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A comprehensive study on the effect of hot water demand and PCM integration on the performance of SDHW system

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ABSTRACT

In this study, a commercial SDHW for Tehran meteorological data is modeled numerically in order to investigate the effect of three main influential sets of parameters, including the solar system characteristics, the water demand profile, and the PCM integration. First, a sensitivity analysis of intrinsic parameters is conducted. Then, the system performance is analyzed under the thermal stratification effects. After recognition of the system, the effect of hot water demand and several time-profile is investigated. Finally, in order to determine the whole range of operating conditions, both fully-mixed (single-node) and fully-stratified (multi-node) tanks are considered for applying phase change material (PCM) as a storage medium. Genetic Algorithm (GA) is used to achieve the best PCM parameters including the melting temperature, and the total volume and its distribution in the storage tank. Sensitivity of the optimized PCM – embedded system to the melting temperature is conducted in order to propose some practical PCMs for use in such systems.

According to the results, in the non-uniform high daily water consumption the thermal stratification is more beneficial which can lead to 9% increase in the ASF. Also, it is found out that a solar water heater system performance is very demand dependent so that it induces up to 8% ASF variation in different demand conditions. Therefore, integration of the PCM in SDHW systems, which can increase the ASF by 4%, is very case dependent with respect to the results of optimization and sensitivity analysis.

1. Introduction

Increasing demand for renewable energy resources has attracted remarkable attention of many researchers. Due to a mismatch between the energy supply and the energy demand, especially in the case of the solar energy, thermal energy storage plays an important role (Shukla et al., 2013; Seddegh et al., 2015). This type of energy accumulation is mainly conducted as a change in the sensible or the latent internal energy of a material. Among all approaches, some applications such as solar heating systems incorporate water as an energy storage medium (Duffie et al., 1994; Ibáñez et al., 2014; Eshraghi et al., 2014). Recently, numerous studies have analyzed the effect of employing phase change materials (PCMs) to enhance the thermal energy storage performance due to their high latent heat (Zalba, 2003; Sharma et al., 2009; Sharma and Sagara, 2005; Baniassadi et al., 2016; Mirkhani et al., 2012). This method can be performed by inserting PCMs either in the storage tank or directly in the solar collector. There is a tangible dispute between researchers about the actual improvement of solar domestic hot water (SDHW) systems efficiency by integrating PCMs in storage tanks as well as other design parameters (Shukla et al., 2013; Seddegh et al., 2015; Sharma et al., 2009; Thirugnanasambandam et al., 2010; Shukla et al., 2009).

Over the past decade, many researchers have tried to investigate the effect of different design parameters and operating conditions on the energy storage tanks performance and to propose some methods to improve the efficiency of these systems (Shukla et al., 2013; Thirugnanasambandam et al., 2010; Nabavitabatabayi et al., 2014; Najafian et al., 2015; Ibanez et al., 2006; De et al., 2011; Khalifa and Jabbar, 2010; Kalogirou, 2000). In order to categorize the different parameters and to distinguish between each outcome, they can be divided into three main groups: (1) external parameters e.g. water demand profile and its temperature, (2) storage tank characteristics including its volume, geometry, and thermal stratification, and (3) additional components such as PCMs. The latter two categories were of more interest in the literature, however, effect of water demand as an external parameter have been observed by Nkwetta et al. (2014). They used three field-measured hot water consumption profiles (low, medium, high) to analyze the effect of control strategies on the thermal

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Nomenclature

A_c	collector surface area (m^2)
ASF	annual solar fraction
AUX	auxiliary
c_p	specific heat capacity (J/kg K)
F'	collector geometrical factor
F^c	collector mass flow rate location factor
F^L	load mass flow rate location factor
F_R	collector heat removal factor
F−M	fully mixed
F−S	fully stratified
G_T	solar irradiation (W/m^2)
i	node number
j	time indicator
k_t	sky clearness index
LH_f	latent heat of fusion (J/kg)
m	mass (kg)
$(mc_p)_s$	storage tank heat capacity (J/K)
$\dot{m}_c$	collector mass flow rate (kg/s)
$\dot{m}_L$	load mass flow rate (kg/s)
$\dot{m}_m$	mass flow rate between nodes (kg/s)
PCM	phase change material
Q_{aux}	auxiliary energy (J)
Q_{loss}	energy loss (J)
	required energy (J)
Q_{solar}	useful energy provided by the sun (J)
Q_{total}	total energy needed (J)
$\dot{Q}_u$	useful heat transfer rate (W/m^2)
SDHW	solar domestic hot water
t	time (s)
T_a	ambient temperature (°C)
T_{ah}	temperature for hour h (°C)
T_{ci}	collector input temperature (°C)
T_{co}	collector output temperature (°C)
T_{Li}	load input temperature (°C)
T_{Lo}	load output temperature (°C)
$T_{m,PCM}$	PCM melting temperature (°C)
T_s	storage tank temperature (°C)
$(UA)_s$	storage tank overall heat transfer coefficient (W/K)
U_L	collector heat loss coefficient (W/m^2 K)
V_{PCM}	PCM volume (L)
$\tau\alpha$	collector optical efficiency
ρ_{PCM}	PCM density (kg/L)

performance of the hot water tank.

