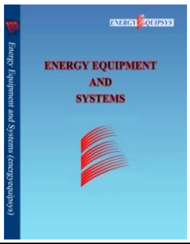
energyequipsys/ Vol 4/No2/Dec 2016/ 271-279

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
www.energyeuquipsys.com



Optimization of the PCM-integrated solar domestic hot water system under different thermal stratification conditions

Authors

Mehrdad Shirinbakhsh [a]
Nima Mirkhani [b]
Behrang Sajadi [b*]

[a] Mechanical Engineering Department, K.N. Toosi University of Technology Tehran, Tehran, Iran

[b] School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

Article history:

Received : 11 February 2016
Accepted : 18 April 2016

ABSTRACT

Many researchers have investigated how to increase the overall efficiency of solar-driven thermal systems. Several key parameters, such as collector efficiency and storage tank characteristics, may impose some constraints on the annual solar fraction (ASF) of such systems. In this paper, the behaviour of integrating the phase change material (PCM) in SDHW systems is modelled and optimized numerically. Coupled collector and partly stratified PCM-embedded storage tank governing equations are utilized to simulate the overall performance of the system. The developed code presents the monthly behaviour of the system including the solar fraction and the storage tank temperature profile. The results indicate that the stratification of the storage tank will increase the ASF up to about 4.6%. Additionally, it is found that the optimum amount for the PCM and its melting temperature is changed as the tank stratification goes from the fully mixed to the fully stratified state. Integrating the PCM in the storage tank leads to increases of 5.3% in the ASF for a single-node tank, while a rise of only 0.7% is seen for the stratified storage tank.

Keywords: Solar Domestic Hot Water System, Phase Change Material, Stratification, Annual Solar Fraction, Optimization.

1. Introduction

Continuous increases in the environmental problem of using fossil fuels including climate change, air pollution, oil spills, and acid rain have made alternative energy resources more popular. Renewable energy resources, such as solar energy, are free of charge and cause less environmental pollution. Solar energy development will increase energy security through reliance on an indigenous, inexhaustible, and mostly import-independent resource.

Solar-driven systems provide energy demand with respect to the available solar irradiation. The amount of solar energy that reaches the earth's surface annually is an order of magnitude that is greater than all estimated fossil fuels and nuclear resources [1]. Solar domestic hot water (SDHW) systems are one of the most prevalent uses of this clean source of energy. The first development of SDHW began in 1760 in Switzerland, and the primary commercial solar water heater called 'The Climax' was built in 1891 in America [2]. Solar water heating(SWH) system usage increased about 30% annually since 1980 [3], and its worldwide capacity enlarged to 185 GWh by the beginning of 2011 compared to

*Corresponding author: Behrang Sajadi
Address: School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran E-mail address: bsajadi@ut.ac.ir

160 GWh at the start of 2010 [4]. Therefore, predicting the behaviour of such systems plays an important role to develop their performance. Numerical simulation as a powerful tool is capable of analysing this behaviour under different design and meteorological conditions. Storage tank characteristics, such as specific heat of the medium, the density, the temperature change, and the amount of storage material, play an important role in the performance of SDHW systems and their effects on the overall efficiency of the system, which means that the ASF should be studied thoroughly [5]. In this matter, stratification and utilization of the PCM could have substantial effects on system operation. In other words, proper temperature distribution over the tank along with surplus energy storage yields better performance and a higher ASF.

Over the last decade, a large number of studies have been dedicated to model the SDHW system with and without the PCM in order to achieve a better understanding of its performance [6–13]. Haillot et al. [6, 11] proposed a validated numerical model for a mixed tank, with the PCM placed in the heat transfer fluid solar loop. They reported significant increases in system efficiency by employing the PCM. Padovan and Manzan [7] conducted an optimization and sensitivity analysis in order to find out the relation between the storage tank content, design parameters, and performance of the system. They found out that application of the PCM has not any tangible impact on the performance. Mather et al. [8] proposed a multi-tank system interconnected by two strings of immersed coil heat exchangers; they concluded that a multi-tank thermal storage system with immersed exchangers is capable of eliminating any need for a load-side heat exchanger in solar heating systems. Rhee et al. [9] proved that stratification is essential to minimize storage tank heat losses due to the mixing and hence affects the maximum energy gained from the collector. Andersen et al. [10] reported that the thermal performance of the system may be improved as the thermal stratification in the storage tank increases. Khalifa et al. [14] compared the operation of an SDHW system with the PCM and those of a conventional DHW system. In this study, the solar collector acts as the PCM thermal storage medium. Their results showed that the temperature difference in the storage collector is 66% higher than that in the conventional one. Nkwetta et al. [15] numerically studied the performance of a DHW tank integrated with different PCM types in various locations by using the TRNSYS simulation software. The stored energy increased with the increases in the PCM. Hence, the integration of the PCM in hot water tanks improves the storage capacity. Furthermore, it may provide energy, shift, and/or smooth peak power demand.

