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An alternative approach for assessing the benefit of phase change materials in solar domestic hot water systems

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ABSTRACT

Phase change materials (PCM) for thermal energy storage in solar energy systems have been the subject of a great deal of research in the literature. Despite this, the research results pertaining to the efficacy of PCMs in enhancing system solar fraction are mixed. The current paper explores this issue numerically within a systems context. A typical solar domestic hot water system is considered. The PCMs are introduced as vertical cylindrical modules contained within the water tank, thus forming a hybrid PCM/water thermal storage. Water flowing along the length of tank is used as the heat transfer fluid. A model was developed based on the enthalpy-porosity method to solve for the phase change process within the PCM modules. The model was thoroughly validated and verified and predictions were in good agreement (less than 5% deviation) with results from the literature. The hybrid tank model was linked with the collector performance and the system was tested for typical days of Canadian weather with a dispersed demand profile. The solar fraction of the hybrid system was compared to that for an identical system using water-only as the thermal storage medium. The system analysis explores the impact of storage volume on solar fraction for systems with and without PCMs included. The systems approach is critical since it allows for the coupled effects of the thermal storage, solar collector, and household load to be incorporated. The analysis clearly shows that incorporation of PCMs into the thermal storage results in enhanced solar fraction at undersized tank volumes relative to the demand. In contrast, as the tank volume is increased, the benefit of the PCMs diminishes and identical performance is obtained between the two systems at large volumes. An energy balance of the system shows that, despite marginally increased heat losses from the hybrid tank, the benefits of the hybrid storage at small storage volumes are due to the reduction in the collector fluid inlet temperature which increases the pump run time and thus the solar energy collected and reduction of collector losses.

1. Introduction

Thermal energy storage is an important component of solar domestic hot water systems to mitigate the temporal mismatch between solar radiation availability and demand for hot water. For residential applications, energy storage systems typically use water as a sensible storage medium due to its low cost and high specific heat. Latent energy storage (LES) systems employ phase change materials (PCMs) and the energy is stored and released in the form of latent heat of fusion. This offers higher energy storage density compared to the water-only systems. PCMs also modulate the system temperature around its melting temperature (T_m) (Zalba et al., 2003). PCMs are mainly classified as organics, inorganics and eutectics (Abhat, 1983). Sari and Karaipekli (2009) performed experiments on a series of fatty acids (including capric acid) and found favourable properties including stability under thousands of cycles of melting and solidification. This phase-change stability makes them suitable for inclusion in solar domestic hot water systems.

The main challenge associated with PCMs operating at low temperatures ($< 100\,^\circ\mathrm{C}$) is their low specific heat capacity and poor thermal conductivity (Desgrosseillier et al., 2011; Sari and Kaygusuz, 2002, 2003). The lower heat capacity degrades the energy storage capacity of PCM when the operating temperature range increases. The poor thermal conductivity impacts on the heat transfer rate to the PCMs and thus can limit the storage capacity of the system for a prescribed charging period (Bergles, 2011). Extensive research has been conducted to tackle this problem using either active or passive techniques. Active techniques involve an external source such as electro-hydrodynamics to enhance the melting rate (Nakhla et al., 2015). Passive techniques include the use of fins, thermal conductivity enhancement, and micro-encapsulation (Jegadheeswaran and Pohekar, 2009; Agyenim et al., 2010; Sanusi et al., 2011; Pokhrel et al., 2010; Velraj et al., 1999;

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Nomenclature

A_c	collector surface area [m^2]
C_{pl}	liquid specific heat capacity [J/kg K]
C_{ps}	solid specific heat capacity [J/kg K]
D	PCM cylinder outer diameter [m]
$E_{delivered}$	energy delivered to the load [J]
$E_{loss,\ coll}$	collector energy loss [J]
$E_{loss,\ tank}$	tank energy loss [J]
E_{mains}	mains water energy [J]
E_{solar}	solar energy incident to the collector [J]
F_R	heat removal factor
f_s	solar fraction
$F_{s,annual}$	annual solar fraction
G	solar irradiation [W/m^2]
k	thermal conductivity [W/mK]
L_c	length of cylinder [m]
$\dot{m}$	mass flow rate inlet to the tank [kg/s]
N_c	number of cylinders in the tank
Nu_c	Nusselt number based on hydraulic diameter
Nu_p	Nusselt number based on Dittus-Boelter correlation
Q_u	collector useful heat gain [kW]
$R_{c,inn}$	inner radius of phase change material cylinder [m]
$R_{c,out}$	outer radius of phase change material cylinder [m]
r_s	latent heat of fusion [kJ/kg]
T	temperature [°C]
T_{amb}	ambient temperature [°C]
T_{in}	temperature of incoming fluid [°C]
T_m	melting temperature of PCM [°C]
T_o	outlet temperature of the collector [°C]
T_{st}	initial temperature of the tank [°C]
U_L	overall collector heat transfer loss coefficient [W/m^2 K]
V_{tank}	tank volume [m^3]

