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Performance assessment of a chimney-type hot water storage tank in dynamic operation: Experimental approach

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ABSTRACT

Hot storage tanks (HSTs) have numerous engineering applications, including hot water boilers, hot water storage tanks in residential buildings, hot water storage in solar collector systems, and molten salt storage in concentrated solar power generation systems. The HST performance improves if the tank is thermally stratified. To improve the conditions of thermal stratification of the HST, accomplished by supplying hot water to users in a shorter time, and reducing energy consumption, a chimney-type hot water storage tank (HWST) is proposed. The static mode of this modified type HWST has been previously performed and found highly improve the thermal stratification in the tank. In this paper, the performance of the HWST under dynamic mode is investigated. Two chimney diameters three-inch and two-inch were used under variable flow rates (0.1 to 3 L/min), the usage period was also investigated (10 min and 18 min) to understand the effect of usage time on the performance of the HWST. The experimental data were compared to theoretical results, an accuracy range between 0.9 to 0.96 were achieved and tank efficiency varied from 0.96 at low temperatures to 0.86 at high temperatures. The 2 in chimney produces high top tank temperature in a shorter time, where safe flow rate gradients (positive temperature change) of 1.2 and 1.5 L/min were registered for 18 min and 10 min usage periods respectively.

Keywords: hot storage tank, chimney type hwst, energy saving, speed heater, thermal stratification.

INTRODUCTION

The hot water storage tanks (HWST) are engineering devices used to store hot water for heating or domestic usage. HWST are used commercially for district cooling or heating applications. The HWST are known to be high energy consuming devices, and many researchers worked on these systems to reduce the energy wasted during operations. Pomianowski et al. (2020) worked on energy recovery from the hot water after usage to increase the domestic HWST system efficiency. HWST has been combined with a geothermal heat pump as a hybrid system to improve its working efficiency (Alkhasov et al., 2021). The energy transition within the HWST was investigated by Kumar & Singh (2021), and they tried to accelerate the thermal energy transition in the HWST systems under multiple transient operations. The capacity of the system energy storage for a long time and a short time has been studied by Shakerin et al. (2022). The storage energy can be enhanced using phase change materials (PCM). Carmona et al. (2020) investigated the various PCMs location using computational fluid dynamics (CFD). D'oliveira et al. (2021) studied the selection of the PCM and concluded that the specific configuration and location of the PCM are needed. The thermal stratification in the HWST may optimize the HWST usable energy efficiency, which is why researchers have great concern about the thermal stratification in the HWST systems (Q. Li et al., 2021). The thermal stratification has been studied theoretically using the CFD (Kropas & Streckienė, 2020; Wilk et al., 2020) used three heating coils to control the thermal stratification in the HWST. Some other researchers found the two-coil system supplies sufficient thermal stratification in the tank (Neril et al., 2020). Finned PCM has been studied numerically (Dai et al., 2021), and found that the temperature change increases with increasing the fin height but increasing the number of fins was not positively correlated to the temperature rate at each point (Zakri et al., 2023). Awad et al. (2023) studied the solar HWST performance under three latent heat storage designs, and they were able to increase the efficiency of the HWST.

HWST has been investigated both experimentally and numerically. Chandra & Matuska (2020) has analysed the mixing number and Richardson number for different flow rates, also the perforated obstacles have been numerically studied to improve stratification in the tank as in (Feng et al., 2022). The turbulent mixing between the cold water and hot water in the HWST has been attached by a movable disk (Lee et al., 2020) which separates the hot water from the cold water in HWST. Malec et al. (2021) made a numerical model for various cold water inlet scenarios straight horizontal inlet, upward elbow, downward elbow, upward elbow with a plate, down word elbow with a plate, also elbows with double plate have been investigated in the presence of two partitions to reach minimum mixing number and good thermal stratification in the HWST. Paing (2022) used baffles to study mixing nature numerically and experimentally, he concluded that even at higher flow rates using a single horizontal baffle can prevent the mixing and keep thermal stratification distribution in the HWST. Beithou et al. (2011) and Beithou (2015) analysed the insertion of a semi-dome cover on the cold water supply of the HWST, while highly stratified nature was achieved, and minimum mixing between the cold and hot water was observed. Maximum amount of hot water from the HWST was collected which indicates the maximum usage efficiency of the tank. The finned type electrical heater was capable of accelerating the heating process of the TT layer. As these HWSTs are used in district heating systems (Yang & Svendsen, 2020) and central heating technology (Li et al., 2020). The speed of heating is a high concern, to accelerate the heating process of the tank top temperature to able to use the HWST hot water in a short time. A chimney type storage tank was proposed (Beithou et al., 2024). The aim of this work is a chimney investigate to cover the heating element of the electrically heated HWST. This chimney will assist in heating a small amount of water (contained inside the chimney), that will rise up to the upper layer of water by natural convection.

