System Simulation Report
System: PCM-water store

A Report of IEA Solar Heating and Cooling programme - Task 32
Advanced storage concepts for solar and low energy buildings

Report C6.4 of Subtask C

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Task 32
Storage

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Report on System Simulation

C6.4: Appendix 4 of report C6

System: PCM-water store

by

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A technical report of Subtask C

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Content

1 Introduction

It is well known that the use of Phase Change Materials (PCM) in Domestic Hot Water Tanks (DHWT) reports some advantages for the system. One advantage is the capability of the PCM to reheat the amount of cold water surrounding the PCM after a partial or total unload of the tank without external heat input. Another one is that the temperature of the water surrounding the PCM is kept constant a longer period of time or decreases slower than the water with no interaction with the changed PCM.

1.1 PCM advantages demonstration: reheating

A simple simulation to show that the PCM-water tank (Type 840) reheats the water surrounding the PCM module that is at a lower temperature than the PCM was done. Fig. 1 shows the structure of the simulation and the types used.

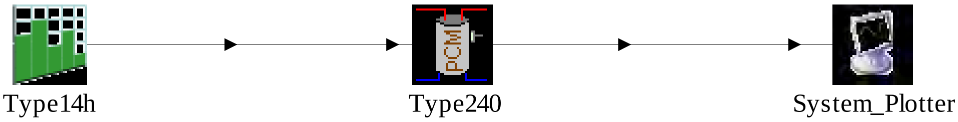
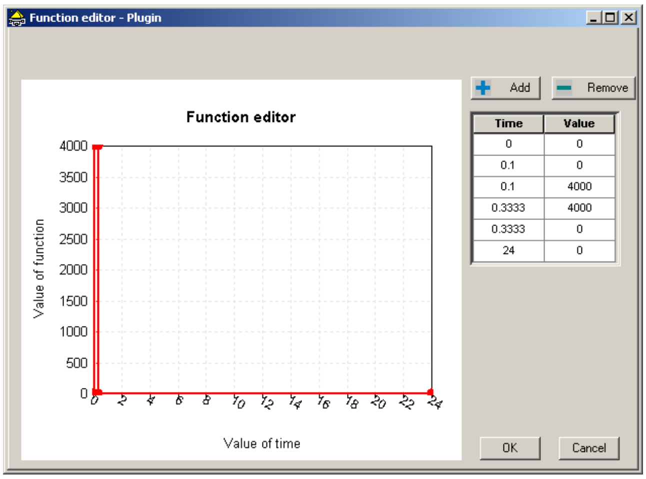


Fig. 1. Reheating test

At the beginning of the test, the temperature of the water into the tank was 70ºC, and then the tank is rapidly drawn-off and filled it again with cold water at 35ºC. The reheating capability consists in warming up the water surrounding the PCM modules. Therefore, to check the reheating capability it was necessary to discharge the tank and fill it again with cold water. To do this in such a way and just once, a forcing function (Type 14h) is necessary. This type is a time dependent forcing function which has a behaviour characterized by a repeated pattern. The pattern of the forcing function (Fig. 2) is established by a set of discrete data points indicating the value of the function at various times throughout one cycle. However, in this simulation the pattern was done to discharge the tank at the beginning and just once during the full simulation (2 hours).



Time	Value
0	0
0.1	0
0.1	4000
0.3333	4000
0.3333	0
24	0

Fig. 2. Pattern of the forcing function

The tank is rapidly discharged and then charged again with cold water. With the system plotter (Fig. 1) the temperatures of the water surrounding the PCM modules and the PCM temperature are plotted as shown in Fig. 3. Water temperatures are referred to the four temperature sensors placed at a relative height of 0.6, 0.716, 0.833, and 0.95 meters, for T1 to T4 respectively from the bottom of the tank. Concerning the PCM temperature, these sensors are placed at the same relative position than the water sensors. The PCM modules have a total relative height of 0.175 m and its relative top position is 0.95 m and the bottom position is 0.775 m. The sensors that are measuring the PCM temperature are PCM-3 and PCM-4 placed at a relative position of 0.833 and 0.95 m respectively.

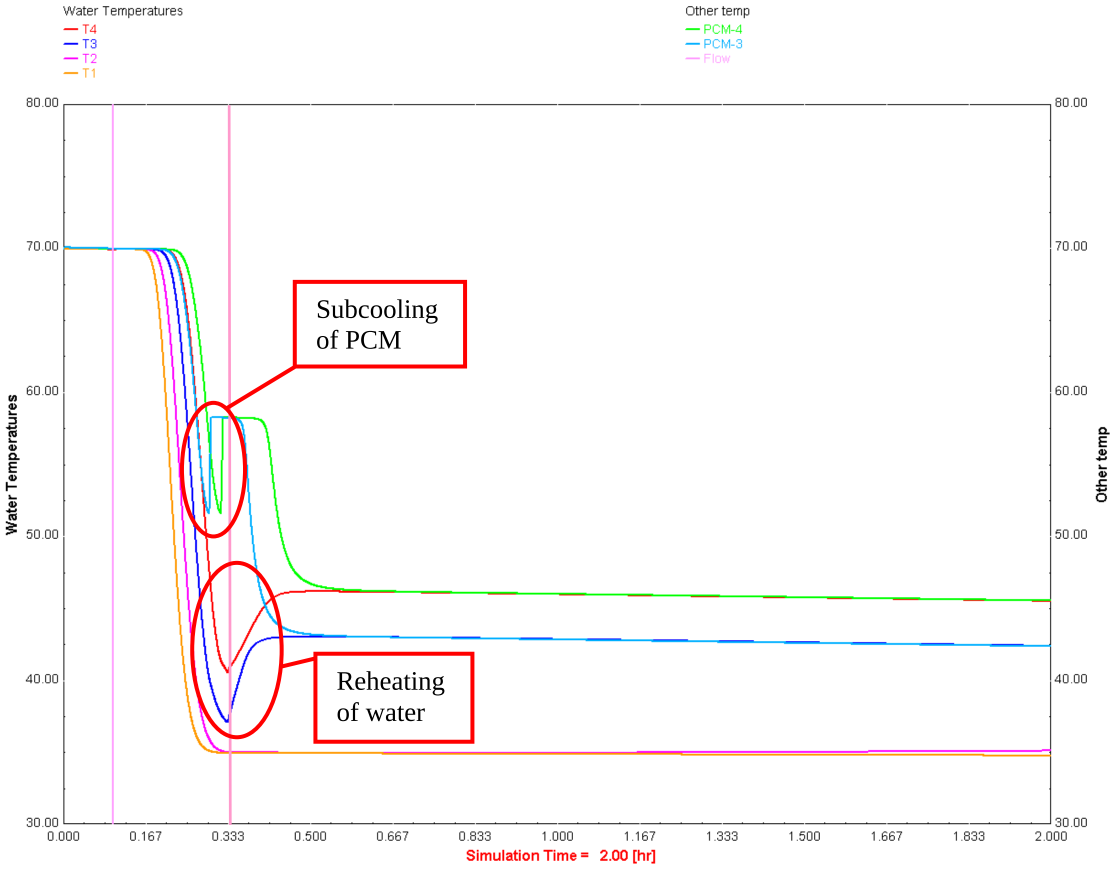


Fig. 3. Water and PCM temperatures and discharge flow rate

The discharge mass flow rate starts at 0.1 h and stops at 0.333 h with a total amount of 4000 kg/h that is 66.7 kg/min. In Fig. 3 it is possible to see that when the mass flow rate stops (at a time of 0.333 h) the water into the tank is around 40ºC meanwhile the PCM temperature is at 58ºC, this means that the PCM is changing from liquid to solid at that moment of the simulation (0.333 h). It is also possible to see the sub-cooling effect, which means that the PCM temperature decreases below 58ºC before the solidification process starts. At 0.333 h, when the mass flow rate stops, it is observed that the water temperature of the layers surrounding the PCM modules (T3 and T4) is increasing.

Therefore, it can be concluded that the PCM-water tank (Type 840) takes profit from the reheating to heat up the water surrounding the PCM modules when the water temperature is lower than the PCM temperature.

1.2 PCM advantages demonstration: slower decreasing of the water temperature

This test wants to demonstrate that the water temperature influenced by hot PCM cools down slower than water with no interaction with this material. To check it a simple simulation with a PCM-water tank was carried out as it is shown in Fig. 4.

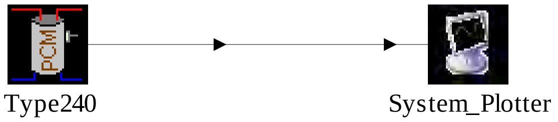


Fig. 4. Slower decreasing of the water temperature

The temperature of the tank was initially at 62ºC, and the tank was let to cool down naturally by thermal looses. The ambient temperature was 0ºC and there was no mass flow rate into or out from the tank. Fig. 5 shows the water temperatures of the four sensor temperatures placed at 0.3, 0.516, 0.733, and 0.95 m respectively from the bottom of the tank for T1 and T4 respectively. Concerning the PCM temperatures, they are placed at the same relative position than the water sensors. The PCM modules have a total relative height of 0.175 m and its relative top position is 0.95 m and the bottom position is 0.775 m, as in the previous simulation. Therefore, in this experiment there is just one PCM sensor (PCM-4 in Fig. 5) that reads the temperature inside the PCM module.

Thus, it is possible to see in Fig. 5 that the layers which are not in contact with the PCM module cool down faster than the upper water layer (T4) which has a very similar shape than the PCM temperature curve and increasing its temperature when the phase change happens. Also the layer in direct contact with the PCM module (T3) increases its temperature when the phase change takes place.

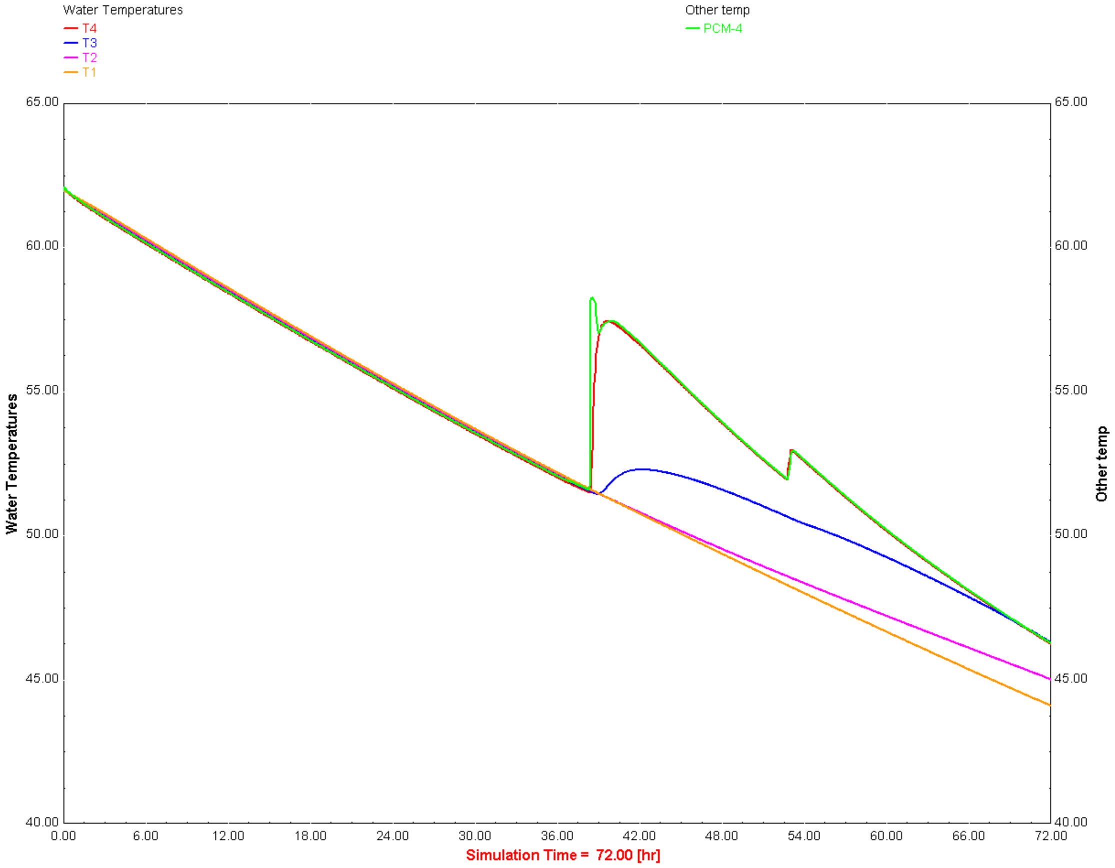


Fig. 5. Water and PCM temperatures

2 Simulations with the Template Solar Combisystem

A simulation for a 60 kWh/m^2·a energy demand house in Madrid with a 6 m^2 collector area and a storage volume of 800 L was performed. The storage tank was filled with sodium acetate + graphite as PCM, placed in the upper part of the tank. The amount of PCM introduced into the tank is defined by the filling ratio P_{area}, which is the cross-sectional area of all modules divided by the cross-sectional area of the storage tank. The P_{area} ratio was fix to 0.25.

2.1 Time step influence. Results

A one day simulation with different time-steps (1, 3 and 6 minutes) showed the importance of such parameter in the PCM evaluation. It is clearly seen in Fig. 6 (6 minutes time step) to Fig. 8 (1 minute time step) that the variation of the time step changes completely the evaluation of the PCM. Fig. 6 does not show any significant variation in the PCM curve at 18 hours approximately, meanwhile Fig. 8 shows a complete different PCM temperature curve at this time.

Therefore, the time step is an important parameter to take into account when a simulation with PCM is carried out. The shorter the time step, the more accurate and precise are the results.

Fig. 6. Simulation with a 6 minutes time step

Fig. 7. Simulation with a 3 minutes time step

Fig. 8. Simulation with a 1 minutes time step

2.2 Annual simulation. Results

With the configuration described above, an annual simulation with a 1 minute time step was performed and the results were evaluated for every month, and more detailed for every Thursday of the third week of each month. The data evaluated in this simulation are the different temperatures and the mass flow rates that come in and out of the storage tank. Table 1 shows the parameters monitored and Fig. 9 shows the relative position of every sensor into the tank that corresponds to each parameter.

