Back-shifting of Heat Pump Operation for Water Heating from Peak to Off Peak Energy Demand Period with Thermal Energy Storage

Agbanigo, A. Olubunmi
Mechanical Engineering Department,
The Federal Polytechnic, Ado Ekiti
Ado Ekiti, Nigeria
E-mail: bagbanigo@yahoo.com

Abstract – **The possibility of back-shifting heat pump operation for domestic water heating from peak to off-peak demand period employing phase change heat storage materials is here investigated using computer models simulated for various operation durations and start/stop set times for the two energy demand periods with ESP-r and analysed for hot water temperatures during occupied period. Test models of a 2-storey detached building with no PCM (base case) in domestic hot water tank were compared with test models of similar building but with phase change materials incorporated into domestic hot water storage tank. Result show proportion of occupied period that hot water temperature dropped below 40^{o}C reduced with increasing proportion of PCM in hot water storage tank and increases as operation duration reduced and is moved into off peak energy demand period. On/off set time 5.00 – 8.00 (5am – 8am), 3 hours operation period, with 37.5% PCM in hot water tank compared very well with the base case model on/off set time 7.00 – 16.00 (7am – 4pm, no PCM), having hot water temperature below 40^{o}C for 12.55% of occupied period against 14.52% for the base case model. 5am – 8am falls within the off peak energy demand period, indicating the potential of phase change heat storage to facilitate off peak operation of heat pump for domestic water heating.**
Keywords – Back-shifting, Heat pump, Peak, Off-peak, Hot water temperature, Phase change materials

I INTRODUCTION

Around 40% of total global energy is consumed in buildings for various purposes, and between 42% [1] and 60% [2] of this is utilised for indoor environment control. In the UK, 30% of total energy is utilised in the domestic sector, with 83% of it employed for heating and cooling purposes [3].

Domestic heating in the UK is done mostly with gas fired boilers where about 18 million units are installed [4], representing about 68% of residential properties [5]. But according to [6], heat pumps are gradually gaining popularity having been identified as viable options for reducing carbon emissions in the domestic energy sector. They are considered as having the greatest potential, especially for reducing domestic CO_2 emissions from heating and power [6]. There is also the potential for reducing overall primary energy consumption, since its greater than 100% efficiency (sometime up to 200%) implies lower overall energy load, because they produce more heat for the same quantity of energy consumed as gas fired (or electric) boilers [8]. Also, because input energy (heat) is sourced from a cheap and abundant source [7].

Energy and cost reduction with heat pump heating systems, as well as network stabilisation is also possible, according to [10], [11] and [12], if operation period/time is manipulated for back shifting from peak to off-peak periods and thermal buffering is applied, whereby excess heat produced during periods of low demand is stored and utilised during periods of high demand.

Thermal buffering for domestic applications can be achieved through a number of thermal energy storage options like thermal fabrics [12], [13] and phase change energy storage materials ([14], [15], [9], [10], [16]. [11]).

Energy storage affords opportunities for better utilisation and management of energy and energy resources. Wastages can be reduced considerably as energy systems would not necessarily have to be designed for maximum load but for an optimum that is some mid-way between highest and lowest demand. Excesses during periods of low demand can be stored away and utilised to meet up supply during periods of high energy demand. This way energy demand and supply profile can be levelled.

As suggested by reference [17], “thermal energy storage can be used to manage electrical loads when deployed with electrically driven heating and cooling systems” like heat pumps (vapour compression systems) and help flatten load profile, and smoothen out energy demand peaks and fluctuations [8].

Latent heat thermal storage systems employed for home and office heating and cooling purposes offer huge benefits and opportunities for reducing cost and CO_2 emissions by buildings, enhancing building ability to stabilize and maintain steady internal temperature conditions ([16], [19], [15], [14]).The fact that phase changes occur at relatively constant temperatures implies that difference between heat storage and heat delivery temperatures need not be large and heat supply and delivery will occur at relatively constant temperatures, which also reduces or limits losses [20].

According to reference [20], phase change materials can truly reshape the way energy is consumed, especially in the domestic sector, and help mitigate some environmental impacts of energy consumption.

Accordingly, back-shifting heat pump operation for domestic water heating employing phase change materials is herein investigated with the aid of dynamic simulations with ESP-r software.

II METHODOLOGY

A 2-storey detached building, indicative of UK building stock, with average insulation and employing air source heat pump water heating system was modelled using ESP-r software. The model, separated into three zones (living, non-living and loft), represents details of building geometry, fabric materials, occupants and equipment heat gains, air leakages and heating systems. The heating system, comprising an air source heat pump and a stratified hot water storage tank, which has provision for inclusion of phase change materials, were treated as components and represented by networks.