Abbreviations

HTF	heat transfer fluid
LES	latent energy storage
PCM	phase change material
SDHW	solar domestic hot water
SES	sensible energy storage
TES	thermal energy storage

Latin symbols

$(\tau\alpha)$	transmittance absorbance product
η	solar collector efficiency

Subscripts

c,inn	inner surface of cylinder
c,out	outer surface of cylinder
conv	convective
In	inlet
l	liquid
m	melting
st	start
t	transition

Stritih, 2004; Yingqiu et al., 1999; Lacroix and Benmadda, 1997). Extended surfaces such as fins increase the heat transfer rate in the thermal system with the increased area (Jegadheeswaran and Pohekar, 2009,; Agyenim et al., 2010) but result in increased weight and system cost. Embedding metallic particles enhances the thermal conductivity of PCM, but the particles tend to agglomerate and settle to the bottom of the tank (Sanusi et al., 2011; Pokhrel et al., 2010; Velraj et al., 1999). Alternatively, heat transfer to the PCMs can be enhanced by increasing the surface area of the modules and reducing the conduction distance. This can be accomplished by encapsulating the materials in thin rectangular slabs or small radii cylindrical or spherical containments (Stritih, 2004; Yingqiu et al., 1999; Lacroix and Benmadda, 1997).

Hybrid tanks containing both water and phase change materials have been studied extensively. The inclusion of PCM in the tank increased the thermal energy stored compared to a water-only tank for isothermal charging conditions (Esen and Ayhan, 1996; Mehling et al., 2003; Nallusamy and Velraj, 2009). The PCM improves the thermal stratification in the tank since it maintains the top layers of the tank at a higher temperature (Mehling et al., 2003). The operating conditions of the system influence its performance. The mass flow rate was found to have a significant effect on the rate of charging TES as it increases the heat transfer coefficient thus the melting time decreases as the mass flow rate increases. In contrast, the PCM melting time increases nonlinearly with increasing volume fraction due to the additional thermal resistance imposed on the system (Nallusamy and Velraj, 2009).

On the system level, the effect of PCM inclusion in the water tank of a SDHW system was investigated by number of researchers. Realistic supply and draw-off patterns as well as approximated ones were considered (Wang et al., 2015; Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013; Nabavitabatabayi et al., 2014; Nkwetta et al., 2014; Talmatsky and Kribus, 2008; Kousksou et al., 2011). The PCM increased the exergy efficiency and the storage capacity due to its latent heat and temperature modulation effect (Wang et al., 2015; Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013). It decreased the delivered temperature swing at night due to the released heat of fusion. This increased the periods of times when the PCM can supply the load with hot water and thus increased the amount of energy delivered by the solar system relative to the total energy required by the load, commonly referred to as solar fraction (Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013). PCM was also found to be beneficial in shifting power demand (Nabavitabatabayi et al., 2014; Nkwetta et al., 2014). The high thermal inertia of the hybrid system (containing water and PCMs) reduced the system temperature variation thus decreased the auxiliary heat required in peak periods (Nabavitabatabayi et al., 2014; Nkwetta et al., 2014).

Talmatsky and Kribus, 2008 raised a question that seemed to contradict the ongoing research on the predicted benefit of PCM incorporation in water tanks. They studied numerically the hybrid tank performance throughout the year and compared the predicted solar fraction to a water-only system. They reported only a marginal gain in solar fraction (around 1%) when PCM is present inside the tank. They argued that the benefit brought by PCM during the day is penalized by increased heat loss from the tank at night. This resulted in overall similar performance by the two systems. Kousksou et al., 2011 subsequently determined that the marginal gain reported by Talmatsky and Kribus, 2008 was a result of the improper selection of PCM melting temperature. The charging period was not sufficient to fully melt the PCM. This caused the PCM to act as a sensible storage most of the time. When Kousksou et al., 2011 lowered the PCM melt temperature in Talmatsky's system; a 14% reduction in the annual electricity backup was achieved. A slight increase in the collector efficiency was also noted.

From the previous studies on the systems level, the effects of PCM inclusion on solar fraction appear to be mixed. Some researchers found that solar fraction is enhanced with the presence of PCM (Wang et al., 2015; Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013; Nabavitabatabayi et al., 2014; Nkwetta et al., 2014; Kousksou et al., 2011) whereas others found only marginal benefits (Talmatsky and