHW system that may be more efficient than a similar DHW system without PCM.

The objectives of the present work are to increase the storage capacity of a solar system or be able to reduce storage volume, thus increase the cost effectiveness of the system and to improve the formation and preservation of the stratification. For this purpose experimental investigations of the operation of the storage tank are carried out both during heating up and draw off.

2. Materials and methods

In general, PCMs present high latent heat of melting or fusion. They absorb energy during melting and release this energy during solidification. For this purpose in the experiments we performed, paraffin is used with a melting temperature of 56°C. The latent heat of melting of the paraffin used is around 200 kJ/kg, which compared to specific heat capacity of water which is about 4.2 kJ/(kg.K) at the range of 20-60°C and dictates the amount of energy stored in water sensibly, offers 47 times more energy storage capacity than water.

The system consists of a storage tank 50 l in volume in which the PCM material was poured in liquid state in the special canister shown in Fig. 1. The canister can be inserted and hanged in a special attachment that is supported on a flange. The canister can hold about a liter of PCM material. This canister or a number of them (up to three) were hinged from the top of the tank on a special flange. This flange is of the type used in storage tanks to insert the immersion heater for auxiliary energy supply, thus its use is well known to the manufacturers of such storage tanks and is in line with their current practices.

To have regulated conditions an immersion electrical heater was used in the tank controlled by an immersion thermostat. During the experiments the temperature of the water entering the tank (make up water) and the temperature of the water outlet were continuously measured.

Fig. 1 Special container for the PCM and special flange used to insert the PCM-vessel in the tank.

The complete system is shown in Fig. 2. Thermocouples are installed at inlet and outlets of the tank as shown to measure the temperature of the water flowing in and out of the system. As was mentioned above, for the testing of the system, the solar system is replaced by the immersion heater, used to heat the water to the required temperature.

Fig. 2 Tank with PCM equipped with thermocouples to measure temperature (left) and during draw off (right)

The PCM used is the normal paraffin (wax), selected because of low cost, which has a fusion temperature of 56°C. This is chosen so to be near the safety temperature of 60°C for Legionella protection. An additional type of paraffin is also tried with a fusion temperature of 45°C.

3. Results and discussion

A number of experiments were performed without and with PCMs installed in the tank. The numbers of experiments performed without and with PCM in the tank are shown in Tables 1 and 2 respectively. The maximum temperature is the setting of the immersion thermostat whereas the flow rate is the draw off flow rate during discharging. For the immersion thermostat a range of temperatures are quoted as it was very difficult to achieve repeated similar settings when this value was changed manually. On the contrary it was relatively easy to use repeatedly the same flow rate controlled by a simple valve as shown in Fig. 2. In this case the water flow rate was measured with a measuring cylinder and a stop watch and could easily be slightly adjusted during the draw off process.

Table 1 Experiments performed without PCM in the tank

Experiment number	Maximum temperature (°C)	Flow rate (l/min)
1	80-85	6
2	70-75	6
3	80-85	1

Table 2 Experiments performed with PCM in the tank

Experiment No.	Maximum temperature (°C)	Flow rate (l/min)	No of PCM tanks
1	80 – 85	6	1
2	70 – 75	6	1
3	80 – 85	1	1
4	70 – 75	6	2
5	80 – 85	1	2
6	70 – 75	3	2
7	70 – 75	1	2
8*	80 – 85	1	1
Notes: * different PCM material with a fusion temperature of 45°C			

In all experiments carried at different initial storage temperatures, number of PCM canisters (1-3) and draw-off rates (1, 3 and 6 l/min) the tanks with PCM show superior performance than the same tank operating in similar conditions without PCM, as depicted from the results shown in the following figures. Typical charging (heating up) and discharging (draw off) performance is shown in Fig. 3.