With a strategy to maintain domestic hot water above 40^{o}C, thus giving heat supply to the domestic hot water storage tank priority, occupied period was set for between 8:00 am and 11:00pm (8.00 – 23.00) while phase change temperature was set at 41.5^{o}C and UK weather data for 1994 was used for the simulations.

Time actuator for on/off time settings, which allowed for manipulation of heat pump start/stop time and running/operation time/period or duration, was adjusted at 2-hour intervals to back-shift start/stop time and running/operating period regressively toward off peak energy demand period.

A base case model was simulated with no PCM in water storage tank for heat pump on/off time settings of 7.00 – 16.00 (i.e. 7am – 4pm) for a week in January (winter) and results analysed for percentage of entire occupied period that temperature of water in domestic hot water tank dropped below 40^{o}C. Other simulations were done for no PCM in domestic hot water storage tank for reducing pump operation time as well as for cases with phase change materials incorporated in the hot water storage tank in steps of 12.5%, 25% and 37.5% of storage tank volume capacity over different start/stop time settings.

All simulations were carried out for a week in January, winter being the coldest season of the year, and results analysed for effect on storage tank hot water temperatures.

III RESULT ANALYSIS AND DISCUSSION

Simulations for the base case model (no PCM), pump on/off set time 7.00 – 16.00 (7am – 4pm) gave total operation time of 9 hours per day for the heat pump. Hot water temperature remained above 40^{o}C for approximately 85% of the entire occupied period and below 40^{o}C for exactly 14.53% (water temperature profile is shown in fig 1).

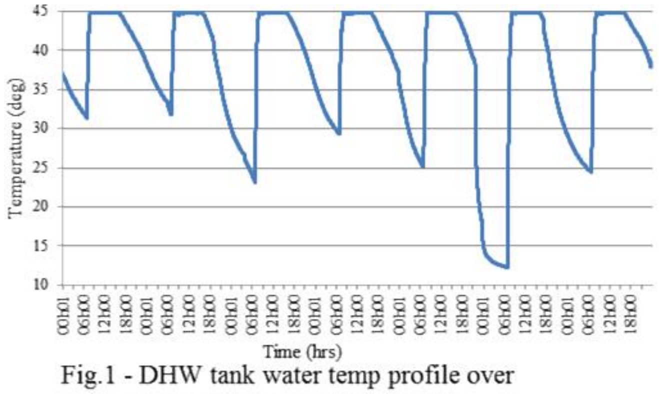

Fig.1 - DHW tank water temp profile over simulation period (7.00 - 16.00)

Reducing operation time by two hour intervals with 7am remaining as the start time, that is, 7am – 2pm (7.00 – 14.00), 7am – 12pm (7.00 – 12.00) and 7am – 10am (7.00 – 10.00), for operation times of 7, 5 and 3 hours produced the hot water temperature profiles shown in fig. 2 – 4.

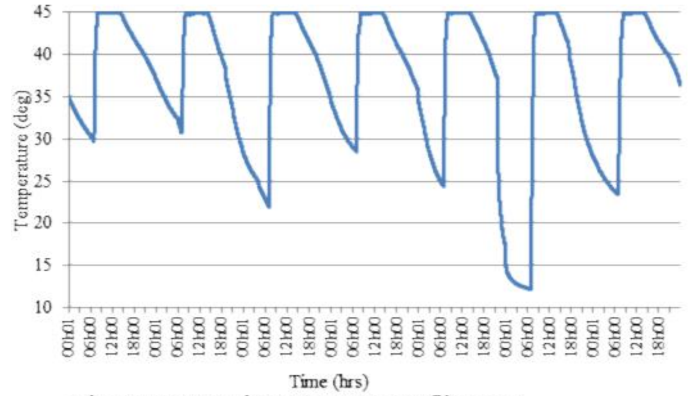

Fig. 2 DHW tank water temp profile over simulation period (7.00 - 14.00)