In the present work, a commercial SDHW system is modelled for Perpignan meteorological data by coupling the governing equations of the collector and the storage tank. This city is chosen since the experimental data for such a system is available and can be employed for validation. At first, a single-node system is modelled as a fully mixed tank. Next, the program is generalized to consider the effect of stratification by dividing the storage tank into any arbitrary number of nodes. The modelled phenomenon accounts for the effects of buoyant forces owing to the temperature gradient in the tank. The number of nodes sufficient to simulate a fully stratified storage tank is obtained as the ASF changes less than 1%. Afterwards, the effect of PCM application in both single-node and stratified tanks is investigated with the help of genetic algorithm optimization. Therefore, the optimum melting temperature and the amount of PCM are calculated.

Nomenclature

$\dot{Q}$	Heat transfer rate (W)
A	Surface area (m^2)
G_T	Solar irradiation (W/m^2)
$\tau\alpha$	Optical efficiency (-)
U_L	Collector heat loss coefficient (W/m^2K)
T	Temperature (°C)
$\dot{m}$	Mass flow rate (kg/s)
c_p	Heat capacity (kJ/kgK)
F'	Collector efficiency factor (-)

Subscripts

c	collector
a	air
L	load
i	inlet
o	outlet
u	useful

2.Studied System

The studied system consists of a domestic hot water tank and the collectors, as illustrated in Fig.1. Despite providing a large proportion of the required energy by the collector, an auxiliary system is utilized in the case of insufficient solar irradiation. This system is mounted on the outlet of the storage tank, and its capacity is set to maintain the demand water temperature at 60°C. In addition, a circulation pump is included to provide the system with forced circulation and to convey the thermal energy from the collector. A threshold of 200 W/m^2 for solar irradiation is considered so that the pump would be turned off when the solar flux is below this level. The outlet water from the collector is sent directly to the storage tank and mixed within it.
As shown in Fig.1, the amount of PCM included in the storage tank will be optimized in order to achieve the maximum ASF. It should be noted that the total storage capacity is considered to be constant and water volume is obtained after calculation of the optimum PCM volume. Table 1 represents the main characteristics of the mentioned system. It is also worth mentioning that the system is designed to provide daily 128 L of hot water at 60°C for domestic use by the normalized profile shown in Fig. 2. It is also worth mentioning that the data for the PCM is calculated based on the commercial ones available in the literature.

3.Governing Equations

The operating equation of the total system is constituted by two major parts: the collector and the storage tank.

- Collector

To calculate the available energy to the storage tank, the collector's characteristics

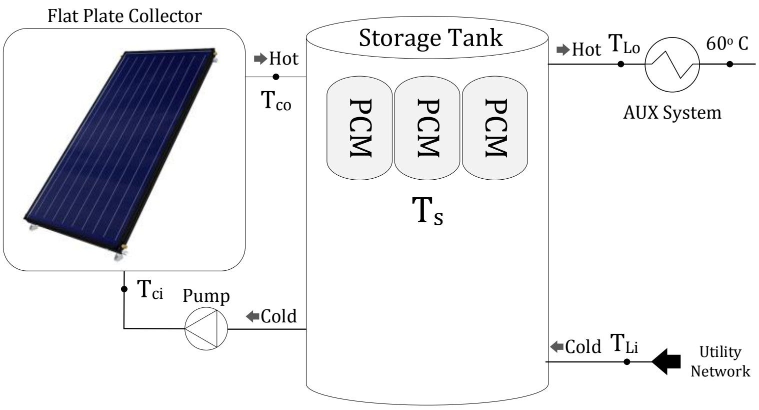


Fig.1. Studied system as SDHW

Table 1. Studied system characteristics

SDHW Characteristics	Value
Collector area	4 m^2
Storage tank capacity	250 L
Storage tank surface area	2.23 m^2
Storage tank loss coefficient	1.45 W/m^{2}K
Collector mass flow rate	0.22 kg/s
Collector plate absorptivity	0.95
PCM density	1.52 kg/L
PCM latent heat of fusion	178.86 kJ/kg

