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Impact of phase change materials types and positioning on hot water tank thermal performance: Using measured water demand profile

Dan Nchelatebe Nkwetta [a], Pierre-Edouard Vouillamoz [b], Fariborz Haghighat [a,*], Mohamed El-Mankibi [b], Alain Moreau [c], Ahmed Daoud [c]

[a] Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, QC H3G 1M8, Canada
[b] Département du Génie-Civil et Bâtiment, Ecole Nationale des Travaux Publics de l'Etat, F-69120 Vaulx-en-Velin, France
[c] Laboratoire des technologies de l'énergie d'Hydro-Québec, Shawinigan, QC, Canada

HIGHLIGHTS

- Performance of hot water tank integrated with PCM investigated numerically.
- Model's prediction was validated with the experimental data.
- PCM keeps the temperature from dropping fast during discharge mode.
- Amount of energy stored is directly proportional to the amount of PCM.

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ABSTRACT

This paper addresses a numerical investigation of the performance of a domestic hot water tank (HWT) integrated with phase change materials (PCM). The predictions made by three TRNSYS types were compared and the most appropriate one was selected as reference model. Then, the existing TRNSYS model for HWT with PCM was validated with the available data. The validated model was then used to investigate the impact of PCM type, its amount and its location within the tank on the system performance using the three real hot water withdrawal profiles; low, medium and high. An improvement in energy storage resulted from the combined use of PCM and sensible heat in a HWT with sodium acetate trihydrate +10% graphite showing the highest storage potential with reduce charging time compared to an industrial grade granulated paraffin wax and RT58-Rubitherm.

1. Introduction

Sensible energy storage is commonly used in building sector to meet the variations in energy demand and consumptions related to domestic hot water demand, space heating and cooling applications. Pérez-Lombard et al. [1] reported that primary energy has grown by 49% and CO_2 emissions by 43%, with an average annual increase of 2% and 1.8%, respectively. Based on the International Energy Agency (IEA) reports [2] on energy consumption trends and promotion of energy efficiency investments, it is estimated that the building sector in developed countries is consuming over 40% of the global energy with 24% of greenhouse gas emissions. Domestic hot water is mostly provided using electric or gas heaters due to their simplicity, installation and operation convenience [3]. Bourke and Bansal [4] reported that the performance of water heaters depends mostly on the position and the number of thermal elements, energy delivery to the fluid stream, the inlet/incoming water temperature, the size and the aspect ratio of the tank, fluid flow rate, and the location of the inlet and outlet.

During peak energy demand periods, the cost of generating, distributing and maintaining electricity by the utility companies is higher than non-peak periods [5–7]. This cost is likely to increase due to emerging techniques such as electronic thermostat with timer, electric gadgets and electric cars. Allard et al. [8] reported that hot water demand in over 90% of homes in Québec (Canada), are provided by electric water heaters totaling over 2.7×10^6 units and a great contributor to the electrical grid peak power demand. Thus representing an opportunity to reduce and/or shift peak the power demand. However, accurate control is needed to avoid

* Corresponding author. Tel.: +1 514 848 2424x3192.
E-mail addresses: Fariborz.Haghighat@Concordia.ca, haghi@bcee.concordia.ca (F. Haghighat).

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shortage of hot water, bacteria growth due to low hot water supply temperature if the heating element is deactivated for a long period and re-activating them at the same time creates another peak. In North America, a standardized residential electric water heater is a cylindrical tank with nominal storage capacities of 180 L or 270 L, representing almost 45% and 47% share of the market, respectively of domestic electric water heater usage [9]. In such a system, cold water enters the storage tank directly via the bottom or via an internal pipe connecting cold water from the top to the bottom while the hot water is withdrawn from the top of the tank (Fig. 1). This figure shows that water is heated by two horizontal heating elements/immersion heaters with a rated capacity ranging from 3 to 4.5 kW, depending on the size of the tank.

These heating elements are regulated using two thermostats in a master and slave mode. In operation mode, the upper heating element has the priority in turning on while the lower heating element is activated only if the upper heating element is off. To meet the above operation condition in practice, the upper and lower heating elements are often having the same set point temperatures (e.g. 60 °C). Due to the thermal stratification in the tank, the lower heating element is activated most of the time, even though it has a lower priority [9]. Recently, three-element water heaters are being introduced as a means to reduce the peak power demand and energy related costs [10]. The three-element water heater heats water more constantly compared to the traditional water heater of the same capacity, allowing to reduce the morning and evening peak demands [10]. The low power bottom thermal element works almost constantly while the middle element comes on only when it is needed to heat the water over a short period of time.

Reduction in the PCMs prices and the increase in the cost of the peak demand on the electric grids drives the need for this research.