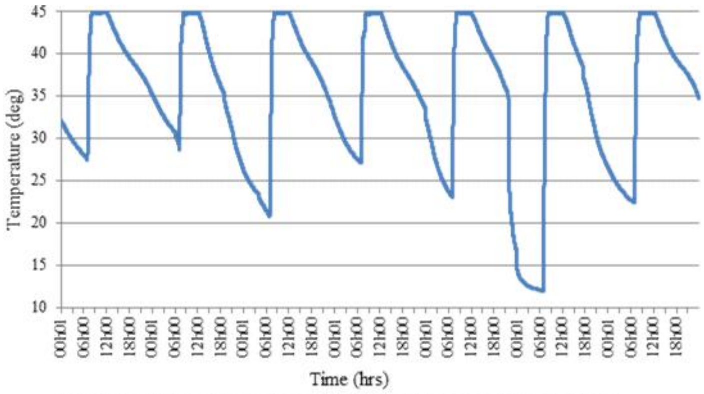

Fig 3 DHW tank water temp profile over simulation period (7.00 - 12.00)

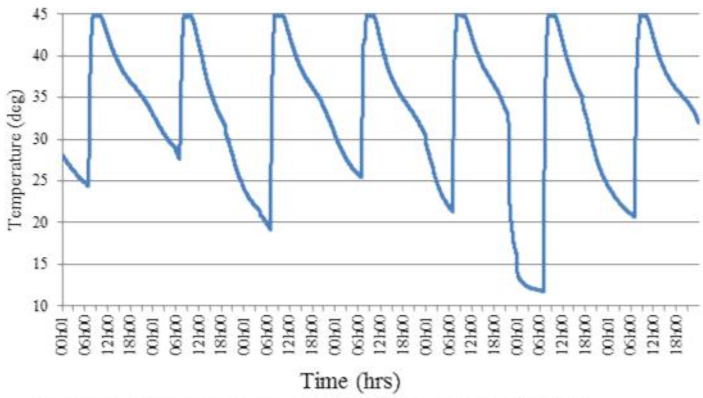

Fig 4 DHW tank water temp profile over simulation period (7 - 10)

The effect of these on percentage of occupied period that hot water temperature falls below 40^{o}C is shown in table (I) and fig. 5.

Table (I): Effect of reducing on/off set time and heat pump operating hours on % of occupied period DHW temperature dropped below 40°C computed from simulation results (No PCM only; 7am start time)

Duration (hrs.)	no PCM
9	14.52
7	24.92
5	43.16
3	63.91

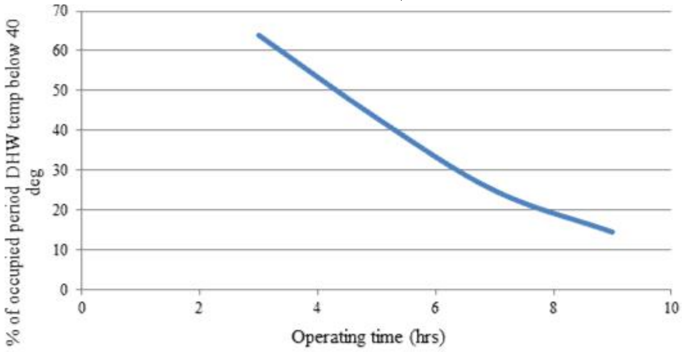

Fig 5 Effect of reducing pump running time (start time at 7am) on proportion of occupied period DHW temp < 40 deg

As expected, percentage of occupied period that hot water temperature dropped below 40°C increased from 14.52%, for base case 7.00 – 16.00 (9 hours operation), to 24.92%, for 7.00 – 14.00 (7 hours operation); 43.16% for 7.00 – 12.00 (5 hours operation) and 63.91% for 7.00 – 10.00 (3 hours operation).

Maintaining constant operating period of 9 hours, start and stop times were adjusted to achieve back-shifting of start time by 2-hour step/interval away from peak energy demand period into the off-peak period. The on/off time settings are 5.00 – 14.00 (5am – 2pm), 3.00 – 12.00 (3am – 12pm) and 1.00 – 10.00 (1am – 10am). Domestic hot water temperature profile and effect on percentage of occupied period that hot water temperature dropped below 40°C are shown in fig. 6 – 9.