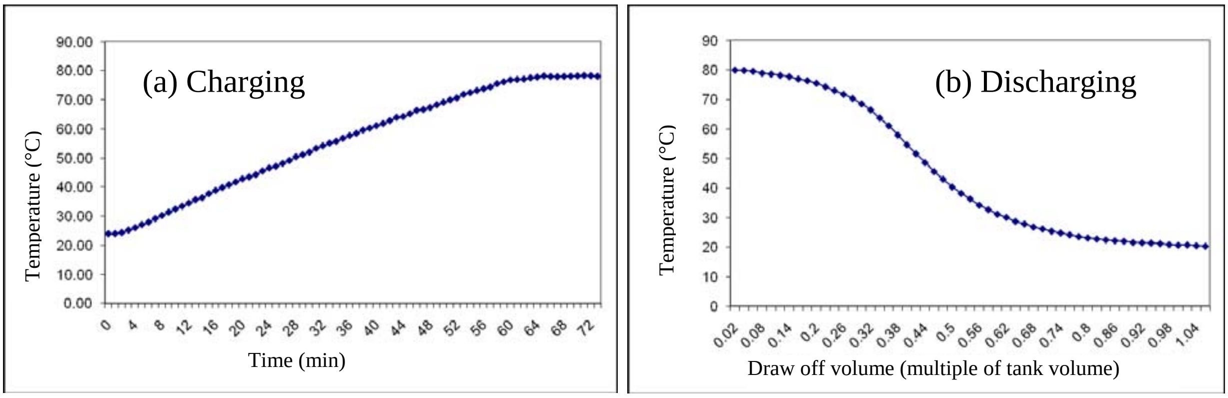

Fig. 3 Typical charging and discharging behaviour of the tank.

What is of interest here is the temperature evolution of the water in the tank. During charging the temperature increases smoothly until the thermostat limit of the immersion heater is reached as shown in Fig. 3(a). During this time the PCM melts smoothly as the tank water temperature rises with a delay according to the mass of the PCM used. The discharge profile is of interest with respect to the amount of water drawn off before a useful temperature of about 40°C is reached. The more volume we get with water above this value the better is the draw off characteristics of the tank. The performance of the system presented in Fig. 3 is not very clear with respect to the enhancement achieved because of the use of the PCM. What is of interest is the comparison between the results from the different experiments. Most important are the comparative graphs during system draw-off for different flow rates of systems with and without PCM in the tank. It should be noted that in order to save space only a few typical results are presented in this paper.

The performance of the system during draw-off for initial water temperature of 85°C, draw off flow rate of 6 l/min without PCM (red line) and for initial water temperature of 75°C with 2 PCM vessels in the tank and same draw off flow rate (blue line), are shown in Fig. 4. The advantage of the system with PCM is obvious, despite the different initial temperature. The extra benefit in hot water volume at a minimum useful temperature of 40°C is shown with dotted lines.