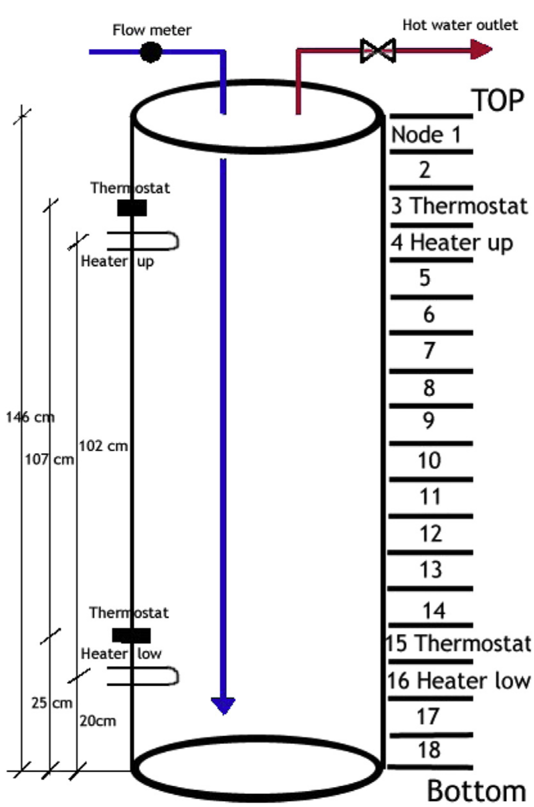

Fig. 1. Hot water tank with cold water entering the storage tank via an internal piping [9].

The use of PCMs ensures that water in the storage tank is heated during off-peak periods and the heat is effectively stored and used during the peak periods. This helps to reduce the peak hour energy usage and the associated cost and may result in potential availability of hot water throughout the day. However, the economical and successful application depends on efficient energy storage option and thus the need for detail and critical analysis of the potential energy storage of different PCMs in hot water tanks. Energy storage does not only improve the performance and reliability of energy systems but also plays an important role in conserving the energy and reducing the mismatch between energy supply and demand. Unlike sensible heat storage (SHS) systems which have been extensively tested, latent heat thermal energy storage systems (LHTES) and combined latent heat thermal energy with sensible energy storage systems are just gaining interest [11]. SHS systems require large storage capacity compared to the LHTES which need smaller unit size due to large heat storage capacity per unit volume and are capable of maintaining near constant temperature changes during the charging and discharging phases [14,15,17–19].

Chan [20] reported that PCMs has a number of merits including storage of thermal energy during the off-peak periods for use during the peak hours, night time storage and daytime release can alleviate grid load in electricity based system and extends the grid capacity in district and cooling sets. Chidambaram et al. [12] and Pinel et al. [13] stated that an efficient hot water tank should remain stratified during the charging and discharging processes. The stratification can increase the overall efficiency and shorten the charging time. One other technique to improve the thermal stratification is the integration of phase change materials (PCM) into hot water tank [14–16]. The application of PCM for LHTES necessitates that the materials exhibits certain desirable thermodynamic, chemical and kinetic properties. The use of PCMs ensures that water in the storage tank is heated during off-peak periods and the heat is effectively stored and used during peak periods. This helps to reduce peak hour energy usage and associated cost and may result in potential availability of hot water throughout the day.

Baetens et al. [21] and Kuznik et al. [22] compared the advantages and disadvantages of organic and inorganic materials as the LHTES. Earlier research reported that paraffin waxes are being used in many applications due to their chemical stability, non-poisonous ability, no phase separation with only a small change in volume during phase transformation with negligible degree of sub-cooling [18,23–26]. They also reported excellent thermal stability resulting from the lack of cycling effect on its properties as well as degrading of thermal behavior due to contact with metals. HWT integrated with PCMs requires PCMs with melting temperatures close to hot water temperature requirements (55–60 °C). Enibe [27] reported that paraffin is used as storage materials due to its availability in large temperature range, safety, reliability, cost-effectiveness and non-corrosiveness. However, only technical grade paraffin, which are chemically inert and stable below 500 °C show little volume changes during melting and have low vapor pressure in the melt form may be used for such application [17,18]. Paraffin, however shows some undesirable properties like: low thermal conductivity, non-compatible with the plastic container and moderately flammable which needs to be partly eliminated by slightly modifying the storage unit [18]. Table 1 provides the thermo-physical properties of different PCMs (sodium acetate trihydrate +10% graphite, RT58-Rubitherm and industrial grade granulated paraffin wax) with melting temperatures suitable for such application [6,7,14,15,19].

The PCM container temperature plays an important role during the melting process and has a strong effect on the melted fraction. An increase in thermal conductivity of container results in a decrease in the time taken for complete melting of the PCM, while