MATERIALS AND METHODS

Experimental setup

An experimental test rig was built to investigate the dynamic behaviour of the chimney type heater (CTH). The test rig consists of an insulated hot storage tank (HST), with a 2 kW electrical heater. The electrical heater is covered with insulated chimney. Eight thermocouples are inserted to collect the temperatures inside and outside the chimney. The thermocouples are attached to a data logger which is in turn connected to a PC to record the temperature with time. To control the water flow rate the test rig is connected to a cold-water supply. The cold-water supply is attached with a flowmeter to measure the water flow rates (Figure 1). The hot water inside the HWST is supplied with different cold-water flow rates from 0.1 L/min to 3 L/min (Table 1). The effect of these flow rates on the hot water supply temperatures was investigated.

Methodology

To study the chimney type heater of HWST performance under the dynamic mode, the 75 L tank was filled to a 63 cm, and chimney height was 56 cm. Three-inch and two-inch diameter chimneys were tested. The thermocouples were connected to the data acquisition system to record temperatures with time (Table 2). The water in the tank was heated with the 2 kW electrical heater and the water flow rate adjusted to the various

Table 1. Technical dimensions and specifications

Part	Dimension
Tank inner height	63 cm
Tank inner diameter	39 cm
Chimney height	56 cm
Heater height	25 cm
Chimney inner diameter	3″, 2″
Chimney contact diameters	1.5 cm
Heater power	2 kW

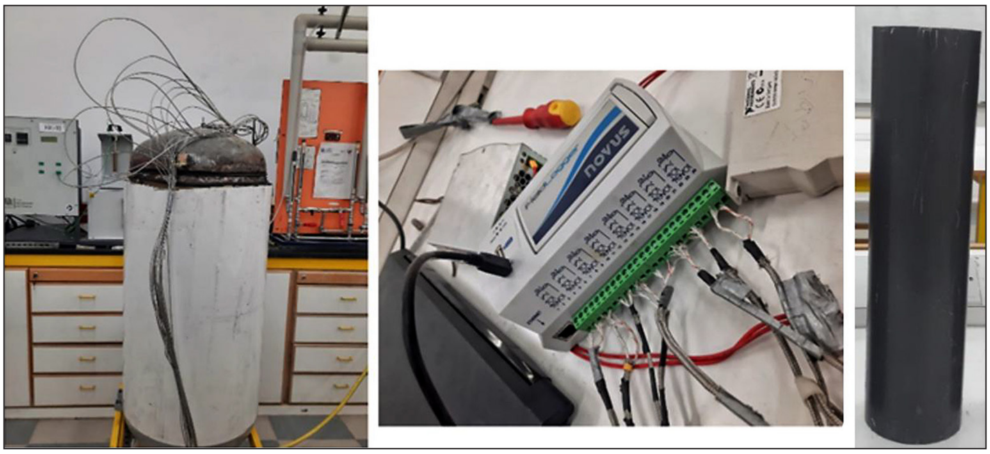


Figure 1. Experimental test rig, data logger and chimney used in the laboratory

Table 2. The thermocouple's location in the hot water storage tank

Thermocouple # (center, side)	Thermocouple location from HWST base (cm)
T1, T5	2
T2, T6	12
T3, T7	42
T4, T8	62

flow rates (from 0.1 to 3 L/min). The system run until steady state in one case and with a fixed period (10 min) for the other case.

Theory and validation

To analyse the HWST performance conservation of mass and conservation of energy have been considered. The HWST is a steady flow device where the mass inside the tank is constant:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

where: $\dot{m}_i$ is the mass flow rate entering the HWST, and $\dot{m}_e$ is the mass flow rate leaving the HWST.