There have been many studies dealing with the storage tank characteristics (Rhee et al., 2010; Andersen et al., 2007; Bracamonte et al., 2015; Knudsen and Furbo, 2004). Ghaddar (1994) investigated an active SDHW system and utilized an inlet diffuser to enhance the thermal stratification in the storage tank. Up to 20% increase in the delivered energy was reported due to the stratification effect. In a work by Mather et al. (2002) a different approach for stratification, i.e. multi-tank energy storage, was studied and economic advantages have been observed for such a configuration. Khalifa et al. (2011) investigated the effect of some operating characteristics including the tank aspect ratio and its heat losses on the thermal stratification. They claimed that higher aspect ratios show more clear stratification in a tank. In a recent work by Yang et al. (2016), the impact of water tank geometry on the thermal stratification and the thermal storage capacity were analyzed. They reported that sphere and barrel shapes show the best storage capacity while the shapes with sharp corners are characterized by highest stratified conditions.

From another point of view, integration of PCMs in an SDHW system was studied by numerous researchers. These studies have mostly focused on the thermo-physical properties of the PCMs and configurations of the PCM in the storage tank (Nkwetta and Haghighat, 2014). However, a unanimous conclusion is not achieved yet due to the existence of many influential parameters in this issue. Mehling et al. (2003) conducted an experimental study and showed that adding PCM at the top of a storage tank can partially compensate for the storage tank heat losses. Afterward, in a work by Cabeza et al. (2006), an experimental pilot solar plant with PCM modules in its stratified storage tank was used. They observed that in the vicinity of the PCMs, the water cools down slower during the night. On the other hand, Talmatsky and Kribus (2008) studied the actual effect of implementing PCMs on the total heat storage under a typical water demand profile. The simulations were performed in different scenarios including different locations and different PCMs volume fraction. They claimed that there is no significant improvement in the energy provided to the end-user. Kousksou et al. (2011) used PCMs with different hypothetical melting temperatures to evaluate its effect on the overall performance of SDHW systems. They reported that the required backup electrical energy changes substantially with the PCM melting temperature. Finally, they suggested that although no remarkable increase might be seen in the annual solar fraction (ASF), it is highly sensitive to the design parameters such as PCM melting point which should be analyzed carefully. Haillot et al. (2012) proposed and analyzed a new type of PCM-integrated solar collector. They observed that the increase of the system efficiency in summer may be compensated by its efficiency decrement during winter. In their other work (Haillot et al., 2013), Haillot et al. studied a new configuration to insert PCMs in SDHW systems, i.e. locating PCMs in a separate fluid loop from the storage tank. Analyzing this configuration under several meteorological conditions and PCM melting points, they reported that the optimum design depends on the weather conditions; and the system efficiency could be increased significantly. Padovan and Manzan examined the PCM effect for two specific weather conditions (Padovan and Manzan, 2012). They used two PCM melting points higher than the required hot water temperature. In addition, the effect of the storage tank volume was investigated. No dramatic increase in solar fraction was seen in their study so that they suggested an optimization process to tune the relevant parameters. In another research work, they employed genetic algorithm optimization to evaluate the sensitivity of SDHW system to the above-mentioned parameters more precisely (Padovan and Manzan, 2014). In order to carry out a more comprehensive work, they adopted both tank geometrical parameters and PCM melting point as optimization variables. Finally, they rejected the claim about PCMs as a promising solution for increasing the overall performance of SDHW systems.

Taking a look at the previous research works, it can be found out that it is necessary to reconcile the contradictory findings. This might be attributed to the fact that some major parameters, including the storage stratification, the hot water demand profile, and all range of PCM choices, have not been considered simultaneously. In addition, in some cases, the performance criterion has not been introduced suitably. In this way, we introduced three main categories for the influential factors on SDHW system, including the solar system characteristics, the water demand profile, and the PCM integration. The first category represents intrinsic features of a system define its behavior. The second one reflects the external factor which is usually ignored in the literature. With the help of a comprehensive assessment of these two groups, it is viable to reach a conclusion about the third factor, i.e. integration of PCMs. To do so, a sensitivity analysis is carried out to investigate the impact of solar system parameters, including the storage tank volume and its heat loss coefficient, the collector area, and the mass flow rate, on the ASF of the system under different stratification conditions.