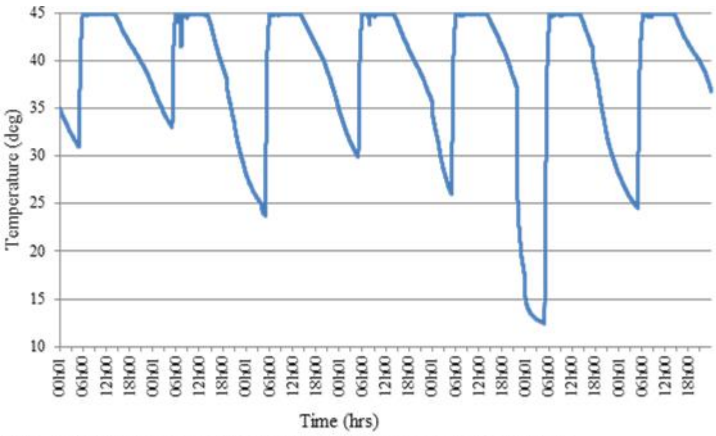

Fig. 6 DHW tank water temp profile over simulation period (5.00 - 14.00)

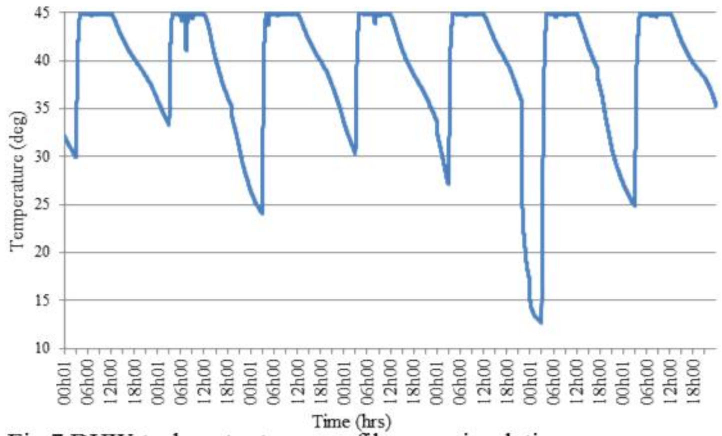

Fig 7 DHW tank water temp profile over simulation period (3.00 - 12.00)

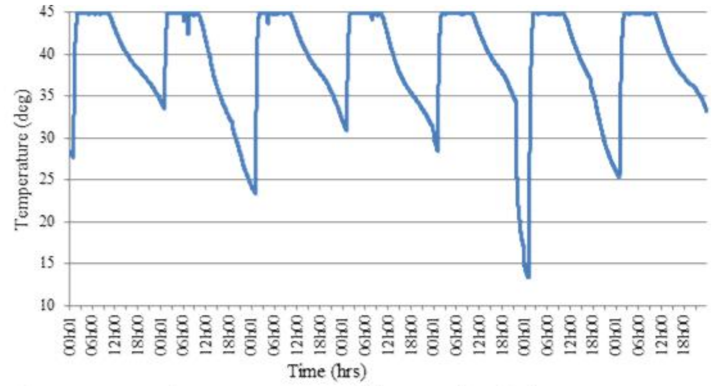

Fig 8 DHW tank water temp profile over simulation period (1.00 - 10.00)

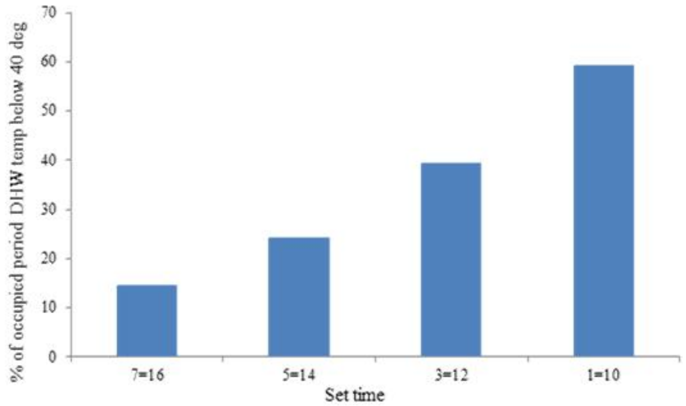

Fig 9 Effect of bach shifting set time duration on % of occupied period DHW temp below 40 deg

The width and depth of the gullies in the graphs are observed to reduce as set time is shifted backwards and heat pump start time draws close to the period of high hot water draw. This did not cause hot water temperature to stay above 40^oC for longer because stop time, heat pump stop/off time, is equally shifted backwards away from the period of high hot water draw. It appears to have a more negative impact on hot water temperature as show in fig. 9.

Percentage of occupied period with hot water temperatures below 40^oC increases from 14.52% to 24.22%, 39.35% and 59.29% for on/off time settings 7.00 – 16.00, 5.00 – 14.00, 3.00 – 12.00 and 1.00 – 10.00 respectively. This is attributable to the fact that the heat pump had to work more due to its starting earlier in the mornings when ambient temperatures are still relatively low.