Table 1. Parameters monitored in the simulation

Variable description	Variable name	Variable description	Variable name
Fluid temperature	Tfluid1	Outlet temperature of DP3 (store → auxiliary)	TSA
Fluid temperature	Tfluid2	Inlet temperature of DP3 (auxiliary → store)	TAS
Fluid temperature	Tfluid3	Outlet temperature of DP4 (store → SH)	TSB
Fluid temperature	Tfluid4	Inlet temperature of DP4 (SH → store)	TBS
PCM temperature	Tpcm	Outlet temperature of DP5 (store → DHW)	TSD
PCM temperature	Tpcm	Inlet temperature of DP5 (DHW (HX[1]) → store)	TXdS
Mass flow rate of store to auxiliary	mSA	Outlet temperature of DP1 (store → solar collectors)	TSC
Mass flow rate of store to SH	mSB	Inlet temperature of DP1 (Solar collectors (HX[2]) → store)	TXsS
Mass flow rate of store to solar collector	mSC	First on/off auxiliary sensor	Tssa1
Mass flow rate of store to DHW	mSD	Second on/off auxiliary sensor	Tssa

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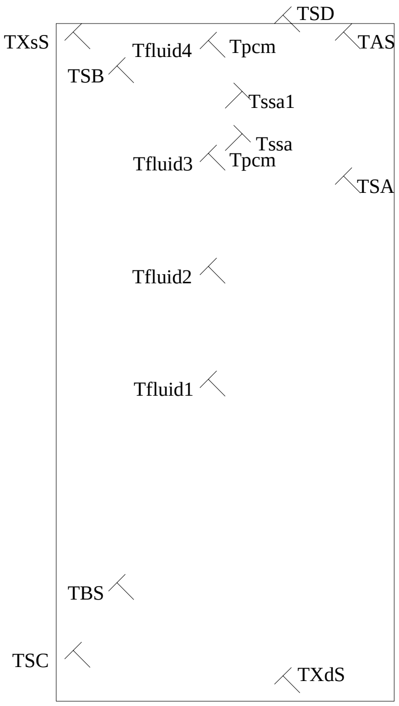
[1] An external heat exchanger is used fort he DHW supply
[2] An external heat exchanger is used fort he DHW supply



Variable	Description	Rel. value
Tfluid4	Fluid temperature at sensor 4	0.95
Tfluid3	Fluid temperature at sensor 3	0.7833
Tfluid2	Fluid temperature at sensor 2	0.6166
Tfluid1	Fluid temperature at sensor 1	0.45
Tpcm	PCM temperature	0.95
Tpcm	PCM temperature	0.7833
TSA	Water temperature from store to auxiliary	0.75
TAS	Water temperature from auxiliary to store	0.9625
TSB	Water temperature from store to space heating	0.9125
TBS	Water temperature from space heating to store	0.15
TSD	Water temperature from store to DHW	0.9875
TXdS	Water temperature from DHW heat exchanger to store	0.0125
TSC	Water temperature from store to solar collectors	0.05
TXsS	Water temperature from solar collectors heat exchanger to store	0.9625
Tssa1	First on/off auxiliary temperature sensor	0.875
Tssa	Second on/off auxiliary temperature sensor	0.8125
PCM top	Top position of PCM module	0.95
PCM bot	Bottom position of PCM module	0.775

Fig. 9. Position of the sensors monitored into the storage tank and PCM module

2.2.1 January results and analysis

Fig. 10 and Fig. 11 show the values of the parameters monitored (Table 1) for Thursday of the third week in January. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

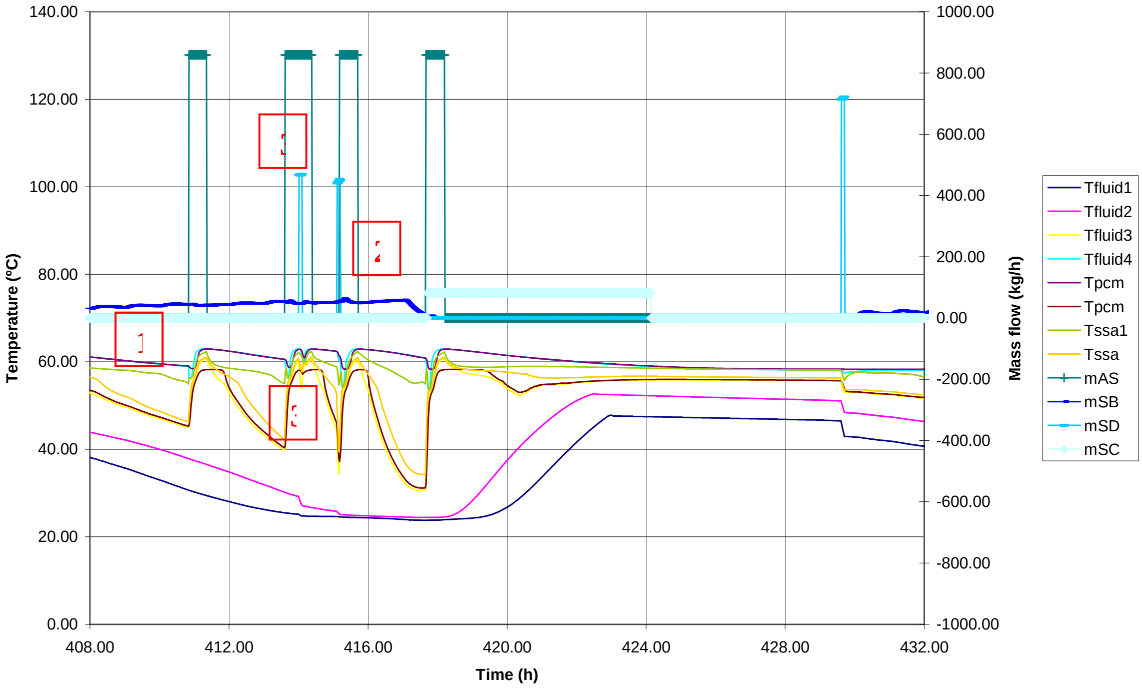


Fig. 10. Fluid and PCM temperatures and mass flow rates for the third Thursday of January

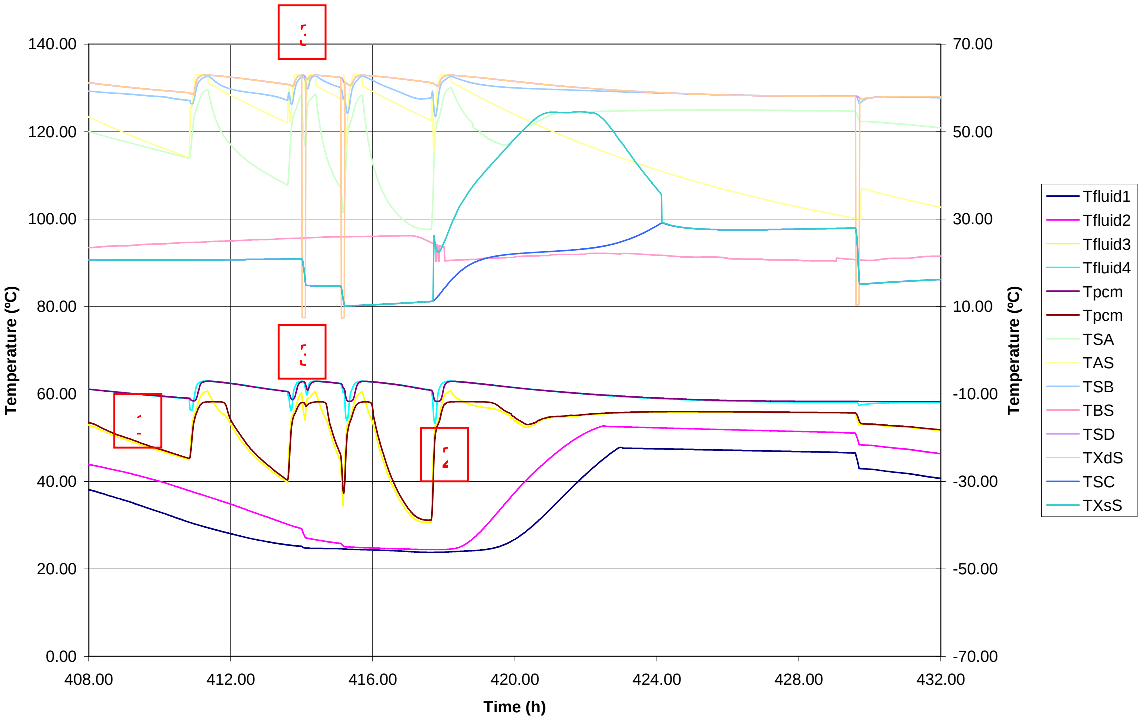


Fig. 11. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of January

[1] It is possible to observe that the PCM does not release all the energy stored. The upper PCM temperature sensor never decreases of 58ºC so it does never solidify. On the other hand, the PCM temperature sensor placed at a lower position (nearly the bottom of the PCM module) reaches a temperature lower than 58ºC so this part of the PCM module discharges completely the energy stored. PCM temperature curves follow the same shape as water temperature; water is stratified and PCM too. Thus, the upper part of the PCM module is still charged meanwhile the lower part is discharged.

[2] It is also shown that very early in the morning the upper part of the tank cools down due to the heating demand. The outlet of the space heating is placed at a relative height of 0.9125 m. The fact that the upper part of the tank decreases its temperature directly affects the behaviour of the boiler since the temperature difference between the first and second on/off auxiliary sensors, Tssa1 and Tssa respectively, also changes. The Tssa decreases faster than the Tssa1 and this means that the auxiliary is switched on. This major decrease is due to space heating demand.

[3] The DHW demand influences the temperature of the water coming from the auxiliary (TAS). Though it is hot water, it can be observed that the temperature decreases at that time. The same and even major effect happens with the water that is going to the auxiliary (TSA). This effect is because a water draw off by the DHW affects the temperature of the water coming from and going to the auxiliary system. These outlet and inlet are placed at very high relative positions, 0.75 m for the TSA (outlet from store to auxiliary) and 0.9625 m for the TAS (inlet of auxiliary to store). They are placed into the auxiliary volume.

Concerning the water supplied to the DHW demand (Fig. 11), its temperature is always higher than 45ºC so no penalties occurred this day. It is also possible to see that when there is DHW demand, even the temperature measured at the outlet of the auxiliary system (TSA) into the tank decreases.

These observations brings to analyse the possibility of changing the outlet of the space heating (TSB) to a lower position since it does not affect the upper part of the tank which is considered the auxiliary volume and should be mainly used for the DHW demand.

As mentioned before, it should be considered the possibility of placing this inlet and outlet of the auxiliary port in lower positions. This idea is also confirmed by the fact that the major responsible for the operation of the auxiliary system is the space heating demand (Fig. 10), so decreasing the position of the auxiliary and placing it directly in the part of the tank used for the space heating (mainly the medium part of the store) should change the operation of the auxiliary.

2.2.2 February results and analysis

Fig. 12 and Fig. 13 show the values of the parameters monitored (Table 1) for Thursday of the third week in February. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

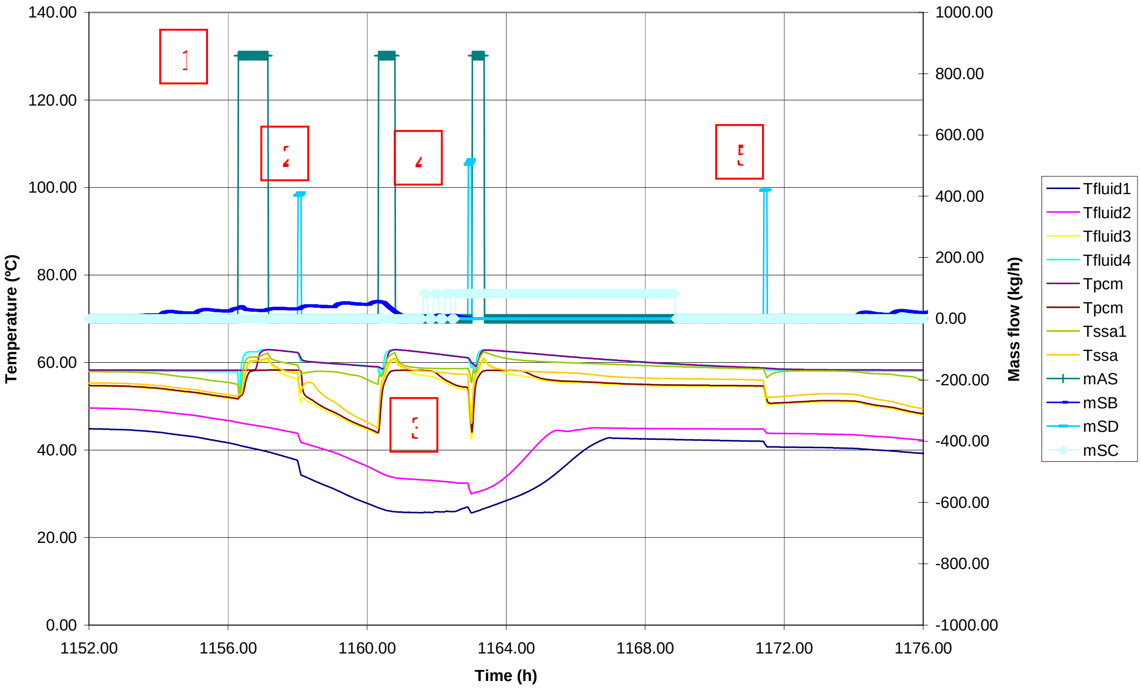


Fig. 12. Fluid and PCM temperatures and mass flow rates for the third Thursday of February

[1] It is observed that the auxiliary system switches on because the first auxiliary sensor (Tssa1) reaches the corresponding temperature for the boiler operation. The temperature to operate the boiler is fixed to 55ºC. This is due to the heating demand which is cooling down the water temperature.

[2] The DHW demand does not imply that the boiler switches on because the upper part of the tank is around 60ºC. Therefore, the DHW demand is completely supplied by the energy stored in the tank.

[3] The PCM is changing its phase to a solid state (it is releasing its energy stored). The operation of the solar loop is cooling down partially the upper layers because the temperature of the fluid coming from the solar is around 30ºC. Although the water is entering the tank through a stratifier device and as a consequence it enters to the most similar temperature layer, there are convection effects into the tank and also some mixing

effects due to the entrance of the water and this is the reason why the PCM and the sensor fluid 3 are decreasing its temperature.

[4] This cooling down of the upper part of the tank together with the DHW demand, decreases to much the temperature of the upper part of the tank and as a consequence the auxiliary is switched on (Tssa1 is lower than 55ºC).

[5] It is seen than though there is some DHW demand, no auxiliary power is needed to supply the demand.

This last observation confirms the necessity of avoiding the effects due to the space heating operation at the upper part of the tank. This means lowering the position of the outlet to the space heating.