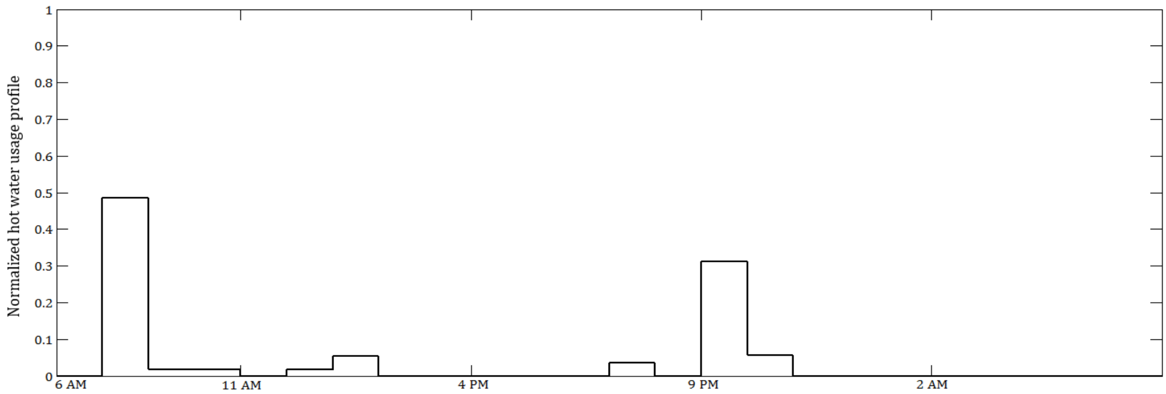


Fig.2. Normalized hot water usage profile

must be obtained on the basis of the operating conditions. To summarize this process, useful energy is calculated from Eq.1:

$$\dot{Q}_u = A_c F_R [G_T(\tau\alpha) - U_L(T_{ci} - T_a)] \quad (1)$$

where F_R is the collector heat removal factor obtained from the collector characteristic such as geometry, mass flow rate, and heat loss coefficient from Eq. 2:

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m}c_p}\right)\right] \quad (2)$$

where F' represents the geometrical consideration. From another point of view, by considering the energy conservation, the collector useful energy can be stated as:

$$\dot{Q}_u = \dot{m}_c c_p (T_{co} - T_{ci}) \quad (3)$$

- Storage tank

In this section, storage tank modelling is divided into two separated approaches including single-node (fully mixed) and multi-node (stratified) storage tanks. The governing equation for a single-node storage tank is:

$$(mc_p)_s \frac{dT_s}{dt} = \dot{Q}_u - \dot{m}_L c_p (T_s - T_{Li}) - (UA)_s (T_s - T_a) \quad (4)$$

The multi-node tank is governed by more complex equations. Referring to Fig. 3, some additional coefficients, F_i^L and F_i^c, are defined in this case to state the location of the water from the collector outlet and the utility network:

$$F_i^c = \begin{cases} 1 & \text{if } i = 1 \text{ and } T_{co} > T_{s,1} \\ 1 & \text{if } T_{s,i-1} \geq T_{co} > T_{s,i} \\ 0 & \text{if } i = 0 \text{ or if } i = N+1 \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

$$F_i^L = \begin{cases} 1 & \text{if } i = N \text{ and } T_{Li} > T_{s,N} \\ 1 & \text{if } T_{s,i-1} \geq T_{L,r} > T_{s,i} \\ 0 & \text{if } i = 0 \text{ or if } i = N+1 \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

The net flow between nodes is defined to simulate the flow caused by the temperature gradient:

$$\dot{m}_{m,i} = \begin{cases} 0 & i = 1 \\ 0 & i = N+1 \\ \dot{m}_c \sum_{j=1}^{i-1} F_j^c - \dot{m}_L \sum_{j=i}^{N} F_j^L & \text{otherwise} \end{cases} \quad (7)$$