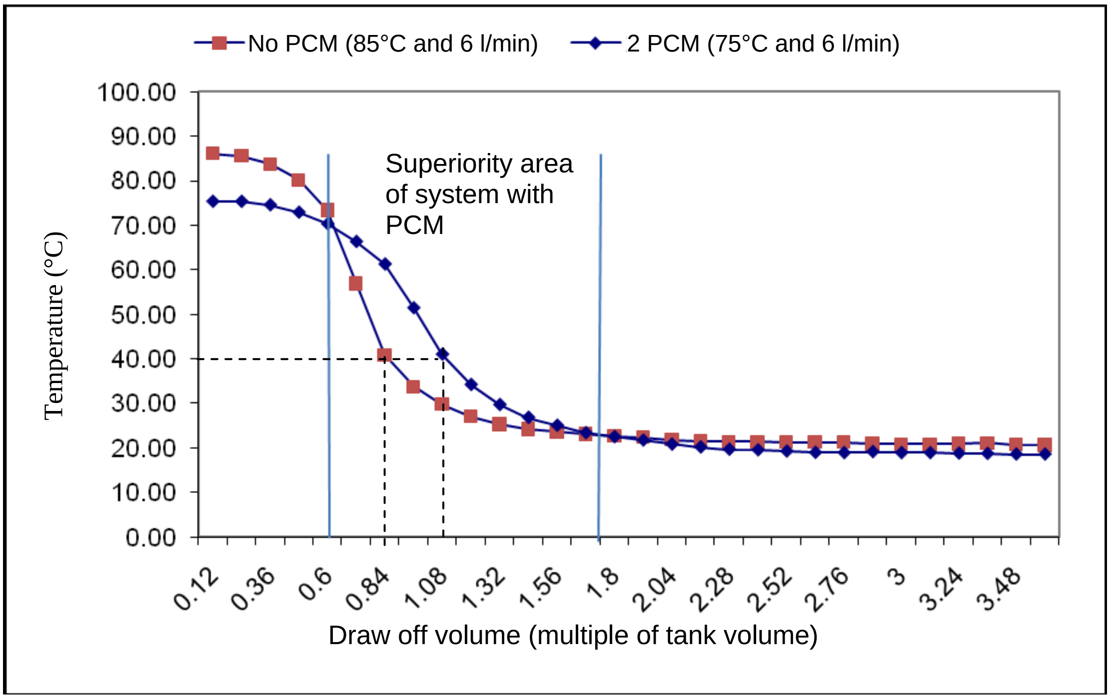

Fig. 4. Comparison of the performance without and with PCM in the tank for initial water temperature of about 80°C and flow rate of 6 l/min

The performance of the system during draw-off for initial water temperature of 80°C, draw off flow rate of 1 l/min without PCM (red line) and for initial water temperature of 71°C with 2 PCM vessels in the tank and same draw off flow rate (blue), are shown in Fig. 5. The advantage of the system with PCM is obvious, despite the different initial temperature. Again here the extra benefit in hot water volume at a minimum useful temperature of 40°C is shown with dotted lines and as can be seen there is a significant increase to what is shown in Fig. 4, which was at a higher draw off flow rate.

As can be seen from above, the draw off flow-rate effects the performance of the system drastically because if a high number is used the flow is very quick and reduced somewhat the effect of the PCM. The initial flow rate of 6 l/min is according to the relevant ISO standard. A comparison for the performance of the system for a flow rate of 1 (red line), 3 (blue line) and 6 (green line) l/min is shown in Fig. 6. As can be seen the system is capable of giving water of higher temperature for more time at low flow rates. Furthermore, the total volume of water is obtained for the higher initial temperature shown in Fig. 4 and it seems that a good compromise between the three flow rates is the middle one, i.e., the flow rate of 3 l/min. Additionally, it was found that the initial value of 6 l/min is not suitable for such a small volume tank.