On/off set time 5.00 – 14.00 yielded hot water temperature below 40^oC for 24.22% of occupied period and below 38^oC for 14.13%. This was taken as below acceptable limit for system performance, which was put at 15% of occupied period for water temperature below 40^{o}C and above 38^{o}C for at least 90% of the 15% of total occupied period. 5.00 – 14.00 (5am – 2pm) was therefore used as starting point for test case models with phase change materials (PCM) incorporated into the hot water storage tank. The same 9 hours duration for heat pump and on/off time settings of 5.00 – 14.00 (5am – 2pm), 3.00 – 12.00 (3am – 12pm) and 1,00 – 10.00 (1am – 10am) were simulated with 12.5%, 25% and 37.5% PCM to DHW tank volume capacity in water storage tank. Temperature profiles for the domestic hot water temperature for each of the time setting and percentage of PCM are shown in fig. 10 – 17.

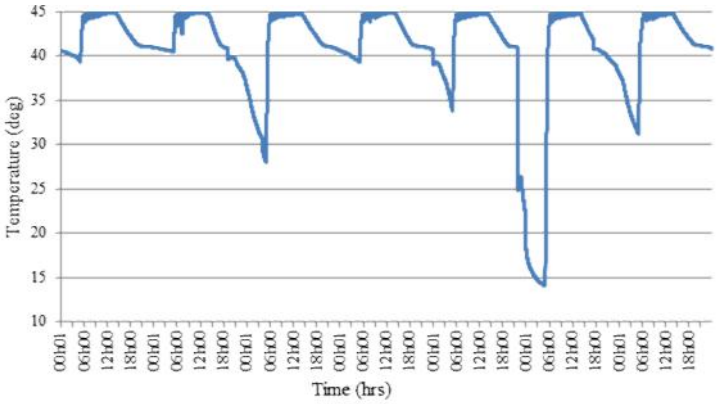

Fig 10 DHW tank water temp profile over simulation period (5.00 - 14.00, 12.5% PCM)

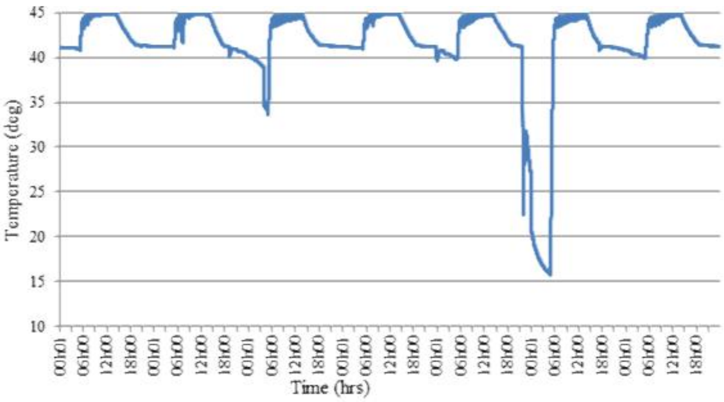

Fig 11 DHW tank water temp profile over simulation period (5.00 - 14.00, 25% PCM)

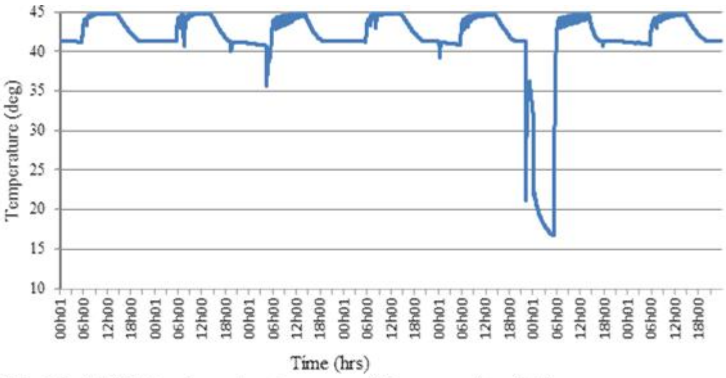

Fig 12 DHW tank water temp profile over simulation period (5.00 - 14.00, 37.5% PCM)

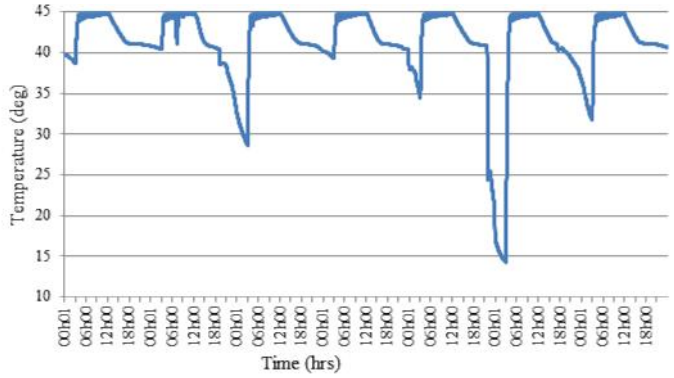

Fig. 13 DHW tank water temp profile over simulation period (3.00 - 12.00, 12.5% PCM)