Therefore, the net energy balance for each node in this case yields:

$$m_i \frac{dT_{s,i}}{dt} = \left(\frac{UA}{C_p}\right)_i (T_a - T_{s,i}) + F_i^c \dot{m}_c (T_{co} - T_{s,i}) + F_i^L \dot{m}_L (T_{Li} - T_{s,i}) + \begin{cases} \dot{m}_{m,i}(T_{s,i-1} - T_{s,i}) & \text{if } \dot{m}_{m,i} > 0 \\ \dot{m}_{m,i}(T_{s,i} - T_{s,i+1}) & \text{if } \dot{m}_{m,i} < 0 \end{cases} \quad (8)$$

- PCM

In this study, the PCM is modelled as an energy package, which can be charged and discharged in cases of surplus and deficit of energy, respectively. Its capacity is defined as follows:

$$PCM_{Capacity} = \rho_{PCM} V_{PCM} LH_f \quad (9)$$

With regard to the assigned data for the density and latent heat of the PCM, the optimum energy package yields the required volume of the PCM in order to satisfy the energy demand.

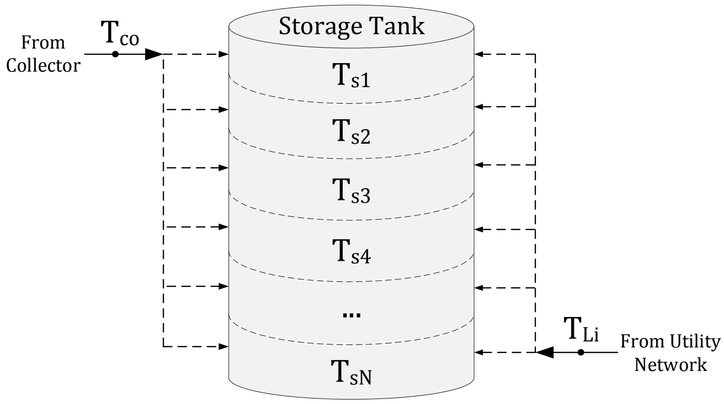


Fig. 3. Stratified tank schematic diagram

- Numerical modelling

In order to solve the equations governing the system, a numerical integration of above equations is carried out by the explicit Euler method. The MatLab software package is used to implement the program capable of solving the discretized equations. The time step size in this study is considered for a minute to achieve an acceptable accuracy and to observe the potential temperature fluctuations.

4.Validation

In order to validate the obtained results of the implemented code, the experimental data presented by Haillot et al. [6, 11] for a commercial SDHW system in Perpignan is used. Code data was adapted to the conditions of their commercial SDHW system, namely 'VFK 900S', and the clearance index k_t was extracted from the meteorological data with the help of the Angstrom-type regression equation for a similar climatic condition. Furthermore, the threshold radiation is set to be 300 W/m^2 according to the mentioned experimental setup. Figure 4 shows experimental and simulation data for every month. The results indicate that the ASF for both single-node and multi-node simulation can achieve values showing less than 10% error from the experimental ones.

5.Results and Discussion

In this section, the results of the numerical simulation are presented and the behaviour of the SDHW is analysed in each condition to achieve the best performance.

- Stratification Effects

The studied system is simulated under different thermal stratification conditions for the storage tank. First of all, the number of

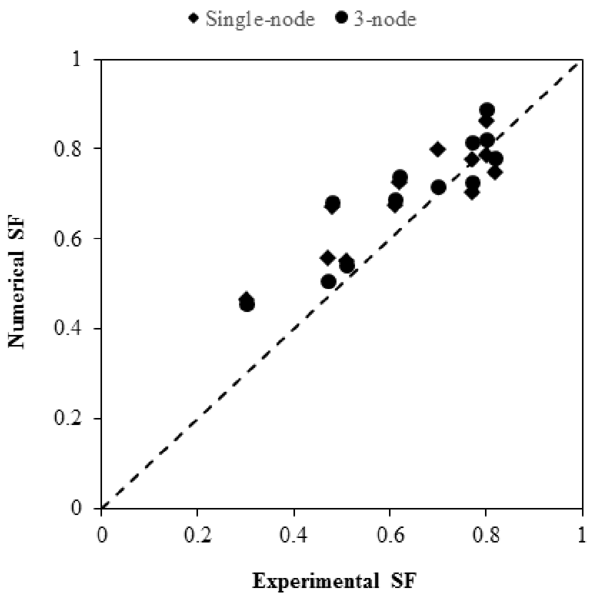


Fig.4. Comparison of the numerical results with the experimental data

sufficient nodes representing a fully stratified tank is calculated. This value is obtained with respect to the criterion of less than 1% change in the ASF. Figure 5 presents the results for different numbers of nodes. As it can be seen, variations in the ASF are negligible after five nodes, and this value could represent a fully stratified storage tank.