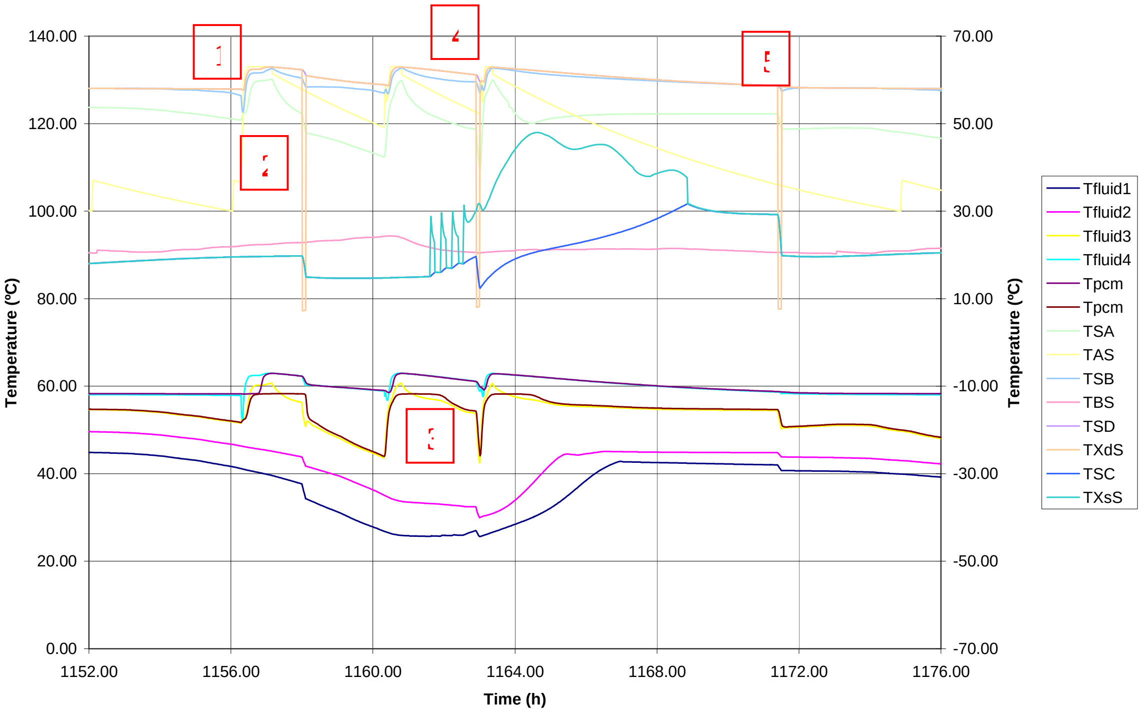


Fig. 13. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of February

2.2.3 March results and analysis

Fig. 14 and Fig. 15 show the values of the parameters monitored (Table 1) for Thursday of the third week in March. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

Fig. 14 and Fig. 15 show that the upper half part of the tank is always hot, the temperature is around 60ºC and the PCM temperature is higher than 60ºC too. The DHW demand is completely supplied by the energy stored into the tank. It is also clearly observed that the energy coming from the solar loop initially cools down the upper half part of the tank but then is highly heated.

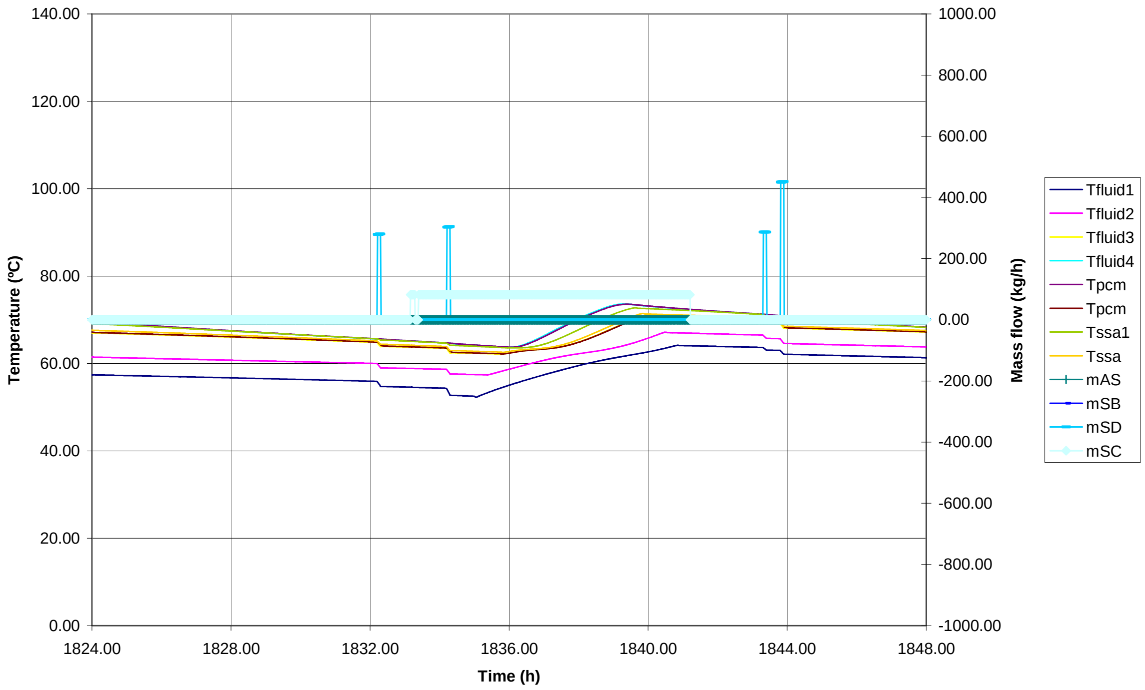


Fig. 14. Fluid and PCM temperatures and mass flow rates for the third Thursday of March

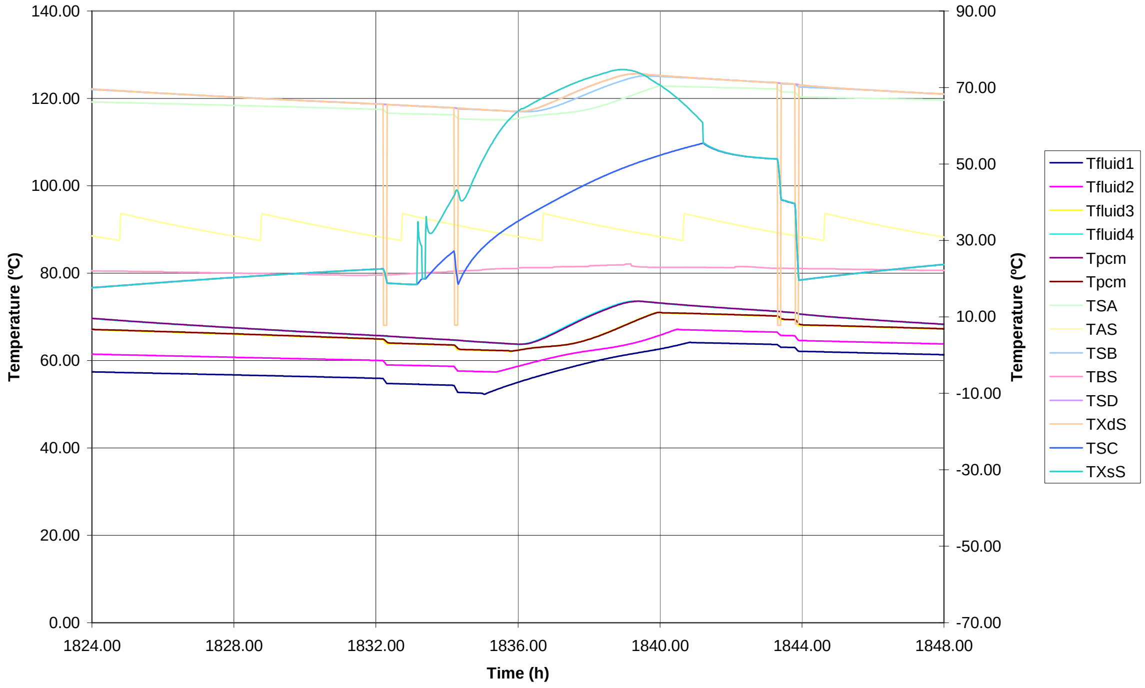


Fig. 15. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of March

2.2.4 April results and analysis

Fig. 16 and Fig. 17 show the values of the parameters monitored (Table 1) for Thursday of the third week in April. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

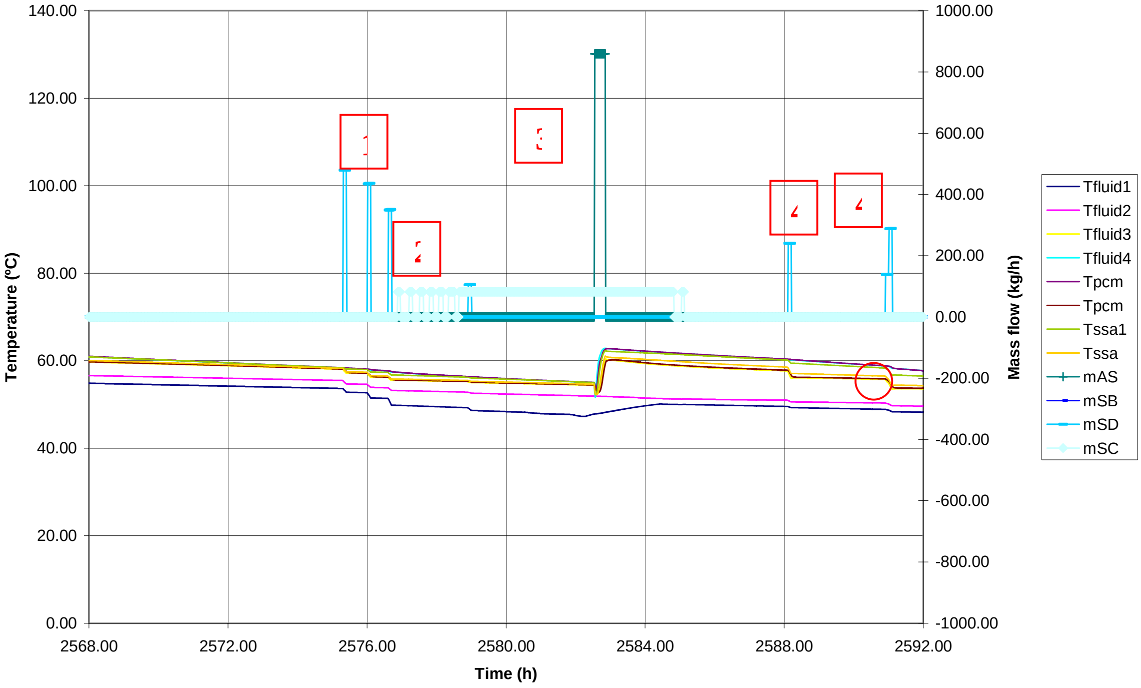


Fig. 16. Fluid and PCM temperatures and mass flow rates for the third Thursday of April

[1] Once again is seen that the DHW demand does not influence directly on the operation of the auxiliary system. Since the water into the tank is high enough to supply water at the set DHW temperature (45ºC), it is not necessary to heat it up with the auxiliary system. The four temperature sensors showed in the figures, which show the upper half part of the tank, are not below 50ºC.

[2] The solar system starts its operation intermittently introducing water at approximately 30ºC. Due to the use of the stratifier device, the water enters to the tank to the most suitable layer according the temperature of the water. At the beginning the water enters to the lower layers but due to mixing effects the temperature of the layers above the entering layer are also cooled down as the water temperature profile shows.

[3] The auxiliary switches on due to the fact that the auxiliary temperature sensor (Tssa1) is below 55ºC. There is no energy demand at that moment, however the temperature decrease because of the thermal losses of the tank. Although the solar loop is operating, it does not compensate the thermal losses in the upper part of the tank because the energy supplied enters to the tank at a lower temperature and, as a consequence, it enters to a lower position.

[4] New DHW demand which is completely supplied by the energy stored into the tank and, also, by the PCM. The phase change process is seen in Fig. 16 and Fig. 17.

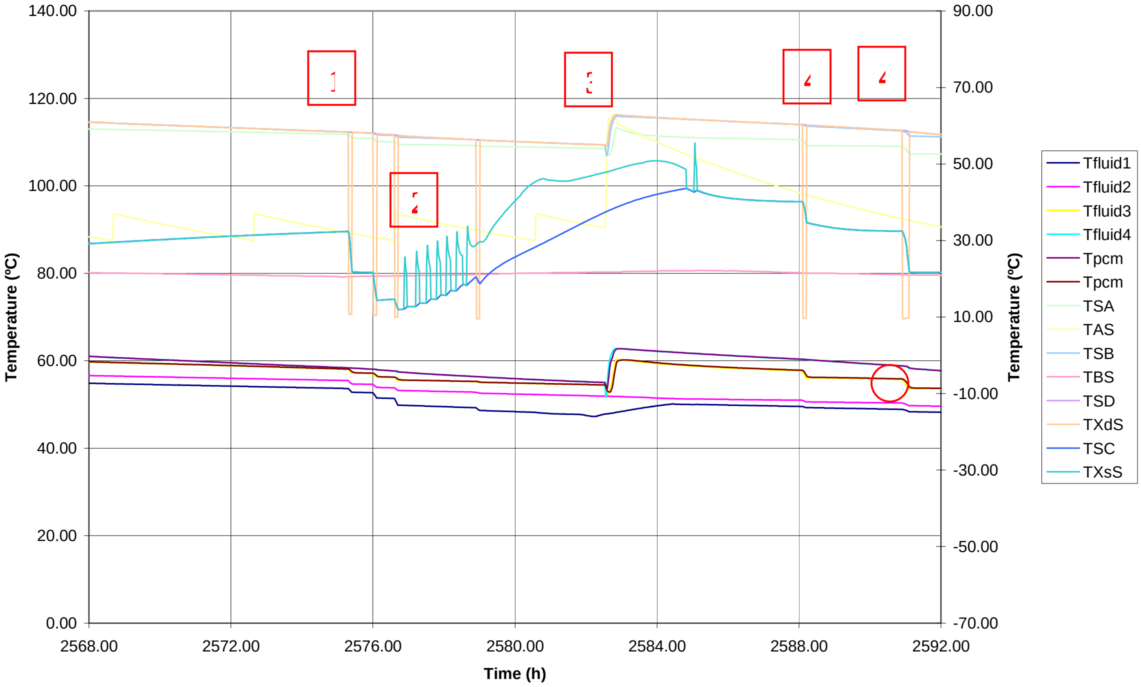


Fig. 17. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of April

2.2.5 May results and analysis

Fig. 18 and Fig. 19 show the values of the parameters monitored (Table 1) for Thursday of the third week in May. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

[1] The auxiliary system switches on automatically when the first auxiliary sensor reaches 55ºC. The decrease in the temperature into the tank until the first auxiliary sensor (Tssa1) reaches 55ºC is because of the thermal losses.