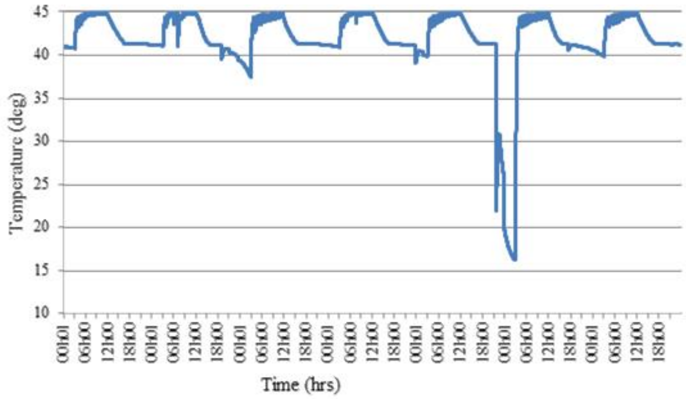

Fig 14 DHW tank water temp profile over simulation period (3.00 - 12.00, 25% PCM)

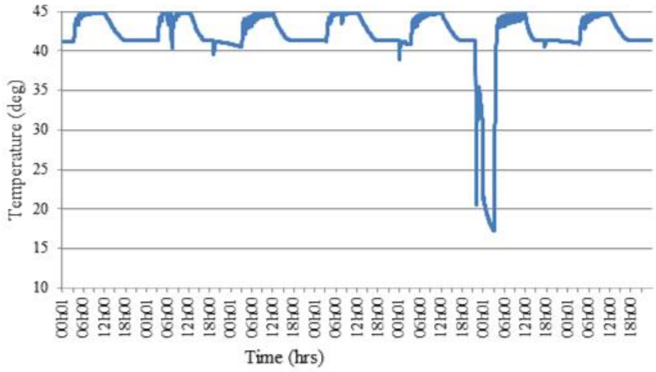

Fig 15 DHW tank water temp profile over simulation period (3.00 - 12.00, 37.5% PCM)

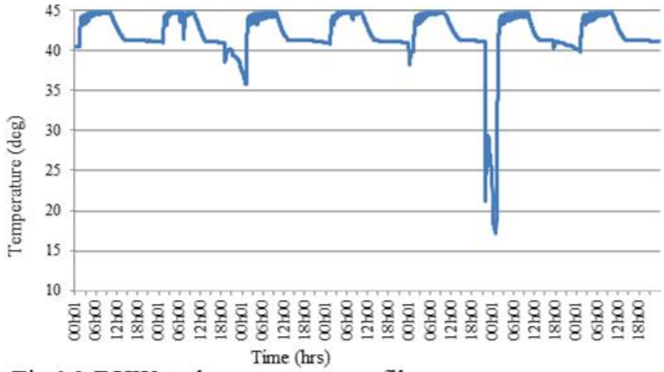

Fig 16 DHW tank water temp profile over simulation period (1.00 - 10.00, 25% PCM)

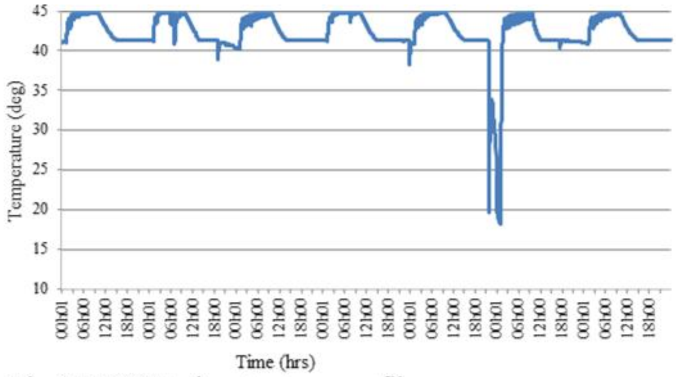

Fig 17 DHW tank water temp profile over simulation period (1.00 - 10.00, 37.5% PCM)

The width and depth of the gullies in the graphs are clearly smaller in comparison with corresponding cases (on/off time settings) without PCM, and they reduce with increasing percentage of PCM. This shows the effectiveness of phase change material to bridge heat/thermal energy supply gap and maintain hot water temperature above set points for a considerable length of the occupied period. With PCM extending heat availability beyond heat pump stop/off times temperature profile is much gentler with fewer gullies. Implying there is sufficient heat to keep hot water temperature up till heat pump's next start/on time.

