

# Potential of cascaded phase change materials in enhancing the performance of solar domestic hot water systems



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## ABSTRACT

The current paper explores a multi-tank thermal storage system for multi-residential solar domestic hot water applications. The thermal storage system includes phase change materials (PCMs) of different melting temperatures incorporated in the tanks. The PCMs are introduced as vertical cylindrical modules and water flowing along the length of tank is used as the heat transfer fluid. An enthalpy porosity model was developed to solve for the phase change process within the PCM modules. The model was validated and verified with previous work and predictions were in good agreement (less than 5% deviation). The hybrid tank model was linked with the collector performance. Typical Canadian weather data and a dispersed demand profile for a multi-residential building were considered. The performance of the hybrid system was judged based on the maximum possible storage volume reduction compared to the water only system with the same benefit to the end user. PCM maintains cooler water temperature entering the collector which results in a reduction of collector losses and extension of pump activation time. This increases the delivered energy to the load and hence increases the solar fraction. It was found that cascading four 75 L tanks containing PCMs of melting temperatures 54 °C, 42 °C, 32 °C and 16 °C gives a similar solar fraction to that for a 630 L water only tank. The multi-tank hybrid system thus allowed for over 50% reduction in the required storage volume.

## 1. Introduction

Thermal energy storage is an essential component of a solar domestic hot water (SDHW) system. Proper sizing is crucial to account for the mismatch between the solar supply and residential demand of hot water. The required storage volume is strongly dependent on the targeted application. A solar hot water heating system for a typical household consisting of four individuals would have hot water storage of 150–300 L (Cruickshank and Harrison, 2009). Hot water demand for a multi-residential building can be supplied through a large single tank or a series of small tanks interlinked together. Large tanks are expensive and difficult to fabricate. In addition, they are not well suited to retrofit situations where the storage vessel must be moved into a building space through existing door openings. Consequently, larger storages are often constructed on site. A multi-tank configuration, consisting of a series of small tanks, is a more economical alternative. The smaller tanks are readily available in the market at an affordable price. Moreover, they can be easily transported through doorways and could be stacked if required.

The performance of the multi-tank thermal storage system has been explored by a number of researchers (Mather et al., 2002; Cruickshank

and Harrison, 2009; Dickinson et al., 2012). They tanks were connected either in series or in parallel. They reported that the multi-tank serial interlinking promotes effective thermal stratification between tanks relative to the single tank configuration. Stratification arranges water layers in the order of their density. Maintaining stratification enhances the solar system performance (Hollands and Lightstone, 1989). Cooler water is sent to the collector which reduces collector losses and hotter water is sent to the demand thus enhancing solar fraction. Solar fraction is the amount of energy delivered by the solar system relative to the total energy required by the load.

Water is typically used as the energy storage medium. An alternative approach is to include phase change materials (PCMs) within the water storage thus creating a hybrid system. PCMs have the potential for high energy density as a result of the latent heat. Moreover, a well designed PCM based storage can modulate the system temperature around the melt temperature (Zalba et al., 2003). PCMs are categorized into three main groups: organics, inorganics and eutectics (Abhat, 1983). Amongst the organic group, fatty acids were reported to be suitable candidates for the solar system because of their high latent heat of fusion and stable properties (Desgrosseillier et al., 2011; Sari and Karaipekli, 2009).

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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 [ $W/m\ K$ ]
$L_c$	length of cylinder [ $m$ ]
$\dot{m}$	mass flow rate inlet to the tank [ $kg/s$ ]
$Q_u$	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 [ $^{\circ}C$ ]
$T_{amb}$	ambient temperature [ $^{\circ}C$ ]
$T_{in}$	temperature of incoming fluid [ $^{\circ}C$ ]
$T_m$	melting temperature of PCM [ $^{\circ}C$ ]
$T_{st}$	initial temperature of the tank [ $^{\circ}C$ ]

$U_L$	collector 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 absorptance product
$\eta$	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