[2] The phase change of the PCM is clearly seen in these figures.

[3] It is also possible to observed that the fluid coming from the solar collectors enters to the tank to an intermediate temperature (respect the temperature sensors). The temperature of the water entering the tank is increasing from 35ºC to 55ºC approximately (Fig. 18) and is heating up the water from the layers where Tfluid1 and Tfluid2 are placed.

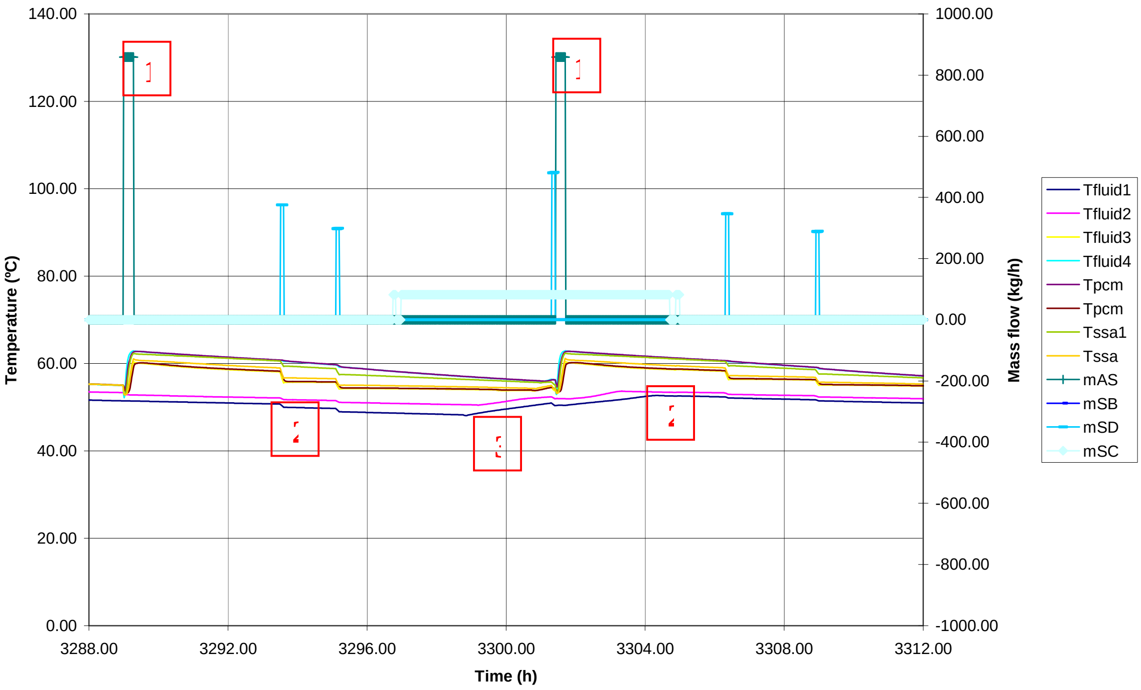


Fig. 18. Fluid and PCM temperatures and mass flow rates for the third Thursday of May

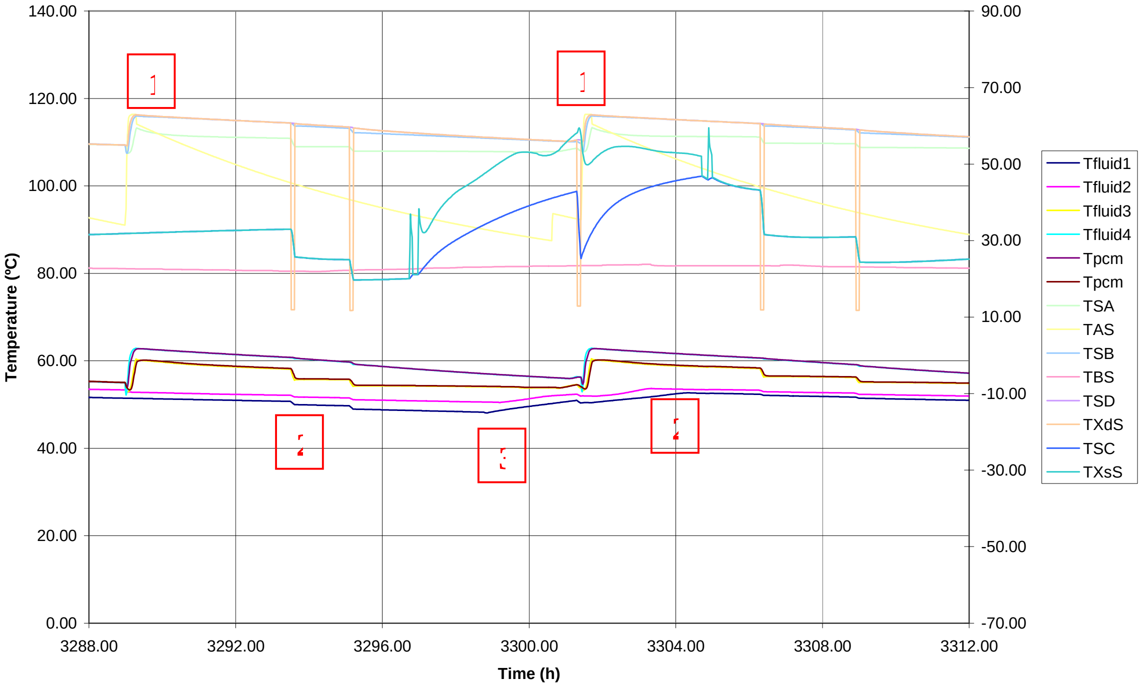


Fig. 19. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of May

2.2.6 June results and analysis

Fig. 20 and Fig. 21 show the values of the parameters monitored (Table 1) for Thursday of the third week in June. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

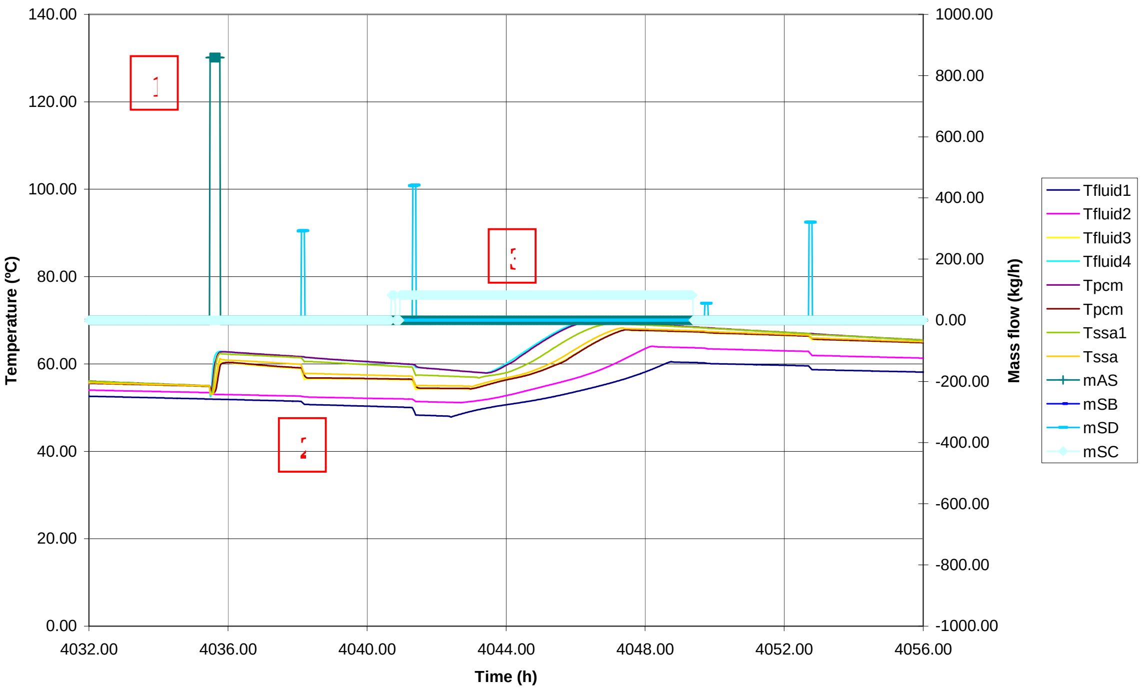


Fig. 20. Fluid and PCM temperatures and mass flow rates for the third Thursday of June

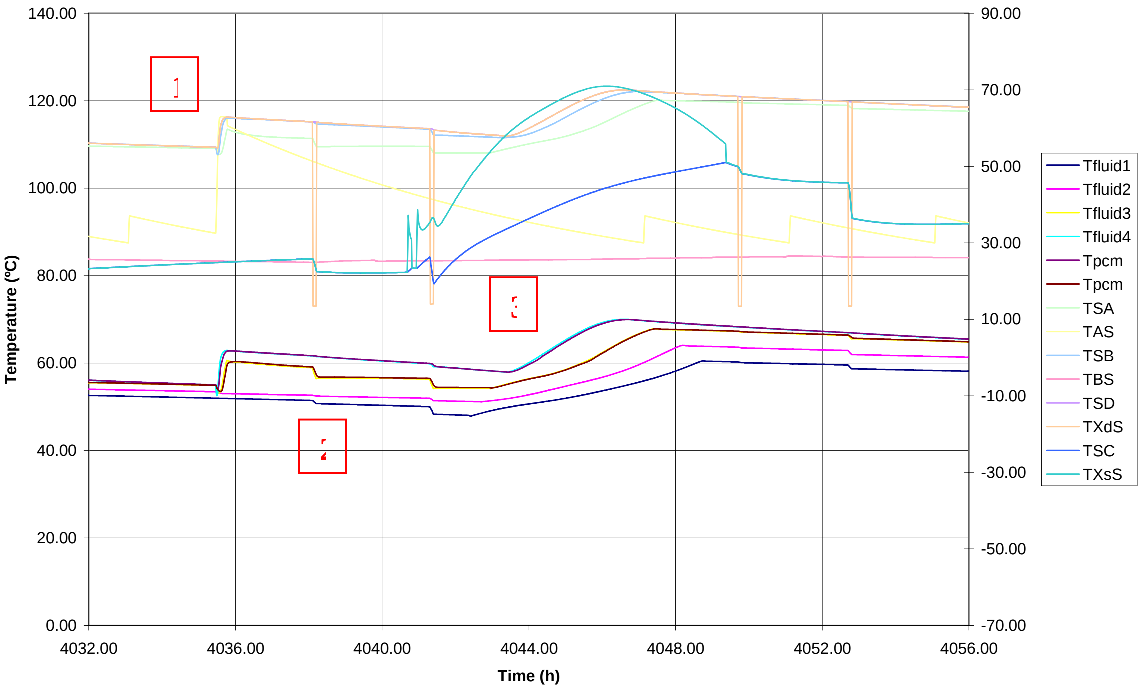


Fig. 21. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of June

[1] The auxiliary system switches on automatically again when the first auxiliary sensor reaches 55ºC due to the decreasing of the temperature because of the thermal loses. Up to now the solar collectors where not enough to compensate completely these loses through the tank. However, the data from June shows that this effect hardly takes place now because the solar provides more energy now than before due to the higher temperature provided by the solar collectors.

[2] The phase change of the PCM is clearly seen in these figures.

[3] As mentioned before, now the solar collectors provided the fluid at a higher temperature which is able to compensate the thermal loses, and therefore, the auxiliary scarcely will switch on.

2.2.7 July results and analysis

Fig. 22 and Fig. 23 show the values of the parameters monitored (Table 1) for Thursday of the third week in July. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

[1] The storage tank is always hot. The upper half part of the tank is nearly always around 70ºC. The energy demand as very low and there is very few interaction with the storage tank and as a consequence, the store hardly cools down.

[2] The energy supply from the solar collectors is high enough to keep constant the temperature of the store (as seen in [1]).

This effect brings to think that the collector area is too high now since the PCM does not work and the storage is getting hotter and hotter because there is not enough heat demand to change the temperatures significantly.

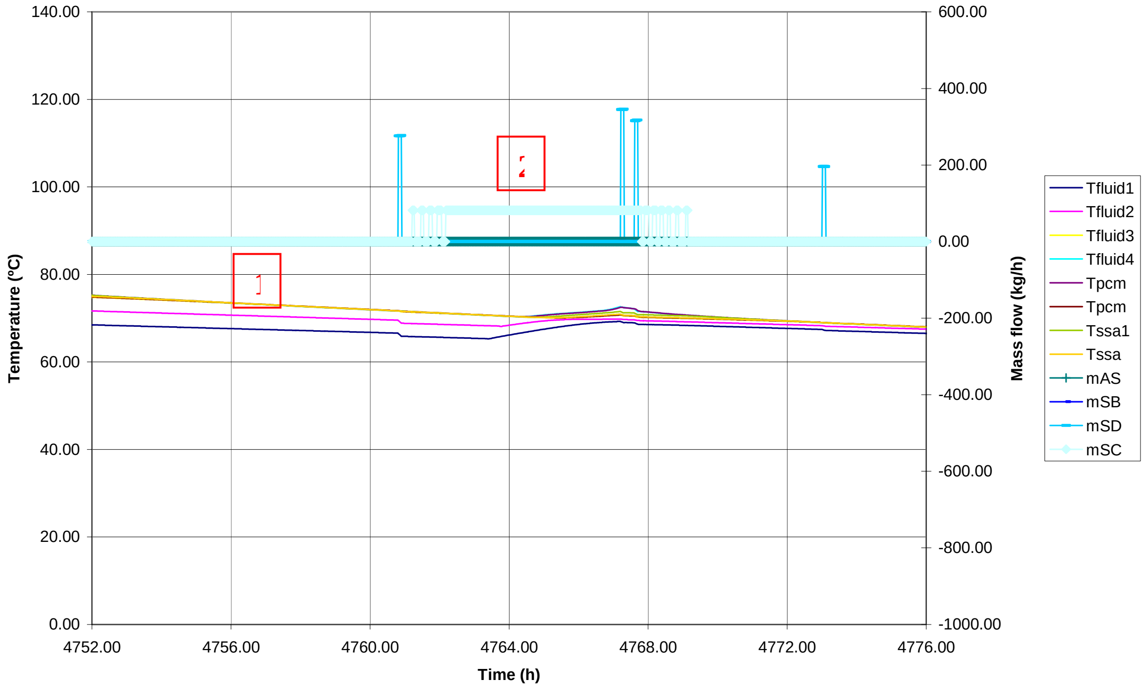


Fig. 22. Fluid and PCM temperatures and mass flow rates for the third Thursday of July