The results indicate that with increases in the number of nodes, the ASF increases due to a rise in the tank's average daily temperature. In other words, a higher average temperature can be achieved by stratifying the storage tank compared to a fully mixed tank. Taking a look at the above data, it can be found that stratification (five-node storage tank) leads to about 4.6% increases in the ASF. It should be mentioned that stratification phenomenon would occur in a realistic storage tank due to the density gradient caused by temperature differences. Thus, a fully mixed tank simulation does not represent the real condition. Also, partial mixing prevents the storage tank from achieving the fully stratified condition. Therefore, a number of nodes lying between the both cases would yield the most realistic results.

- PCM Effect

After investigating the stratification effect, the influence of integrating the PCM in the storage tank is studied. In this section, the three-node storage tank is a realistic condition, which is between a fully mixed (single-node) and fully stratified (five-node) tank and it is selected to find the optimum parameters for the PCM. To explain more, the melting temperature and the volume of the PCM are selected as decision variables in each generation of the genetic algorithm (GA). The goal of the optimization is to maximize the ASF under the operating conditions for both single- and multi-node configurations. In summary, the optimum parameters of the PCM for both configurations are presented in Table 2.

- Single-node

In the absence of any stratification due to the higher maximum temperature in the single-node storage tank, it is predictable that more amounts of PCM would be melted in this configuration. Therefore, the ASF is

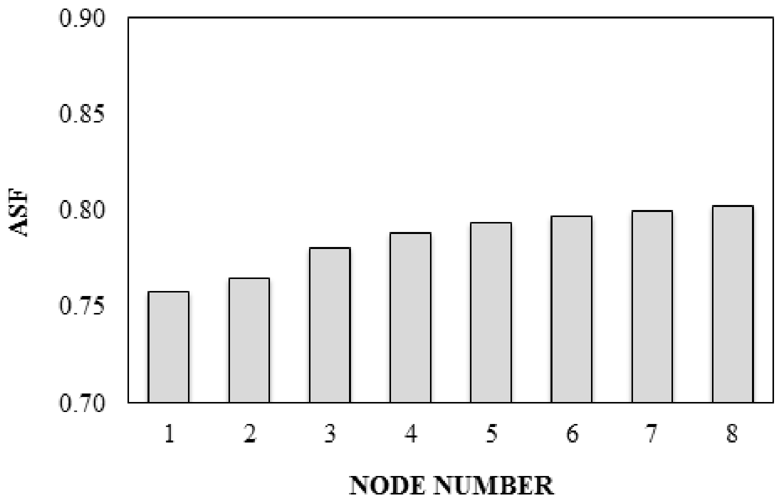


Fig. 5. ASF for different numbers of nodes

Table 2. Optimum PCM parameters in fully mixed and stratified tank

Specification	Single-node	Three-node
PCM melting point	57.34 °C	58.37 °C
PCM volume	98.89 L	30.05 L
Annual solar fraction	79.16	78.51
Improvement	5.32%	0.63%

influenced more by the addition of the PCM, and its increase is higher relative to the three-node storage tank. The optimum daily temperature profiles in January and July are presented in Fig. 6. In addition, Table 3 shows the effect of PCM on the solar fraction with single-node simulation.

The optimum melting temperature of the PCM almost approaches the desired temperature for hot water, which is 60°C in this study. Furthermore, the PCM is melted only in summer months such as July, albeit not completely, while the temperature profiles show the same trend in winter months without any PCM melting. It may be mentioned that in addition to energy storage in the PCM, variations in containing the water volume might also affect the ASF. Small changes in the ASF for months with no PCM melting actually stem from this phenomenon. Overall, a combination of these effects leads to an increase of 5.3% in the ASF.