Despite their high latent heat storage capability, PCMs have poor sensible properties. Their low specific heat ( $\sim$  half of water) reduces the energy storage capacity if the operating temperature range is large. Also, the poor thermal conductivity ( $\sim$  third of water) adversely impacts the heat transfer rate to the PCMs and thus can limit the storage capacity of the system for a prescribed charging period (Bergles, 2011). Active and passive techniques have been proposed to resolve the low conductivity problem. Active techniques involve an external source such as electrohydrodynamics to enhance the melting rate (Nakhla et al., 2015). Passive approaches include the usage of extended surfaces, embedding metallic particles to improve conductivity, and micro-encapsulating PCMs (Jegadheeswaran and Pohekar, 2009; Agyenim et al., 2010; Sanusi et al., 2011; Pokhrel et al., 2010; Velraj et al., 1999; Stritih, 2004; Yingqiu et al., 1999; Lacroix and Benmadda, 1997).

Fins increase the area of the system which enhances the heat transfer rate, but it also increases the overall volume and cost of the system owing to the added material (Jegadheeswaran and Pohekar, 2009; Agyenim et al., 2010). Embedding highly conductive metal particles in the PCM matrix acts to enhance thermal conductivity (Sanusi et al., 2011; Pokhrel et al., 2010; Velraj et al., 1999) but can be ineffective since the added particles tend to agglomerate and settle. The third passive technique is micro-encapsulating PCM in thin rectangular slabs or small radii cylindrical and spherical containments. Those micro-encapsulations reduce the conduction resistance imposed by the PCM on the system and increase the surface area to volume ratio (Stritih, 2004; Yingqiu et al., 1999; Lacroix and Benmadda, 1997). The previous enhancement techniques were mainly focused on low temperature applications. PCMs suitable for high temperature applications such as concentrated solar power applications have higher conductivity compared to those in low temperature applications ( $\sim$  3 times higher). Cascading PCMs of different melting temperature has been reported as a heat transfer enhancement technique for those applications (Michels and Pitz-Paal, 2007; Seeniraj and Narasimhan, 2008; Tian and Zhao, 2013). This is because it maintains a higher temperature difference between the heat transfer fluid and PCM relative to the single PCM case. Cascading PCMs in the system enhance energy storage capability and

exergy efficiency (Michels and Pitz-Paal, 2007; Seeniraj and Narasimhan, 2008; Tian and Zhao, 2013).

Inclusion of PCM in the water tank of a SDHW system has been the focus of relatively recent research. Researchers tested realistic supply and draw-off patterns as well as approximated ones (Wang et al., 2015; Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013; Nabavitatabaybi et al., 2014; Nkwetta et al., 2014; Kousksou et al., 2011). PCM increases the storage capacity of the system and increases the exergy efficiency (Wang et al., 2015; Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013). The modulation of temperature around PCM melting point decreases the delivered temperature swing at night. Therefore, the system can supply the load with hot water for a longer period. This increases the predicted solar fraction (Al-Hinti et al., 2010; Fazilati and Alemrajabi, 2013; Kousksou et al., 2011).

The current research explores the coupling of the multi-tank thermal storage concept together with the inclusion of PCM to supply hot water for a multi-residential building. To maximize the benefit from PCM inclusion, different PCMs are cascaded in the tanks in a descending order of their melting point. This modulates the temperature operating range in each tank around its PCM melting point and the effect of latent heat becomes more pronounced. Although multiple PCMs were reported in concentrated solar power applications (Michels

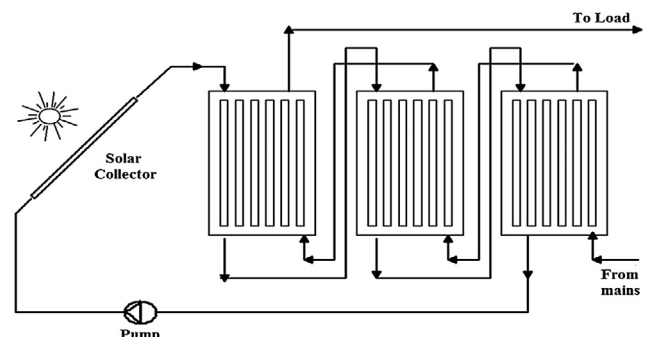


Fig. 1. Schematic of the cascaded multi-tank PCM solar thermal system.

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