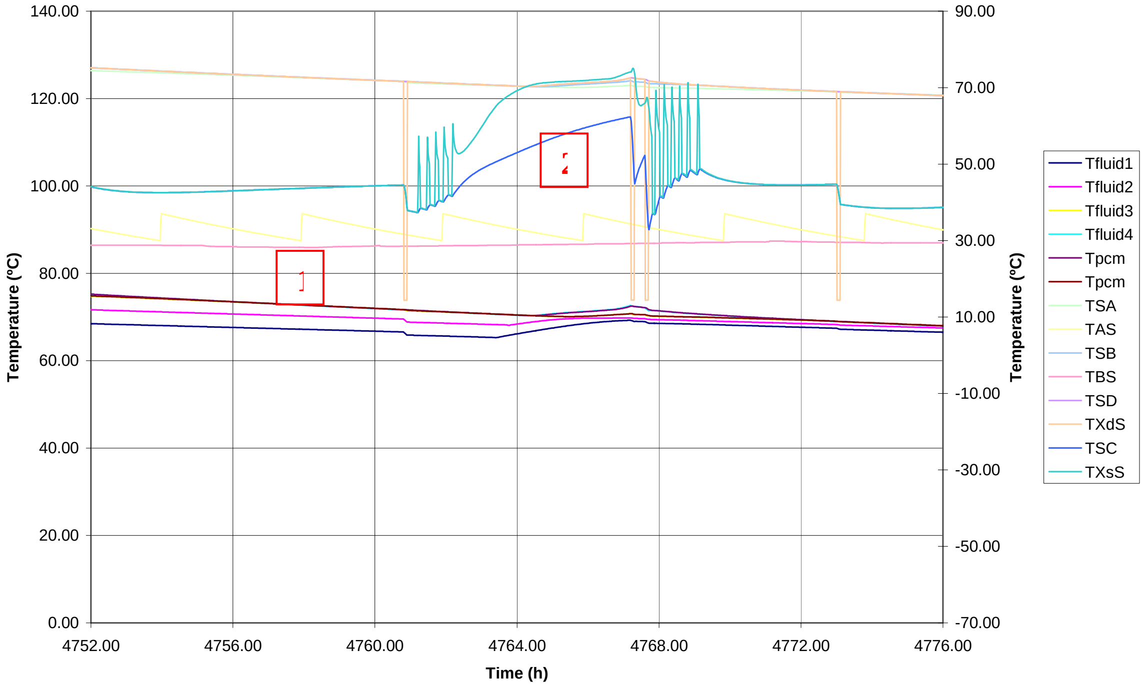


Fig. 23. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of July

2.2.8 August results and analysis

Fig. 24 and Fig. 25 show the values of the parameters monitored (Table 1) for Thursday of the third week in August. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

[1] The storage tank is always hot since the energy demand (just DHW) is very low. The upper half part of the tank is nearly always around 70ºC.

[2] The solar operation provides fluid at nearly 90ºC to the upper part of the tank.

This observation confirms the idea pointed out before that the collector area is too high for this part of the year.

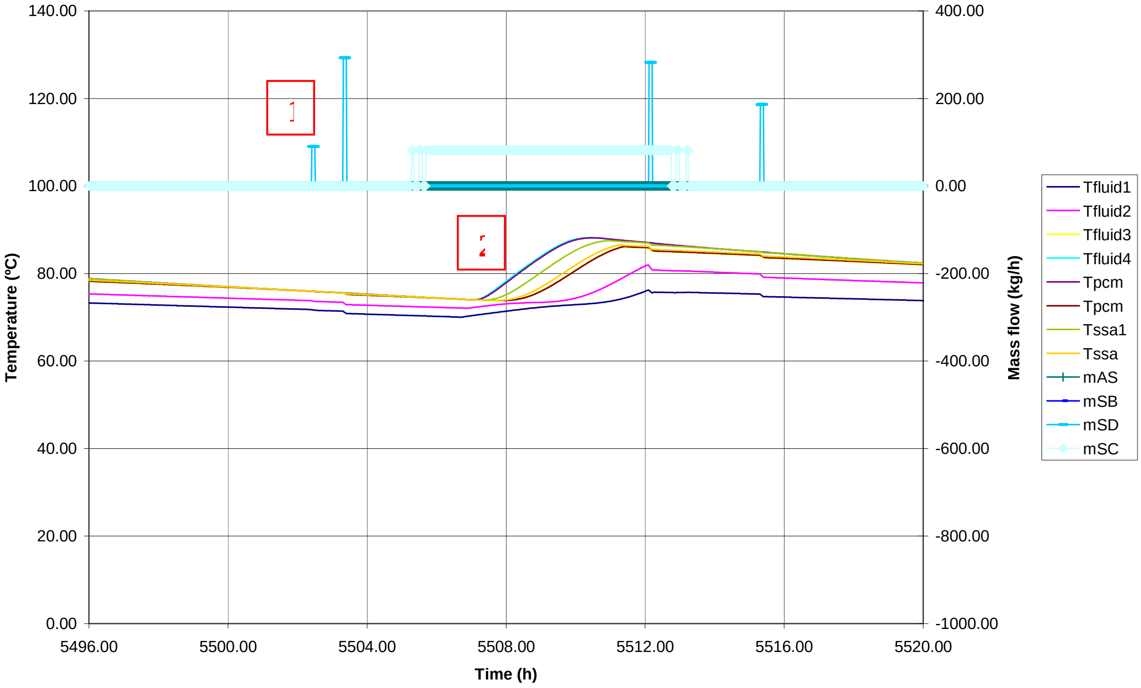


Fig. 24. Fluid and PCM temperatures and mass flow rates for the third Thursday of August

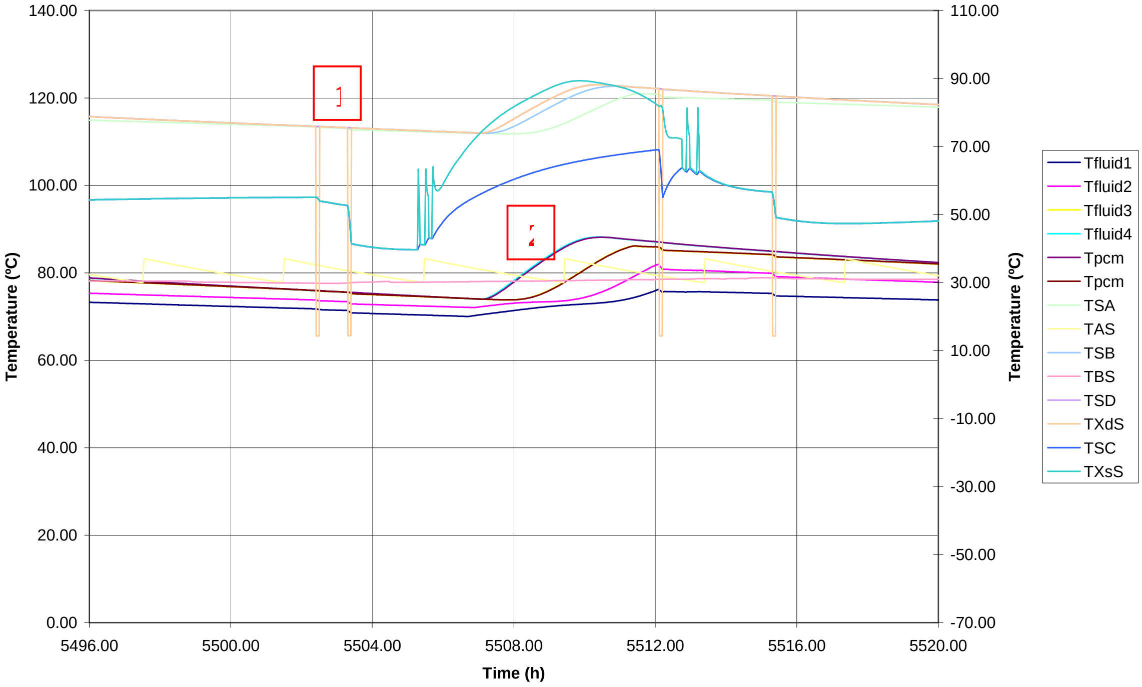


Fig. 25. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of August

2.2.9 September results and analysis

Fig. 26 and Fig. 27 show the values of the parameters monitored (Table 1) for Thursday of the third week in September. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

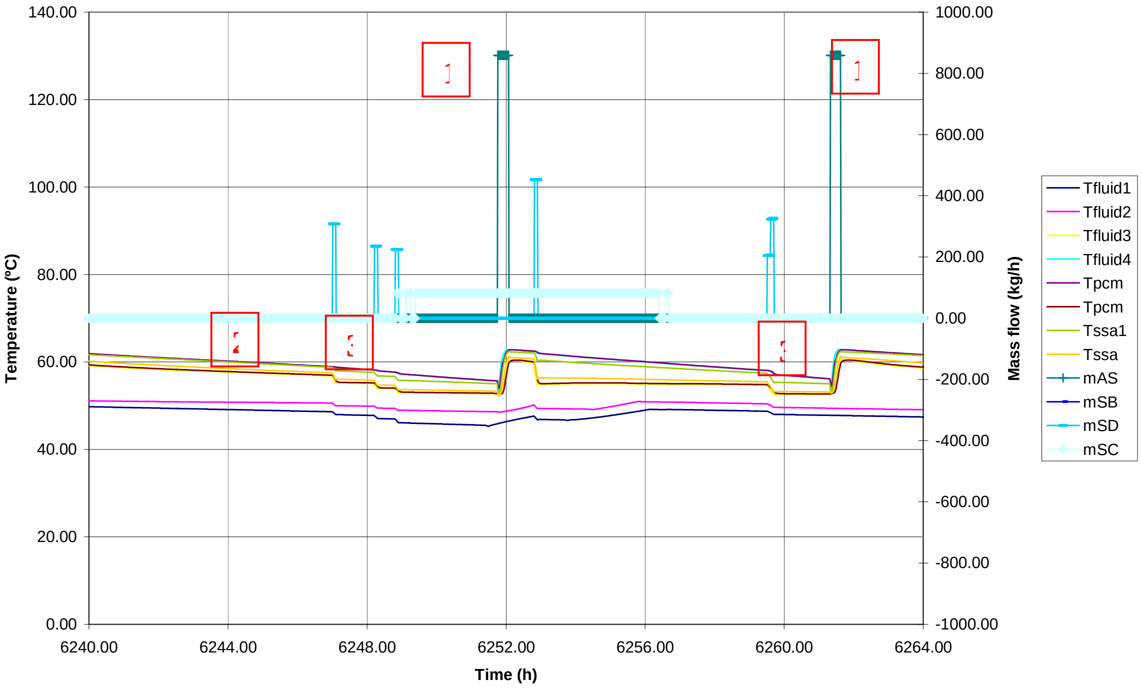


Fig. 26. Fluid and PCM temperatures and mass flow rates for the third Thursday of September

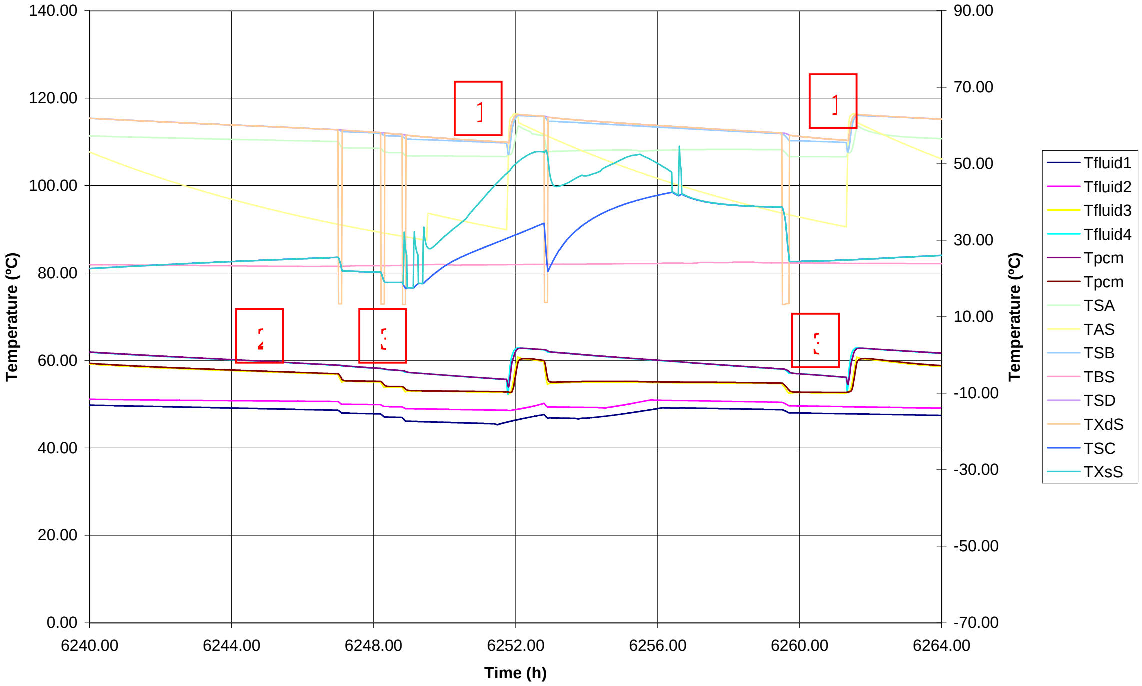


Fig. 27. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of September

[1] The auxiliary system switches on automatically because the first auxiliary sensor (Tssa1) reaches 55ºC because the solar operation is cooling down the upper part of the store due to mixing effects when the water enters into the tank. The second operation of the auxiliary is due to the thermal loses. Because of the DHW demand the upper part of the storage tank stores less energy which is not enough to compensate the thermal loses.

[2] The DHW demand is completely supplied with the energy stored in the water and the PCM. But because of this demand and the thermal loses the auxiliary can be needed (as happen in the second [1]). It is also observed that now the tank temperatures are lower than the previous months.

[3] The phase change of the PCM is clearly seen in these figures.

2.2.10 October results and analysis

Fig. 28 and Fig. 29 show the values of the parameters monitored (Table 1) for Thursday of the third week in October. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

[1] The DHW demand is supplied with the energy stored in the water and the PCM.

[2] The auxiliary system switches on automatically because the first auxiliary sensor (Tssa1) reaches 55ºC because the temperature of the fluid coming from the solar collectors is entering at 50ºC approximately and it is not compensating the thermal loses in that part of the store.

[3] A long phase change of the PCM is clearly seen in these figures, approximately 7 hours for the PCM placed in the half bottom part of the PCM module. The PCM is completely charged and it compensates the thermal loses of the storage tank. It is seen that the Tfluid 3 and Tfluid4 which corresponds approximately to the auxiliary volume and it has a volume of 200 L is always at a higher temperature than 50ºC.