- Multi-node

Thanks to GA, the optimum parameters relating to the employed PCM is obtained for the realistic stratified storage tank. The optimum daily temperature profiles in July for node No.1 and No.3 are shown in Fig. 7. In addition, Table 5 summarizes the effect of the PCM on the solar fraction with three-node simulation.

In this case, the melting temperature hovers near the hot water demand temperature, similar to the mixed tank. As mentioned previously, because of the smoother temperature profile, the optimum PCM volume is lower than the single-node tank. In other words, a lesser amount of PCM is melted in July, the warmest month. In this configuration, optimization results show an increase of about 0.7% in the ASF—lower than the one for the mixed tank, as it was predicted. Again, it can be seen that the storage water volume change justifies small variations in the ASF for months with no PCM melting.

6.Conclusion

In this paper, the effect of stratification and integration of the PCM in the storage tank of an SDHW system has been investigated. By coupling the governing equations of the collector and storage tank containing the

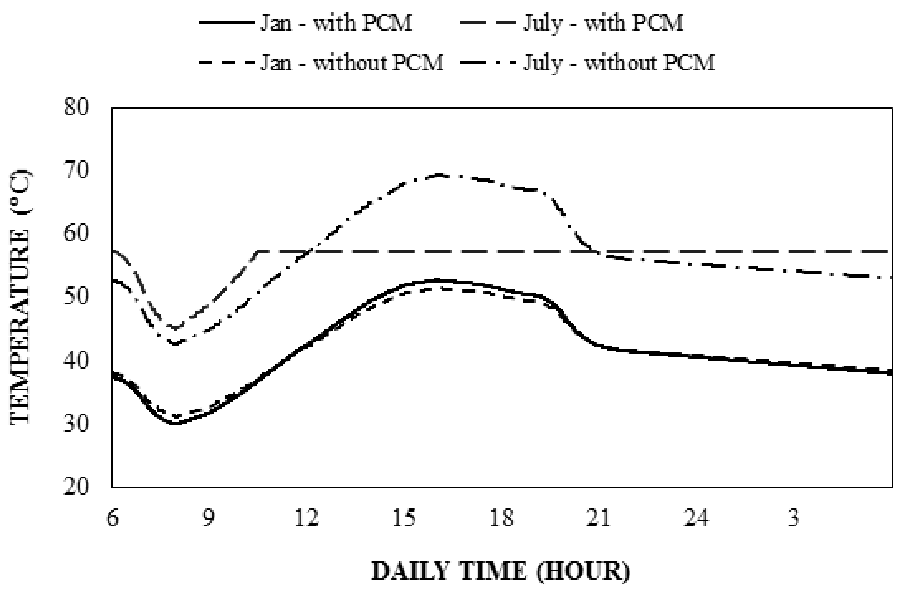


Fig. 6. Daily temperature profiles for January and July in single-node simulation

Table 3. PCM effect on the solar fraction with single-node simulation

Solar Fraction	With PCM	Without PCM	Improvement (%)
In January	70.14	70.57	-0.61
In July	91.14	87.84	3.76
Annual	79.16	75.16	5.32