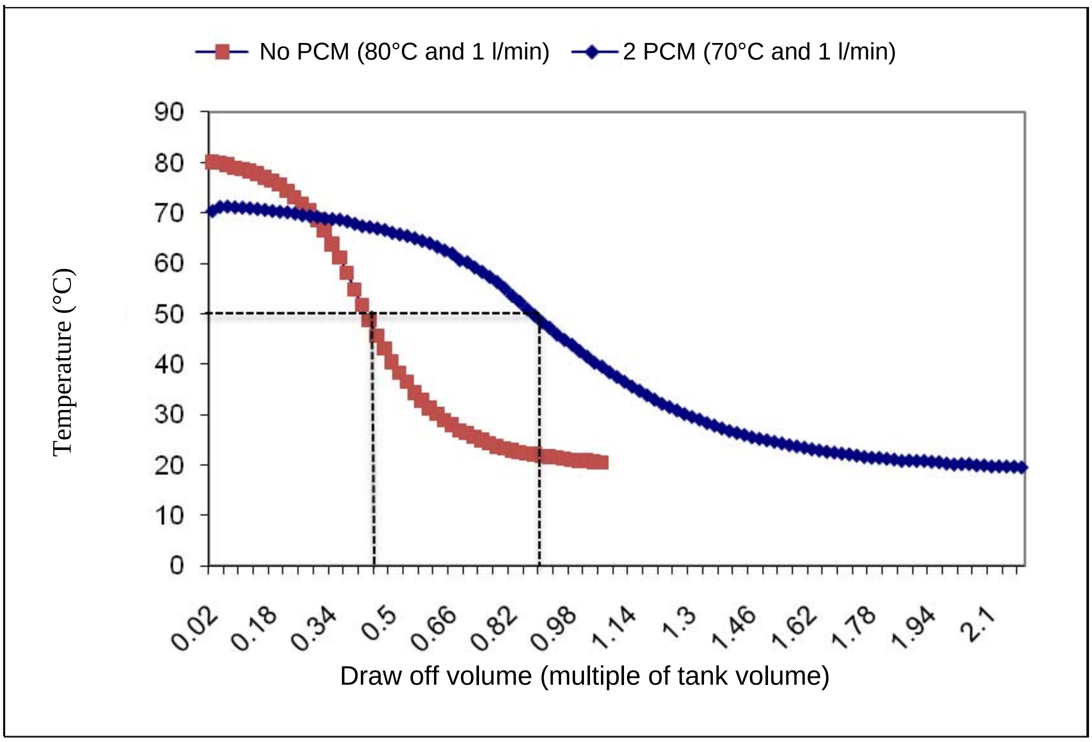

Fig. 5. Comparison of the performance without and with PCM in the tank for initial water temperature of about 77°C and flow rate of 1 l/min

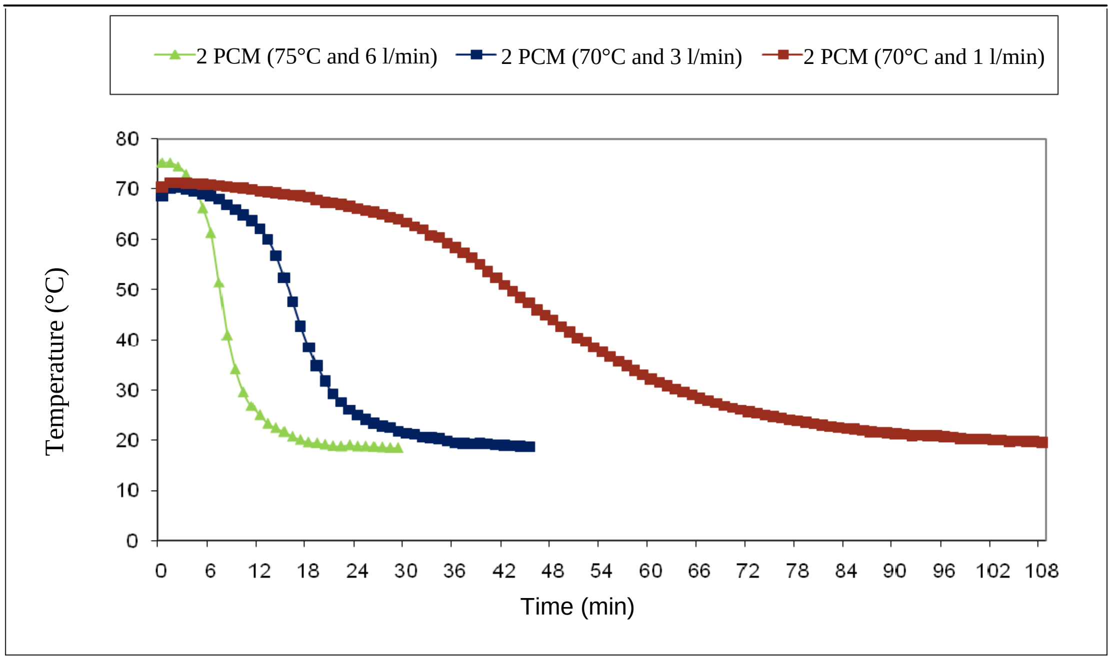

Fig. 6. Comparison of the performance of 2 PCM vessels in the tank for initial water temperature of about 70°C and flow rate of 6, 3 and 1 l/min

A comparison of the system with the same initial temperature of about 76°C and draw off flow rate of 6 l/min for 1 (blue line) and 2 (red line) PCM vessels in the tank is shown in Fig. 7. As can be seen the 2-PCM system is better.