Placing the Tssa1 sensor in an upper position where the PCM is also acting could help to avoid the operation of the boiler to heat up the store because of the thermal loses when the solar is under operation. A higher position for the Tssa1 sensor could avoid this operation since before reaching this 55ºC the PCM should start to release its energy, keeping the temperature at that layer nearly constant. The current position of Tssa1 is also influenced by the PCM but its effect is lower because the PCM is also quite stratified as it is the water in that area. Therefore, an upper position could really help.

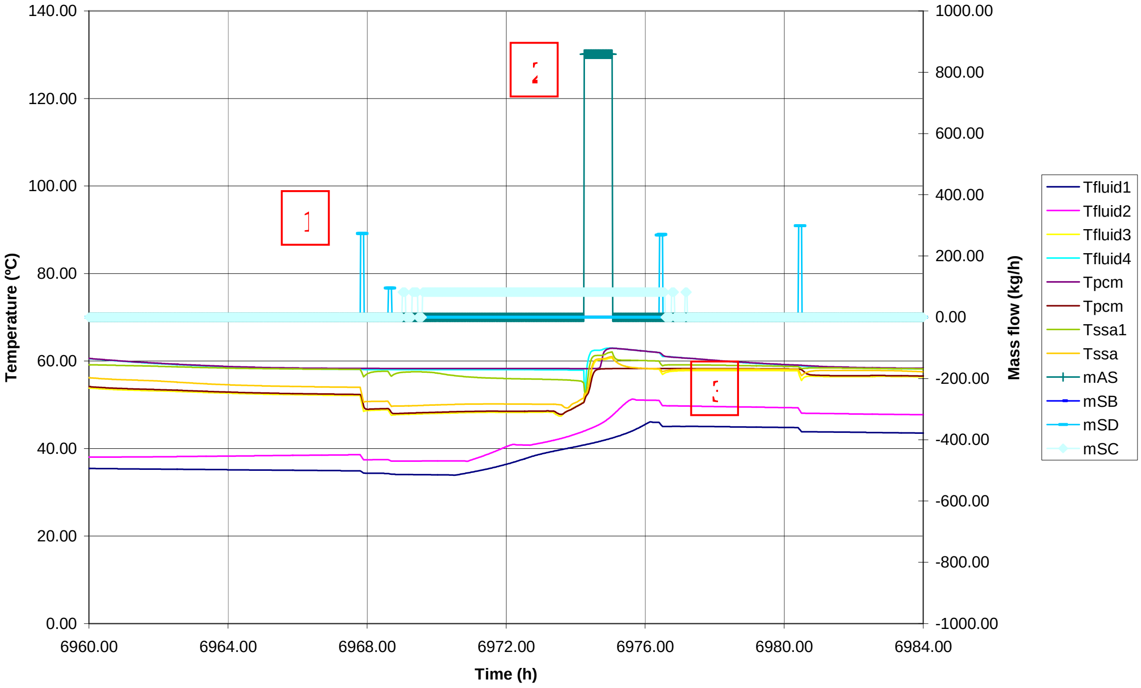


Fig. 28. Fluid and PCM temperatures and mass flow rates for the third Thursday of October

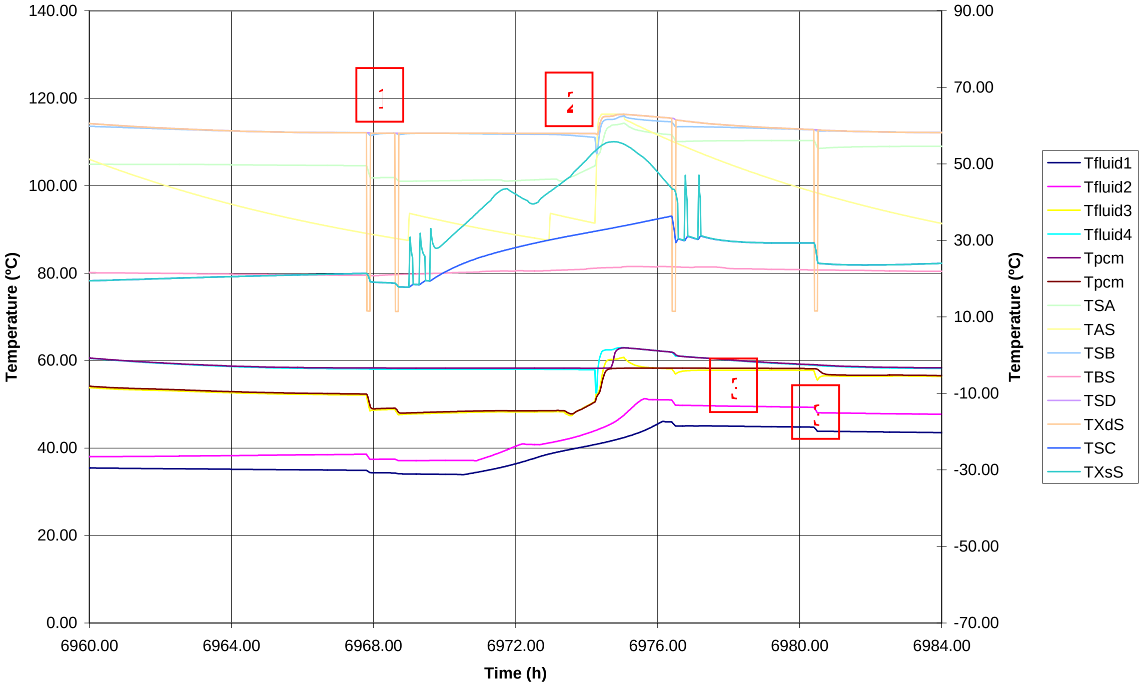


Fig. 29. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of October

2.2.11 November results and analysis

Fig. 30 and Fig. 31 show the values of the parameters monitored (Table 1) for Thursday of the third week in November. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

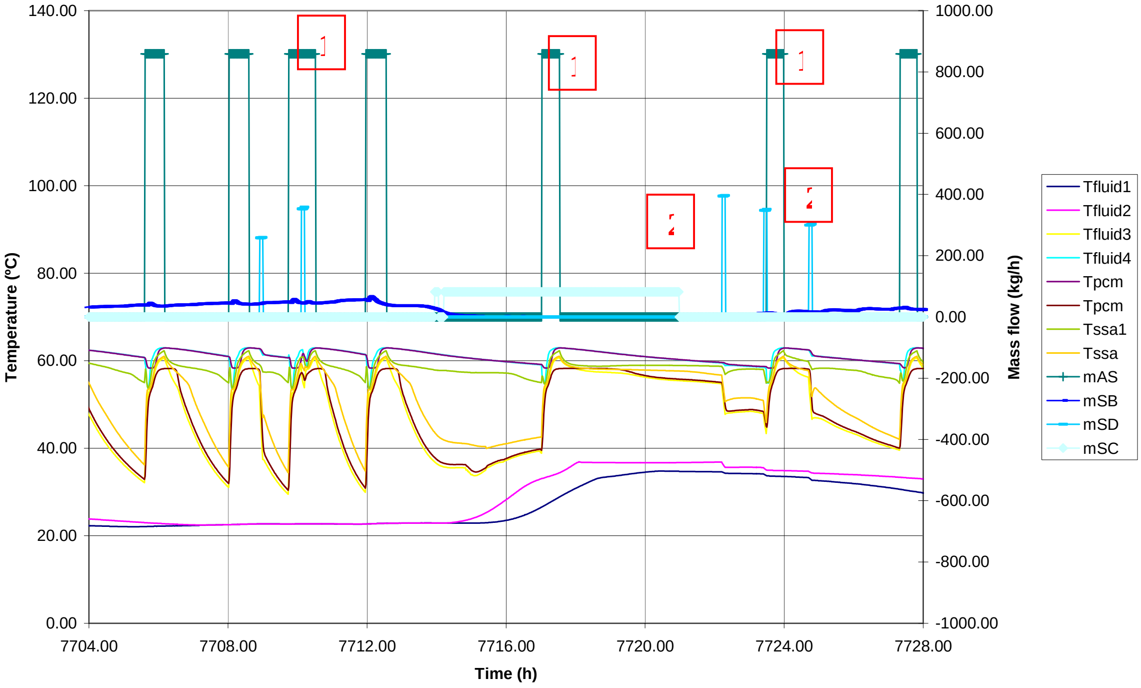


Fig. 30. Fluid and PCM temperatures and mass flow rates for the third Thursday of November

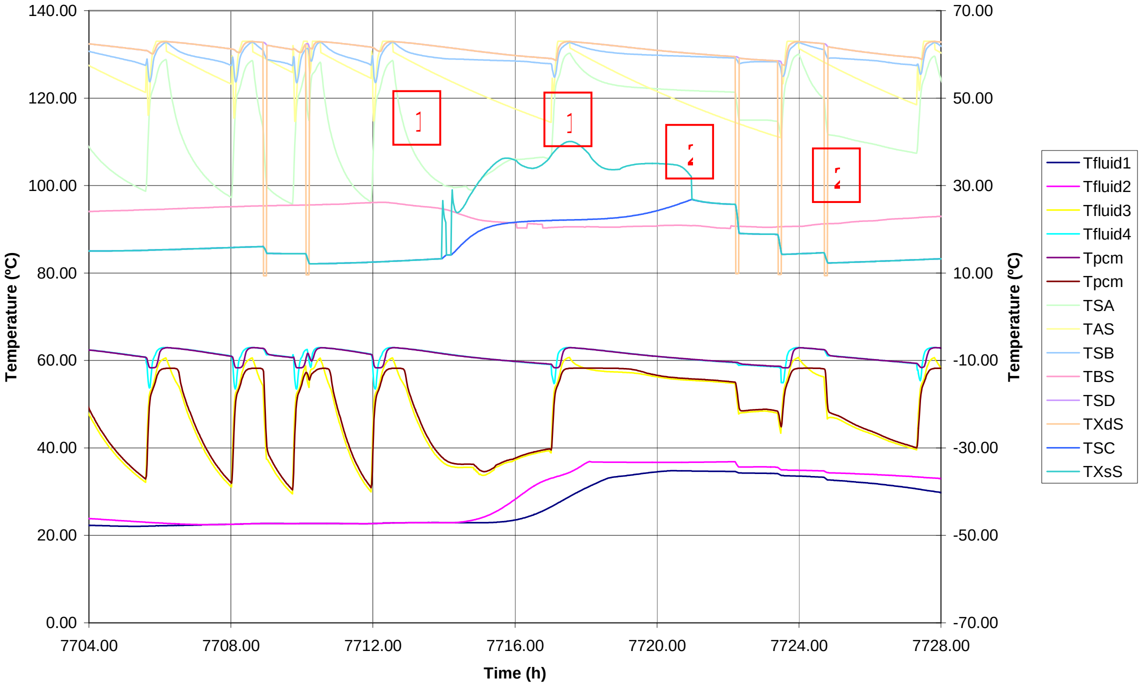


Fig. 31. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of November

[1] It is observed that the auxiliary system switches on because the first auxiliary sensor (Tssa1) reaches the corresponding temperature for the boiler operation. The temperature to operate the boiler is fixed to 55ºC. This is due to the heating demand which is cooling down the water temperature because the output of the store to the space heating is placed in a high position (0.9125 m) and is directly affecting the temperature measured by the Tssa1 sensor placed at (0.875 m). Therefore, when the heating system is working, the upper part of the tank is cooling down because the hot water is going to the space heating circuit.

[2] As mentioned before in other figures, it can be observed that when the store is hot enough, the DHW demand does not involve that the auxiliary has to switch on.

A solution to avoid the operation of the auxiliary because of the heating demand could be lowering the outlet of the heating loop and placing it out of the auxiliary volume, which is considered to be used for the DHW demand and not for the heating demand.

2.2.12 December results and analysis

Fig. 32 and Fig. 33 show the values of the parameters monitored (Table 1) for Thursday of the third week in December. Water temperature into the tank and PCM temperature are referred in the left axis meanwhile mass flow rates and fluid temperatures coming in and out of the store are referred in the right axis.

[1] The auxiliary switches again because the first auxiliary sensor reaches 55ºC, which is the set temperature for the boiler operation. Due to the heat demand and its very high position, the temperature of the upper part of the tank is getting cooled down progressively, until the auxiliary is switched on.

[2] Here, the operation of the boiler is due to the solar loop temperature that enters into the tank. The temperature of the collector loop is not high enough, around 30ºC, and due to mixing and convection effects, it also cools down the upper part of the tank.

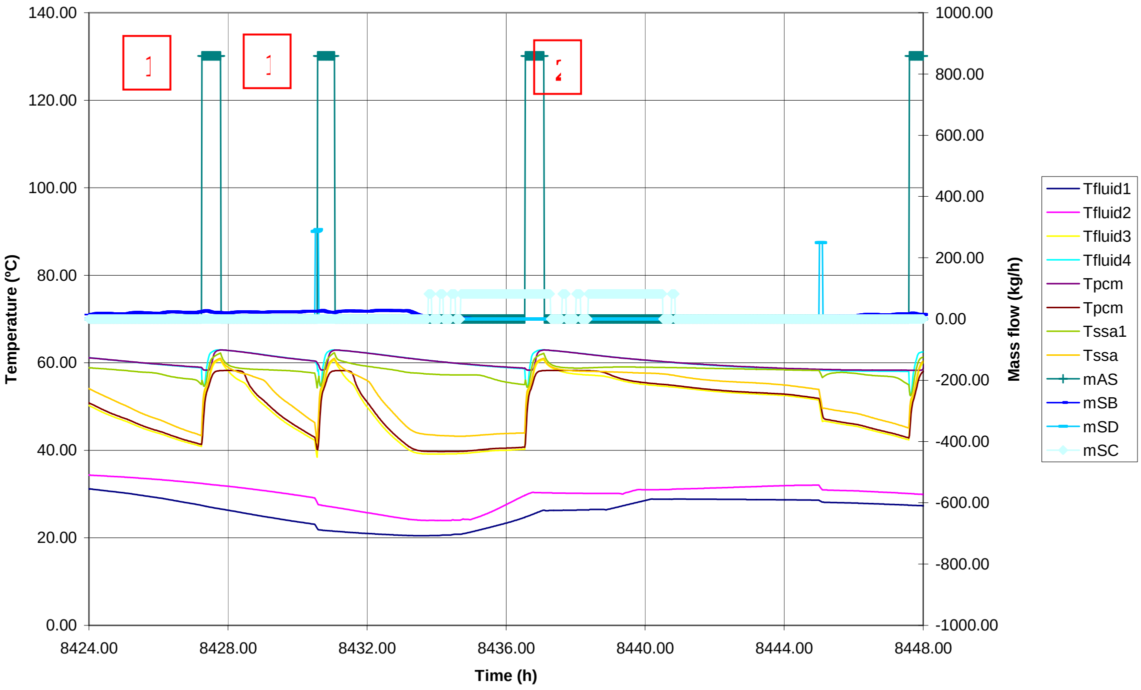


Fig. 32. Fluid and PCM temperatures and mass flow rates for the third Thursday of December