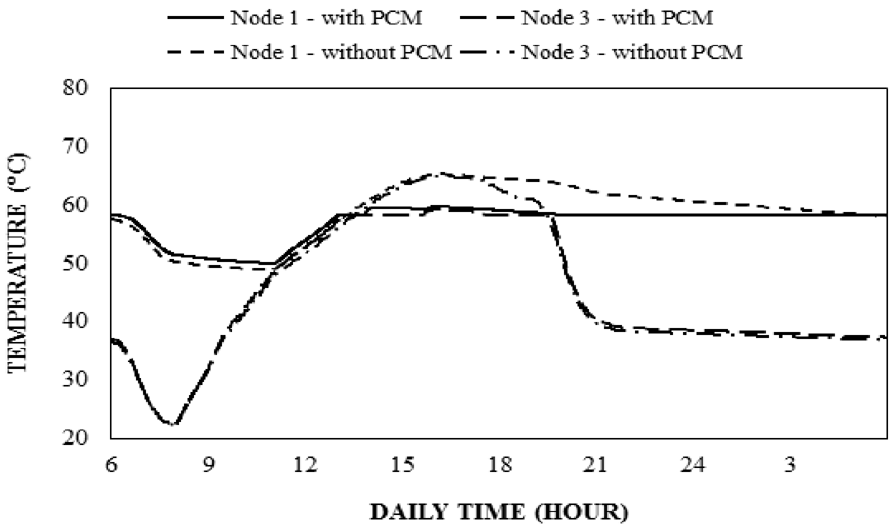


Fig.7. Daily temperature profiles for July in three-node simulation

PCM, the system behaviour is analysed with the storage tank under different thermal stratifications. The system performance is modelled during days representing the average conditions for a month. The results indicate that five nodes are capable of describing a fully stratified tank, and stratification can increase the ASF about 4.6%. Afterwards, the influence of integrating the PCM for energy storage is studied for both a mixed tank and a realistic stratified tank with three nodes. Although the single-node tank shows lower ASF without the PCM, its ASF exceeds it for the stratified tank in case of application of the PCM. This phenomenon is attributable to a higher maximum temperature, which leads to more melting. In this way, the single-node tank shows a rise of about 5.3% in the ASF compared to a multi-node tank's 0.7%. Therefore, it can be concluded that the PCM as an energy storage medium and indirectly as a storage water volume tuner will increase the overall performance of SDHW systems.

References

[1] Thirugnanasambandam M., Iniyan S., Goic R., A Review of Solar Thermal Technologies, Renewable and Sustainable Energy Reviews (2010) 14: 312–322.

[2] Shukla A., Buddhi D., Sawhney R.L., Solar Water Heaters with Phase Change Material Thermal Energy Storage Medium, A Review, Renewable and Sustainable Energy Reviews (2009) 13: 2119–2125.

[3] Sharma A., Chen C.R., Solar Water Heating System with Phase Change Materials, International Review of Chemical Engineering (I. RE. CH. E.) (2009) 1: 297–307.

[4] Shukla R., Sumathy K., Erickson P., Gong J., Recent Advances in the Solar Water Heating Systems, A Review, Renewable and Sustainable Energy Reviews (2013) 19:173–190.

[5] Sharma S.D., Sagara K., Latent Heat Storage Materials and Systems, A Review, International Journal of Green Energy (2005) 2: 1–56.

[6] Haillot D., Nepveu F., Goetz V., Py X., Benabdelkarim M., High Performance Storage Composite for the Enhancement of Solar Domestic Hot Water Systems, Part 2, Numerical System Analysis, Solar Energy (2012) 86: 64–77.

[7] Padovan R., Manzan M., Genetic Optimization of a PCM Enhanced Storage Tank for Solar Domestic Hot Water Systems, Solar Energy (2014) 103: 563–573.

[8] Mather D.W., Hollands K.G.T., Wright J.L., Single-and Multi-Tank Energy Storage for Solar Heating Systems, Fundamentals, Solar Energy (2002) 73: 3–13.

[9] Rhee J., Campbell A., Mariadass A., Morhous B., Temperature Stratification from Thermal Diodes in Solar Hot Water Storage Tank, Solar Energy (2010) 84: 507–511.

[10] Andersen E., Furbo S., Fan J., Multilayer Fabric Stratification Pipes for Solar Tanks, Solar Energy (2007) 81: 1219–1226.

[11] Haillot D., Franquet E., Gibout S., Bédécarrats J.P., Optimization of Solar

DHW System Including PCM Media, Applied Energy (2013) 109: 470–475.
[12]Duffie J., Beckman W., Worek W.M., Solar Engineering of Thermal Processes, 2nd Edition, 1994. DOI:10.1115/1.2930068.
[13]Sharma A., Tyagi V. V, Chen C.R., Buddhi D., Review on Thermal Energy Storage with Phase Change Materials and Applications, Renewable and Sustainable Energy Reviews (2009) 13: 318–345.
[14]Khalifa A. J. N., Jabbar R. A. A., Conventional Versus Storage Domestic Solar Hot Water Systems, A Comparative Performance Study, Energy Conversion and Management (2010) 51: 265–270.
[15]Nkwetta D.N., Vouillamoz P.E., Haghighat F., El-Mankibi M., Moreau A., Daoud A., Impact of Phase Change Materials Types and Positioning on Hot Water Tank Thermal Performance, Using Measured Water Demand Profile, Applied Thermal Engineering (2014) 67:460–468.