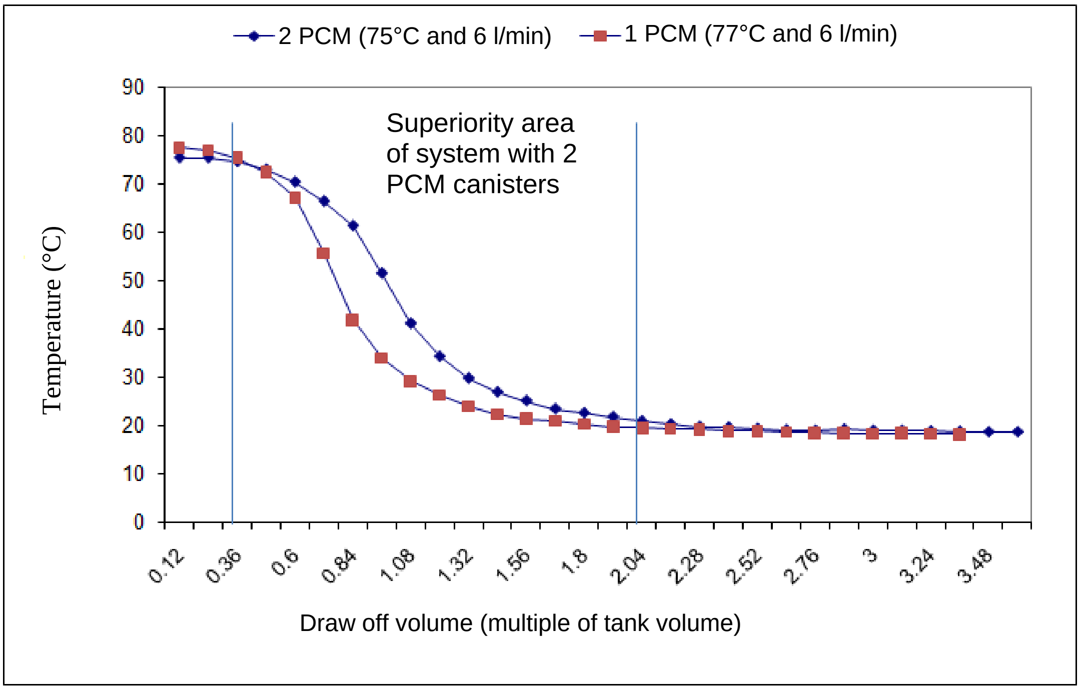

Fig. 7. Comparison of the performance of 1 and 2 PCM vessels in the tank for initial water temperature of about 76°C and flow rate of 6 l/min

Another comparative performance presented is the use of the different type of PCM as shown in experiment 8 in Table 2. The results are shown in Fig. 8 for a draw off flow of 1 l/min and about 80°C initial temperature. The performance of the new PCM is much lower than the PCM used in the experiments so far.