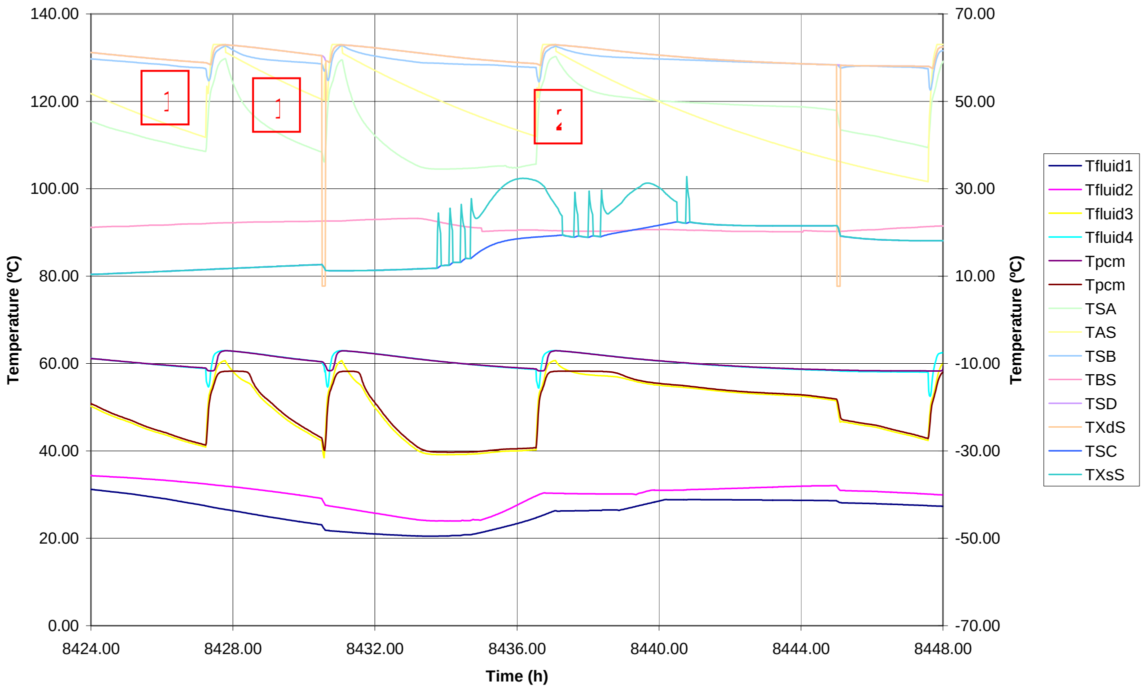


Fig. 33. PCM and water temperatures into the tank and coming in and out of the store for the third Thursday of December

3 Conclusions

From the deep analysis done before, some conclusions can be extracted:

- ✓ First of all, the election of the time step is a crucial point for the final performance of the PCM application. The shortest the time step, the major the influence of the PCM.

- ✓ The outlet of the space heating demand (TSB) should be placed in a lower position, out of the auxiliary volume used for the DHW supply. When the space heating is under operation, its current relative position (0.9125 m) affects directly the operation of the boiler since the drawn-off of hot water for the space heating demand cools down the upper part of the tank, affecting directly the first auxiliary sensor (Tssa1) for the boiler operation.

- ✓ The position of the first auxiliary sensor (Tssa1) should be changed to an upper position where the PCM would have more influence. In a higher position, would be more difficult to reach the set temperature for the boiler operation (set to 55ºC by the user in this simulation) since the PCM would release its energy stored. Currently the Tssa1 sensor is placed in an area where the PCM has also influence but it corresponds to the medium part of the PCM module. It has been observed that the PCM temperature curve follows the same shape as the water temperature. Therefore, whether the water is stratified, the PCM is also stratified. It has been observed some operation of the auxiliary in June and September that could be avoided with this change since these operations were caused by the cooled down of the tank by thermal losses, and as a consequence, the Tssa1 sensor reached the set temperature (55ºC) for the boiler operation. Placing it at a higher position, the PCM would be responsible of keeping the temperature in the area where Tssa1 was placed at a nearly constant temperature and it could compensate the thermal loses of the tank.

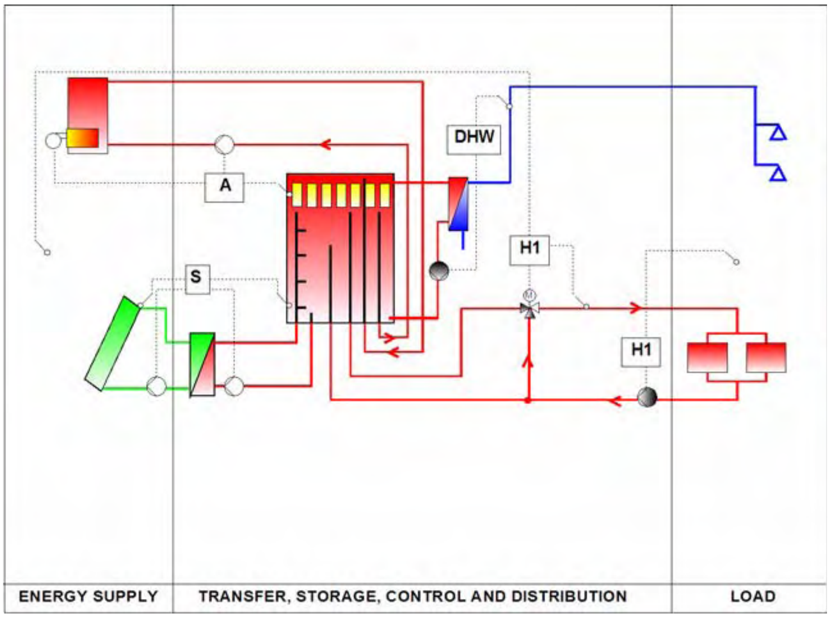
- ✓ The inlet and outlet of the auxiliary system into the tank are placed at very high positions, 0.9625 m for the inlet of the auxiliary into the store, and 0.75 m for the outlet from the store to the auxiliary. When the auxiliary is switched on, water at a relative position of 0.75 m is taken out to the auxiliary. This water could be still hot enough to supply energy to the space heating demand. However, this conclusion is difficult to confirm since this part of the tank is highly affected by the operation of the heating system. But it seems reasonable to decrease slightly the inlet and outlet of the auxiliary into the tank. Besides, in Fig. 10 and Fig. 11 it was shown that the DHW demand influenced on the temperature of the water that was going to and coming from the auxiliary system. This confirms the suitability of decreasing the position of the inlet and outlet of the auxiliary.

- ✓ It is seen that in the hotter seasons, the collector area is too big and the temperature reached into the tank is too high (even 90ºC in August, Fig. 24 and Fig. 25). It is also observed that since March and April, the half part of the tank is usually at 60ºC making difficult to take any advantage from the PCM. So as a consequence, in hotter seasons (June-August), the temperature is even higher and the PCM does not work any more since cooler seasons. It should be remembered that the simulation was done for Madrid. And here, it takes a lot of sense the new Spanish law that forces the use of dissipating systems or the use of less solar collectors to avoid overheating of the systems.

4 General description of a PCM-water storage tank in a combisystem

Main features

The system is designed for a single family house to provide energy for the space heating (SH) and domestic hot water (DHW) demand. Certain amount of phase change material (PCM) is contained in the upper part of the tank in cylindrical modules to support the DHW demand but not the SH demand. The amount of PCM introduced into the tank is defined by the filling ratio P_{area} that is the cross-sectional area of all modules divided by the cross-sectional area of the storage tank.



Heat management philosophy

Solar loop:

If the temperature at the collector outlet is higher than the one at the bottom of the tank, then the pump of the collector loop is switched on. The secondary circuit pump starts only when the temperature at the heat exchanger inlet, at the collector loop side, is higher than the one at the bottom of the tank. The fluid enters into the storage tank through a stratified pipe. The solar loop is switched off when the temperature at the top of the tank reaches 90ºC and is switched on again when the temperature decreases 5ºC.

Auxiliary boiler:

If the temperature into the store does not reach the set temperature either for the DHW or the SH, then the gas boiler switches on to avoid penalties because of not meeting the requirements specified. The auxiliary heats the water up until the temperature of the first auxiliary sensor is approximately 60ºC.

Space heating:

The space heating loop is provides energy to the building with a radiator system with a PID controller. The water flows through the radiator system and new hot water coming from the store enters to the loop when the temperature does not meet the requirements for the temperature.

Preparation of DHW:

DHW service is always available in the storage tank as there is always hot water at the top of the tank at approximately 60ºC. If not enough energy is stored in the water and the PCM to supply at the set temperature, then the burner is switched on.

Influence of auxiliary energy source on system design and dimensioning

Gas is used as the energy source for the auxiliary system.

Cost (range)

This system is not commercialised so it is difficult to give an approximate cost.

Market distribution

This system is not commercialised.

5 Modelling of the system

5.1 TRNSYS model

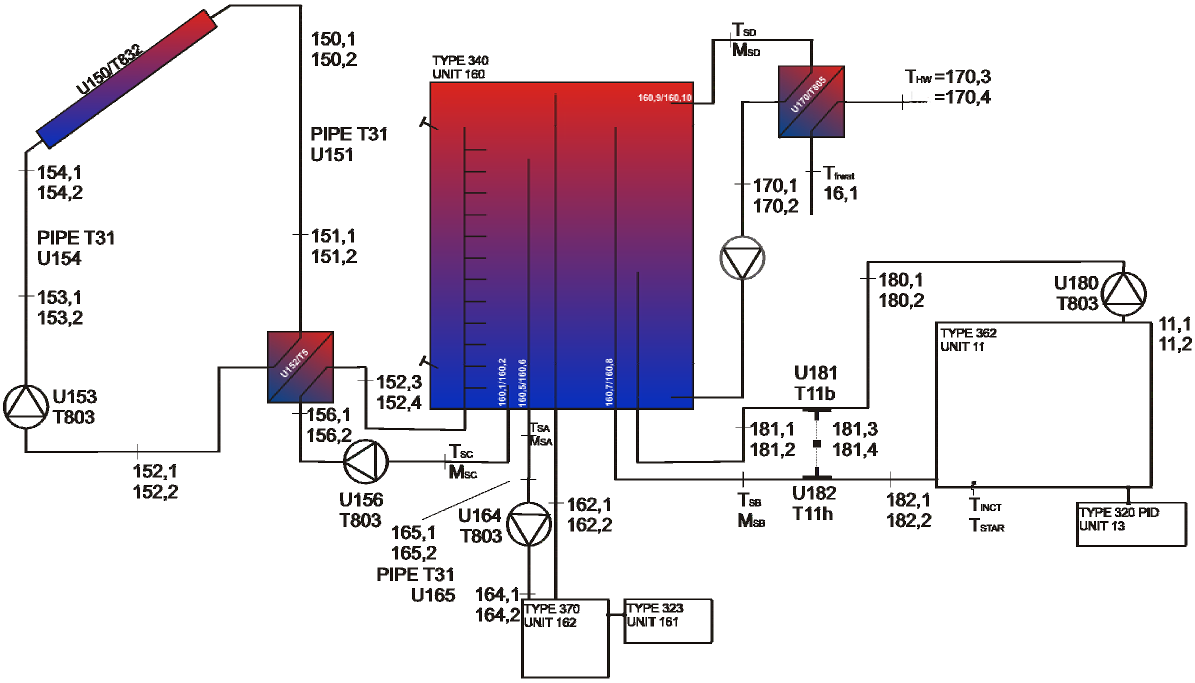


Fig. 34. Modelling of the System in TRNSYS (additionally PCm were placed in the top of the tank)

5.2 Definition of the components included in the system and standard inputs data

5.2.1 General Setting in the TRNEDIT template

General Settings (to be chosen by TRNEDIT):

Main	
simulation timestep	1/60 h
tolerance integration / convergance	0.003 / 0.003
length of simulation	12 months
climate	Madrid
building	SFH60
Auxiliary	
Nominal Power of Auxiliary	36000 kJ/h
Set temperature Auxiliary into store	63 °C
Auxiliary temperature rise	10 K
Collector	
type	flat plate non-selective (ref)
aperture area	6 m^2
tilt angle	45°
azimuth (0° = south, 90° = west, 270° east)	0°

primary loop specific mass flow rate	15 kg/hm^2
upper / lower dead band (switch on / off)	7 K / 4 K
relative height of low temperature sensor in store	0.1
cut-off temperature of collector	90 °C
boiling temperature of collector fluid	110 °C
Store	
storage volume	0.80 m^3
insulation thickness (λ=0.042 W/mK)	0.15 m
correction factor for heat loss	1.4

5.2.2 Collector

Type: 832 Version Number: 2.06

Collector	η_0	0.75 -
	a_1	5.46 W/m^2-K
	a_2	0.021 W/m^2-K^2
	inc. angle modifier (50°)	0.88 -
	Area	6 m^2
	Specific mass flow	15 L/m^2h

5.2.3 Heat exchanger of collector loop

Overall heat transfer coefficient of the heat exchanger	3094.4 kJ/h·K
Specific mass flow secondary side	13.68 L/m^2h

5.2.4 Pipes between Collector and Storage:

Model: One Type 31 for hot side and one Type 31 for cold side
Pipes: Inner diameter: 0.00758 m Total Length: 15.0 m

Insulation:

Thickness 10 mm (6.07 W/m^2-K)
Thermal Conductivity: 0.042 W/m-K

5.2.5 Control of the collector loop

Type 2

Reason	***Sensor***	***Off-Criteria***	***Hyst.***
Upper dead band (Udb)	Collector temperature (T-coll) and storage collector control (St-coll)	On: T-coll>st-coll + Udb	
Lower dead band (Ldb)	Collector temperature (T-coll) and storage collector control (St-coll)	Off: T-coll>st-coll + Ldb	
Collector stagnation	Collector Temperature	Boiling Temp. of fluid as defined by user (TRNEDIT)	15 K
Storage tank protection	Temperature in the uppermost Node of the store	Cut-off Temperature T_in as defined by user (TRNEDIT)	5 K

5.2.6 Storage:

Type: 840	Version Number: 1.11	
Storage tank	Total volume	0.8 m^3
	Height	1.906 m
	Store volume for auxiliary	0.20 m^3
	Number of nodes	40
	Media:	Water
	Insulation thickness, thermal conductivity	15 cm, 0.042 W/m-K
	Start $\Delta\vartheta$, hysteresis, Collector loop	10 K, 8 K