Consequence of back shifting on percentage of occupied period that hot water temperature dropped below 40^{o}C is compared for the base case, no PCM, and test cases with different proportions of PCM in domestic hot water tank and is shown in table (II) and fig. 18.

Table (II): Effect of back shifting on percentage of occupied period DHW temperature dropped below 40^{o}C computed from simulation result (9 hours operation)

Set time	no PCM	% PCM		
		12.5	25	37.5
7.00 – 16.00	14.52			
5.00 – 14.00	24.22	6.96	1.14	1.14
3.00 – 12.00	39.35	7.77	1.38	1.24
1.00 – 10.00	59.29		3.53	1.32

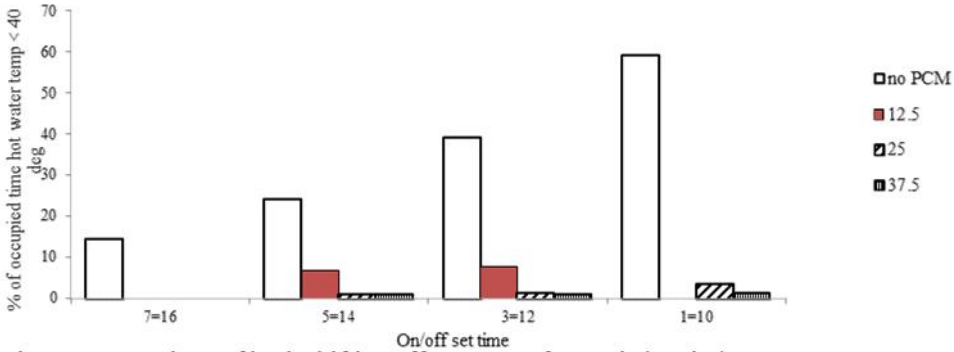

Fig 18 Comparison of back shifting effect on % of occupied period water temp < 40 deg for no-PCM and different percentage of PCM in DHW tank

Further reduction of heat pump operation time by 2 hours step with 5am maintained as start/on time for off peak energy demand period operation produced the result shown in table (III) and fig.19.

Table (III): Effect of reducing heat pump operating hours on % of occupied period DHW temperature dropped below 40^{o}C computed from simulation results (with PCM only; 5am start time)

Duration (hrs.)	% PCM		
	12.5	25	37.5
9	6.96	1.14	1.14
7	8.3	1.65	1.25
5	14.27	6.3	1.37
3		21.95	12.55

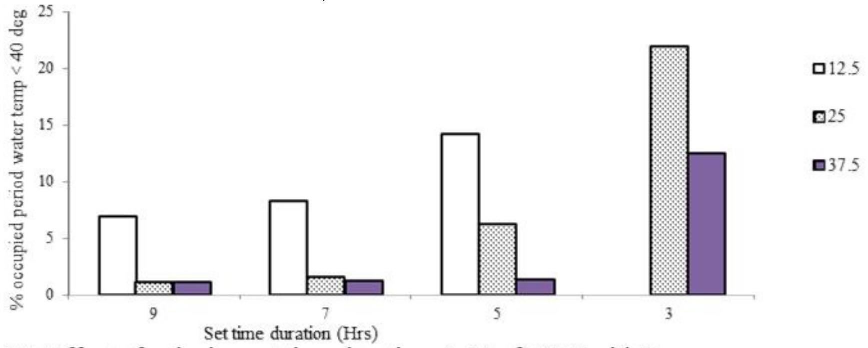

Fig 19 Effect of reducing set time duration & % of PCM with 5am as start time on % occupied period water temp < 40 deg (PCM in water tank)

Percentage of occupied period that hot water temperature falls below 40^{o}C increases as heat pump operating time reduced but decreases with increasing proportion of PCM. This is because additional PCM permitted more heat energy to be stored, enabling heating system to maintain hot water temperature above 40^{o}C for longer. A final comparison is done for effect of start/stop (on/off) time, heat pump operating time and proportion of PCM on percentage of occupied period that hot water temperature falls below 40^{o}C and presented in table (IV) and fig.20.