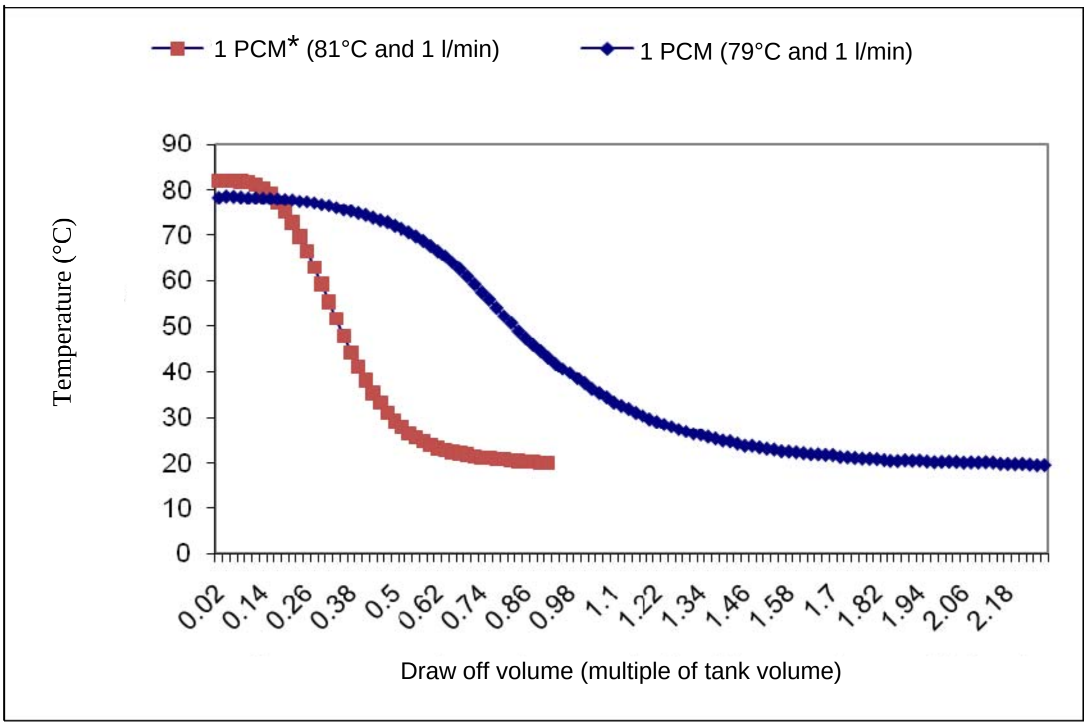

Fig. 8. Comparison of the performance of 1 PCM vessel in the tank of different type of PCM material for initial water temperature of about 80°C and flow rate of 1 l/min

It can be concluded from this work that for the tank used, which is of 50 liters capacity, the best performance is obtained with two PCM canisters and a draw off profile up to 3 l/min. The flow of 6 l/min seems to be excessive for small storage volume as the high flow rate does not allow the PCM to give its heat of solidification to the flowing water.

Another experiment performed is the intermitted withdrawal of water from the storage tank so as to simulate the actual use. During this test a number of thermocouples were inserted in a special tube just outside the PCM canister so as to record the temperature of water at different heights in the tank. The locations of the thermocouples are shown in Fig. 9. The procedure was to warm the water in the storage tank and then apply a water draw off rate of 10 liters every 15 minutes.

The results are shown graphically in Fig. 10. For this experiment one PCM canister was used. The draw off pattern can be seen clearly from the blue line which is the temperature of the water drawn from the tank. As can be seen when the water flow stops the energy contained in the PCM recovers somewhat the temperature of the water into the storage tank that would be much lower when the cold water replacing the hot water draw off is mixed with the water remaining into the storage tank after a few minutes. This is more clearly shown from line #4 which presents the temperature at the centre of the storage tank. Additionally, the temperature at point #2 at the top of the tank, shows that the PCM preserves stratification which is one of the main objectives in using PCM in storage tanks. This is proved by the fact that the temperature at this point is higher than the temperature of the water drawn from the cylinder (#1).