Heat Exchanger N°1: Media: Glycol (40%) / Water
Type of heat exchanger: external plate heat exchanger
Heat Transfer Coefficient: 3094.40 kJ/h·K = 859.55 W/K

Heat Exchanger N°2: Media: Water / Water
Type of heat exchanger: external plate heat exchanger
Heat Transfer Coefficient: 19200 kJ/h·K = 5333.3 W/K

Relative heights of store doubleports and temperature sensors

Doubleport description	***relative height***	***Dp Nr.***
inlet of collector loop (stratified)	$=1-\frac{1.5}{N_{\max}}$	1
outlet of collector loop	0.05	1
inlet of auxiliary heating	$=1-\frac{1.5}{N_{\max}}$	3
outlet of auxiliary heating	$=1-\frac{V_{aux}}{V_S}$	3
inlet of DHW loop	$=\frac{0.5}{N_{\max}}$	5
outlet of DHW loop	$=1-\frac{0.5}{N_{\max}}$	5
inlet of space heating loop	0.15	4
outlet of space heating loop	$=1-0.5\cdot\frac{V_{aux}}{V_S}+\frac{1.5}{N_{\max}}$	4

Sensor description	***relative height***
Collector control temperature	user defined (TRNEDIT)
Storage protection temperature	$=1-\frac{0.5}{N_{\max}}$
First auxiliary On/Off temperature	$=1-0.5\cdot\frac{V_{aux}}{V_S}$
Second auxiliary On/Off temperature	$=1-\frac{V_{aux}}{V_S}+\frac{1.5}{N_{\max}}$

5.2.7 Auxiliary boiler:

Type 370 – Specific Type, data defined by Heimrath, Haller 2007

Nr.	***Description***	***Value(s)***
1	temperature setpoint for auxiliary DHW to store	63 [ºC] $T_{aux,set}$ [°C] set by the user (TRNEDIT)
2	Fueltype	2 (natural gas high)
3	ambient temperature at location of boiler	15 [°C]
4	standby temperature	35 [°C]
5	hysteresis for standby temperature	5 [K]
6	maximum water temperature	90 [°C]
7	nominal power	10 kW set by the user (TRNEDIT)
8	air surplus (lambda) value	1.2
9	lowest modulation factor	0.25
10	mass of the boiler water	17.5 [kg]
11	temperature difference between flue gas and return temperature of water	10 [K]
12	radiation losses	3.5 [%]
13	standby losses as percent of nominal power	1.5 [%]
14	simulation mode	0 (original)
15	number of nodes in heat exchanger	10
16	exhaust gas temperature at entrance of heat exchanger	1000
17	minimum flow on water side	859.18 [kg·h] $=P_{aux}/(dT_{aux}*Cp_{Wat})$ [kg/hr]

Type 323 is used as auxiliary controller.

Nr.	***Description***	***Value(s)***
3	ambient design temperature	-7 [ºC] (Madrid) taken from dataset for location chosen by the user
4	room set temperature	20 [°C]
6	set temperature for auxiliary heat supplied to store for DHW preparation	63 [ºC] $T_{aux,set}$ [°C] set by the user (TRNEDIT)
7	nominal mass flow rate for DHW preparation	859.18 [kg·h] $=P_{aux}/(dT_{aux}*Cp_{Wat})$ [kg/hr]
9	radiator exponent n	0.2
10	radiator exponent m	0.3
12,13	minimum time off, minimum time on	1 [min] MAX(dtSim*60;1) [min]

5.2.8 Building

Type56 – One Zone Model, (Geometric Data defined in defined by Heimrath, Haller 2007)

5.2.9 Heat distribution

Radiators Type 362

Nr.	***Description***	***Value(s)***
1-5	length of supply pipe and exhaust pipe respectively	not used
6	specific heat of fluid	Cp_{Wat} = 4.18 J/kg·K
7	max. flow rate of fluid	$\dot{m}_{B,\max}$ = 712.18 [kg/h]
8	radiative fraction of total emitted power	0.35
9	nominal power of radiator	$Q_{Rd,n}$ = 74032.4 [kJ/h]
10	radiator exponent	n_{Rd} = 1.3
11	thermal capacitance of radiator	1150 [kJ/K]
12	initial temperature	55 [°C]

(Data defined in defined by Heimrath, Haller 2007)

The mass flow in the radiators is determined by simulation of a thermostatic valve with the PID controller Type 320.

Nr.	***Description***	***Value(s)***
1	temperature width of PID band	3 [K]
2	proportional gain PID band	0.8 [1/K]
3	integral gain PID band	0.05 [1/Kh]
4	differential gain PID band	0 [h/K]
5	proportional gain P band	0.5 [1/K]
6,7	not used	0, 0

1	set temperature	room temperature setpoint
2	feedback temperature	room temperature of last timestep
3	control inversion option (direction of action)	2 (decreasing action)

5.2.10 Draw-Off loop

Type 805. The overall heat transfer coefficient of the heat exchanger has been set to a value which results in a return temperature of 15 °C to the store in the case of 10 °C cold water temperature, 60 °C temperature from store and a secondary mass flow rate (DHW) of 1200 kg/h.

Nr.	***Description***	***Value(s)***
1,2	specific heat capacity of primary and secondary side fluid respectively	Cp_{Wat} = 4.18 J/kg·K
3	maximum allowed flow rate on primary (hot) side	1400 [kg/h]
4	temperature setpoint for secondary side outlet	45 [°C]
5	overall heat transfer coefficient UA of heat exchanger	19200 [kJ/hK]

5.3 <u>Validation of the system model</u>

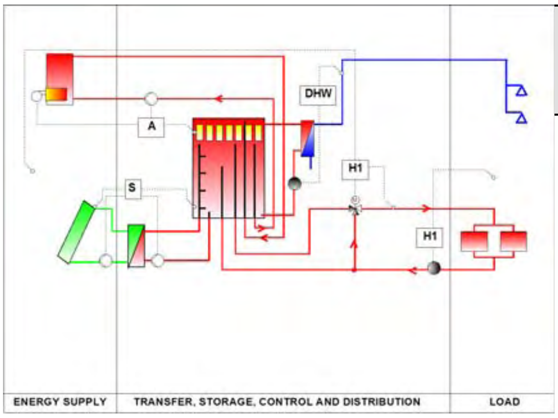
No validation has been carried out with a real system.

6 Simulations for testing the library and the accuracy

The used simulation time step is 1/60 h and the tolerances for convergence and integration are 0.003.

7 Sensitivity Analysis and Optimization

7.1 Presentation of results



PCM-water storage tank, Centralised Heat Production, Distributed Heat Load, Stratified Storage (Spain)

Main parameters (optimised Base Case (BC)):			
Building:	*SFH 60*	Storage medium	*water*
Climate:	*Madrid*	Storage Volume:	*0.8 m³*
Collectors area:	*6 m²*	Auxiliary volume	*0.2 m³*
Collector type:	*Flat Plate Non-selective*	Storage height	*1.906 m*
Specific flow rate (Collector)	*15 kg/m²-h*	Thermal insulation	*15 cm*
Collector azimuth/tilt angle	*0 / 45°*	Nominal auxiliary heating rate	*10 kW*
Collector upper/lower dead band	*7 / 4 K*	Rel. position of top/bottom PCM modules	*0.95/ 0.775*
Simulation parameter:		Storage nodes	*20 l/Node* *40 nodes*
Time step	*1/60 h*	Tolerances Integration Convergence	*0.003 / 0.003*

Summary of Sensitivity Parameters			
Parameter	Variation	[1]Variation in $f_{sav,ext}$	
Base Case (BC)	-	35.0%	
[2]Outlet to Space Heating Rel. Height [-]	0.9125 – 0.7 and Water / P_{area} = 0.25 / P_{area} = 0.5	52.4 - 54.7%	Fig. 35
[2]First auxiliary on/off sensor [-]	0.875 – 0.95 and Water / P_{area} = 0.25 / P_{area} = 0.5	52.4 - 54.7%	Fig. 35
[2]Boiler Inlet Rel. Height [-]	0.875 – 0.95	52.4 - 54.7%	Fig. 35

[1] The variation if fractional savings indicated in the table does not represent the values for the extremes of the range, rather the minimum and maximum values for the range indicated.

[2] The thermostat settings for store charging and electrical heater were NOT changed for these variations. Adjusting the setting to just meet the demand of the period with the highest load would probably lead to different results.

Sensitivity parameter:	Rel. Height of Outlet to Space Heating Boiler Inlet into Store First auxiliary on/off sensor (fixed store size 0.8 m^3)	0.9125 – 0.7 0.9625 – 0.85 0.875 – 0.95

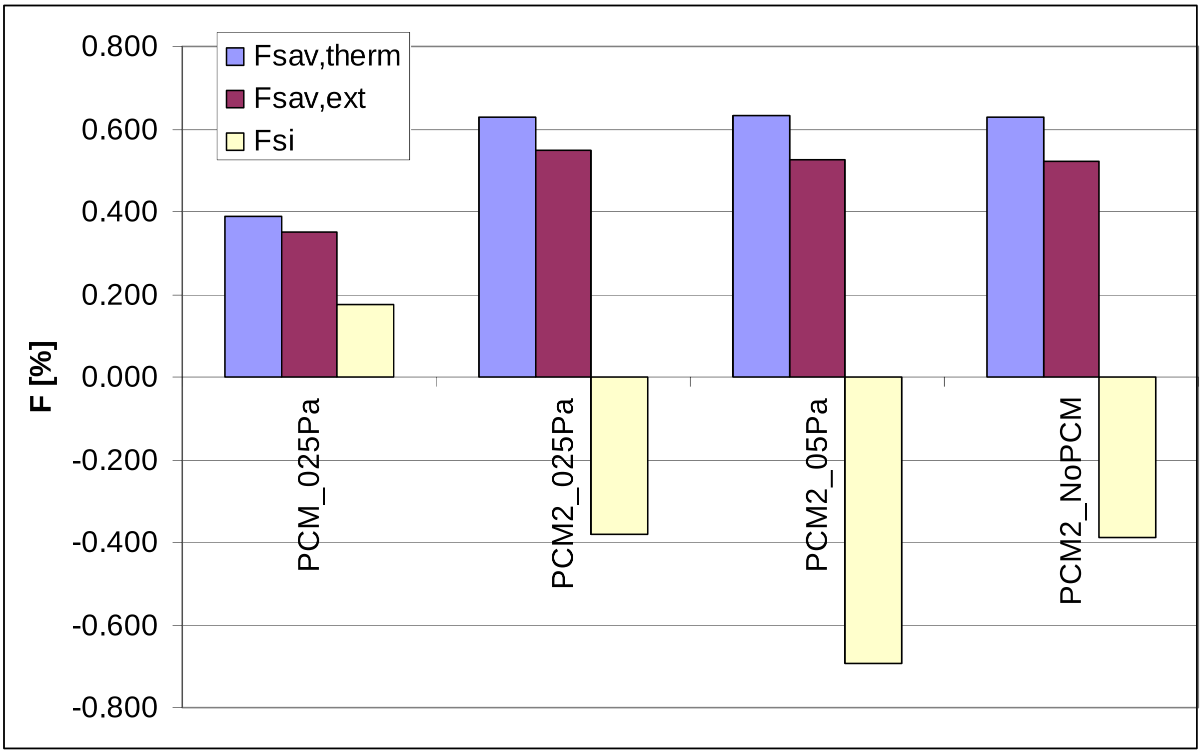


Fig. 35. Variation of fractional energy savings with P_{area} and the position of the Outlet to Space Heating, Boiler Inlet Rel. Height and First auxiliary on/off sensor.

Differences from Base Case (BC)

Different values of the P_{area} ratio are tested which ranges from no PCM to 0.5 P_{area}. The relative position of the outlet to space heating, the inlet of the boiler into the store and the position of the first on/off auxiliary sensor are also different from the base case.

Description of Results

It is shown in Fig. 35 that the performance of the system is highly influence by the position of the relative height of the outlet to space heating, the inlet of the boiler into the store and the position of the first on/off auxiliary sensor.

Comments

None

8 Analysis using FSC

The solar heating system has not been analysed using the FSC-method.

9 Lessons learned

From the deep analysis done at the beginning, some conclusions can be extracted:

- ✓ First of all, the election of the time step is a crucial point for the final performance of the PCM application. The shortest the time step, the major the influence of the PCM. As it is shown in chapter 2.1, the time step is a parameter to be considered when a PCM simulation is done. A long time step could skip some PCM operation and skip its influence in the final results because the PCM could act few minutes, and unfortunately they could coincide with the minutes which are not simulated. However, a short time step will always detect the PCM operation. Besides, as it is shown in Fig. 6 to Fig. 8, the shape of the PCM curve can also be different because in a long timestep, it is possible to miss some PCM operation.

- ✓ The outlet of the space heating demand (TSB) should be placed out of the auxiliary volume used for the DHW supply because when the space heating is under operation, its current relative position could affect the operation of the boiler since the drawn-off of hot water for the space heating demand could cool down the upper part of the tank, affecting directly the first auxiliary sensor (Tssa1) for the boiler operation.

- ✓ The higher the position of the first auxiliary sensor (Tssa1), the more influence would have on the PCM module. The higher the position, the more difficult would be to reach the set temperature for the boiler operation (set by the user) since the PCM would release its energy stored.

- ✓ It has been observed that the PCM temperature curve follows the same shape as the water temperature. Therefore, whether the water is stratified, the PCM is also stratified. Placing the Tssa1 sensor at a higher position, the PCM would be responsible of keeping the temperature in the area where Tssa1 was placed at a nearly constant temperature and it could compensate the thermal loses of the tank.

- ✓ The position of the inlet and outlet of the auxiliary system into the tank should not be placed in the auxiliary volume because it was shown that the DHW demand influenced on the temperature of the water that was going to and coming from the auxiliary system.

- ✓ The collector area is too large for the hotter seasons and the temperature reached into the tank is too high. In warmer seasons, the half part of the tank is usually at 60ºC, making difficult to take any advantage from the PCM. Simulation was done for Madrid and the Spanish law forces the use of dissipating systems or the use of less solar collectors to avoid overheating of the systems.

10 References

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11 Appendix 1: Description of Components specific to this System

These are components that are

a) not part of the TRNSYS standard library AND
b) not part of the types used as "standard" by Task 32.

11.1 Type 840 : Multiport PCM store model

Version 1.1

Parameters: 101
Inputs: 12
Outputs: 63 + number of nodes + number of temperature sensor

Please refer to TRNSYS Description of Type 840 – Description of a Storage Model for Phase Change Materials by Peter Puschnig, IWT, Graz, Austria

Availibility : IWT, Graz