Table (IV): Combined effect of on/off set time back shifting and duration reduction on % of occupied period DHW temperature dropped below 40oC computed from simulation results (7.00-16.00 only for no PCM)

Set time	no PCM	% PCM		
		12.5	25	37.5
7.00 – 16.00	14.52			
5.00 – 14.00		6.96	1.14	1.14
3.00 – 12.00		7.77	1.38	1.24
1.00 – 10.00			3.53	1.32
5.00 – 12.00		8.3	1.65	1.25
3.00 – 10.00			4.86	
1.00 – 8.00			7.58	4.45
5.00 – 10.00		14.27	6.3	1.34
3.00 – 8.00		36.88	7.58	5.55
5.00 – 8.00			21.95	12.55

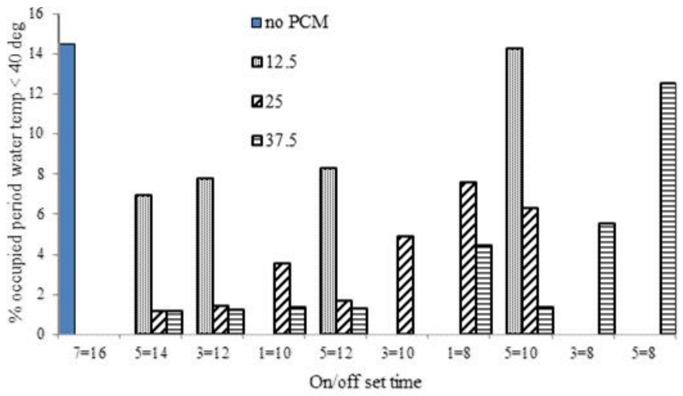

Fig 20 Comparison of Effect of on/off set time and % PCM on % occupied period wter temp < 40 deg

The shortest heat pump running/operating time for which hot water temperature remained above 40°C for more than 85% of occupied period was 3 hours, for on/off time setting 5.00 – 8.00 (5am – 8am). At 37.5% PCM, hot water temperature was below 40°C for 12.55% of occupied period. This is entirely in the off peak energy demand period, showing the possibility of running system entirely in the off peak energy demand period. Hot water temperature profile for on/off time setting 5.00 – 8.00 and 37.5% PCM is shown in fig.21.

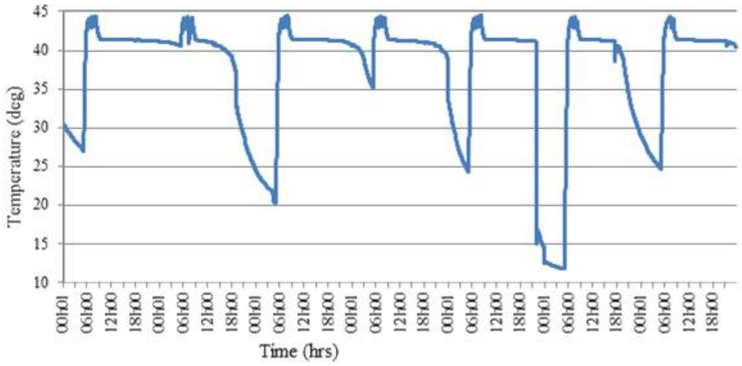

Fig 21 DHW tank water temp profile over simulation period (5.00 - 8.00, 37.5%PCM)

IV CONCLUSIONS

Results presented above show the potential of including of heat storage in domestic water storage tank in enabling heat pump operation for domestic water heating to be shifted backwards from peak to off-peak energy demand period. Analysis for percentage of occupied period that hot water temperature dropped below 40°C is observed to reduce with increasing proportion of PCM in hot water storage tank and increased as operating time reduced and is moved into off peak energy demand period. This is an indication of the effectiveness of phase change material to bridge heat/thermal energy supply gap by extending heat availability beyond heat pump stop/off times, so that hot water temperatures remain relatively high up until heat pump starts again.

Simulation results for time setting 5.00 – 8.00 (5am – 8am) with 37.5% PCM in hot water tank showed good comparison with results for the base case model (7.00 – 4.00; no PCM), with 12.55% of occupied period for time setting 5.00 – 8.00 (5am – 8am) against 14.52% of occupied period for 7.00 – 16.00 (7am – 4pm). Three hours operation of the heat pump, entirely in the off-peak energy demand period, was possible with inclusion of heat storage phase change material to 375% of tank volume in water storage tank. This shows the ability of phase change heat storage material to supply heat sufficient to maintain hot water temperature above set points for a considerable length of the occupied period.

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