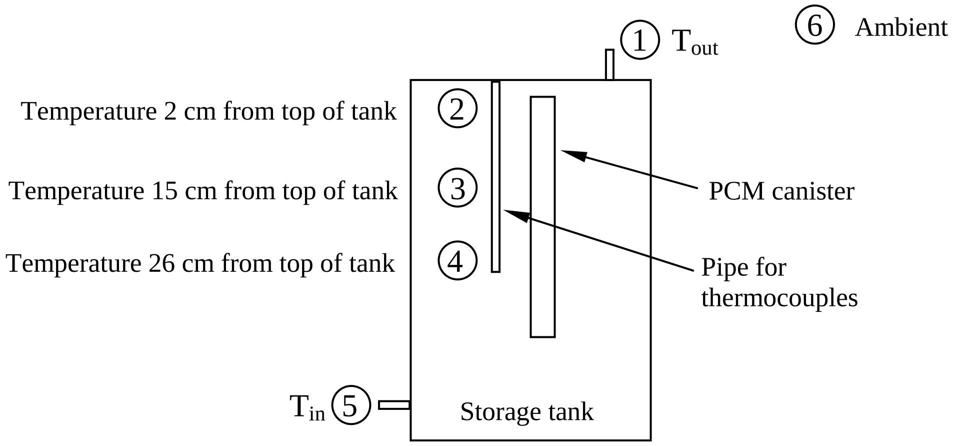

Fig. 9 Location of thermocouples for the intermitted draw off experiment

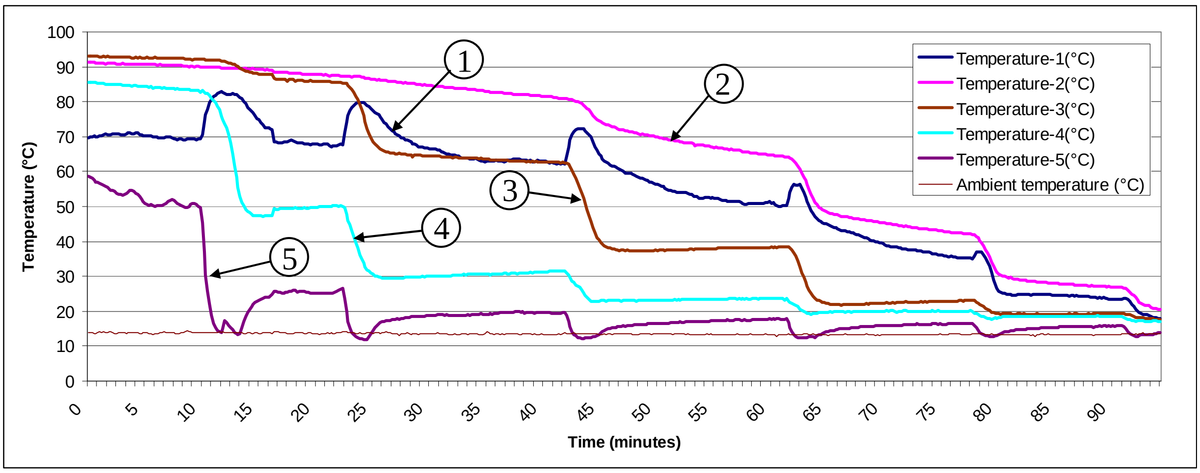

Fig. 10 Performance of the system at intermitted draw off (temperature numbers correspond to Fir. 9)

4. Conclusions

The objective of this work is to increase the storage capacity of a solar system or to be able to reduce the storage volume and by doing so to increase the cost effectiveness of the system. It is also required to have better formation and preservation of stratification. The experimental investigations of the operation of the storage tank were carried out both during heating up and draw off.

From this work it is concluded that the use of PCM gives improved storage capacity of the system and considerable improvement of system behaviour during draw-off. This was done in a cost effective method without getting away from the production line of the manufacturers of storage tanks. Additionally, it was proved that the flow of 6 l/min seems to be excessive for small storage volume.

Another experiment performed was the intermitted withdrawal of water from the storage tank so as to simulate the actual use. The results were also positive and proved the effectiveness of the PCM to preserve stratification.

In the future, we plan to use 6 l/min flow in a larger volume cylinder and use the cylinder with PCM on a real solar water heating system to investigate its performance during real solar operation.

5. **Acknowledgements**.

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6. References

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