The energy conservation of the steady flow device HWST is:

$$Q - W + \sum E_e - \sum E_i = \sum \Delta E_{CV} \tag{2}$$

where: Q – heat [J], W – work [J], E – energy [J].

$$\sum E_i = \left(\dot{m}_i \cdot C_i\, T_i + \dot{Q}_{Elec}\right) \cdot \Delta t \tag{3}$$

where: $\dot{Q}_{Elec}$ = 2000 W electrical heater with a length 25 cm as shown in Table 1, C_i is the heat capacitance of the cold water entering the tank [J/kg K], T – temperature [K], and Δt is the flowing period [s].

The exit energy is calculated as:

$$\sum E_e = (\dot{m}_e \cdot C_e\, T_e + \dot{Q}_{Loss}) \cdot \Delta t \tag{4}$$

where: C_e is the heat capacitance of the hot water leaving the tank [J/kg K].

To find $\dot{Q}_{Loss}$, the thermal resistance of the tank is:

$$\dot{Q}_{Loss} = \frac{\Delta T}{R} = \frac{T_{av} - T_{amb}}{R} \tag{5}$$

$$R = \frac{\Delta x}{k\, A} = 0.0192 \text{ K/W}$$

where: T_{av} is the HWST water average temperature, and T_{amb} is the ambient temperature.

To verify the results obtained in this study, the experimental results were compared with the theoretically calculated values from the conservation laws. Figure 2 shows the accuracy of the experimental data and the efficiency of the HWST.

The water in the HWST has been divided into two parts the water in the chimney and the water outside the chimney. The total energy of the water has been calculated over the period of the experiment and compared to the values obtained from the energy of conservation (Equation 2), left hand side of the equation were compared to the right-hand side, and the accuracy of the experimental results were calculated. An accuracy of 0.9 to 0.96 were recorded, at the start of the experiments the change in temperatures is high which affected the accuracy of the results, good accuracy of the experimental results was recorded at about 0.905, as the temperature increased in the tank and the change in the values gets more stabilized the

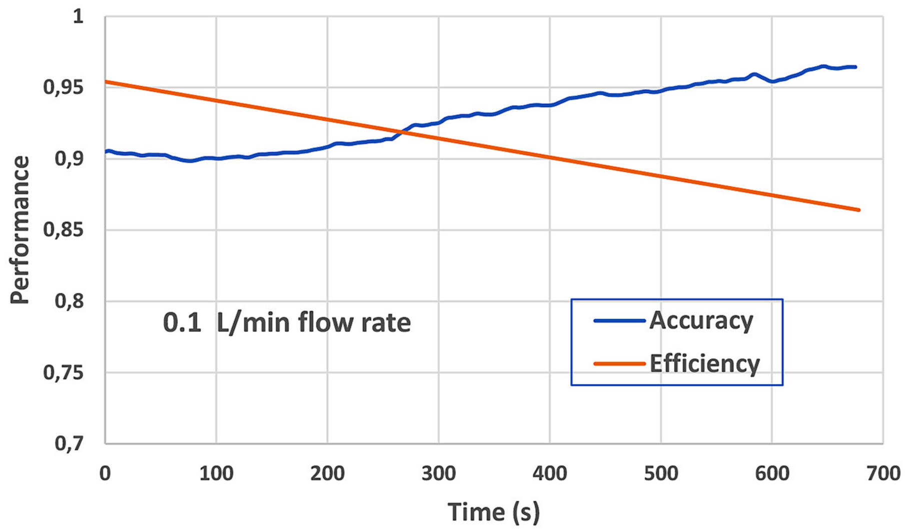


Figure 2. Accuracy of the experimental data and the efficiency of the hot water storage tank

accuracy increases to 0.964. The efficiency of the HWST was also investigated to validate the system experimental data, as shown in Figure 2, the efficiency of the HWST which depends on heat losses mainly varies between 0.96 to 0.86 due to the increase in the water temperature thus increase in heat losses to the outside as expected.

Results

The HWST performance has been investigated under dynamic mode for both 3 in and 2 in chimneys under variable flow rates (0.1 to 3 L/min), The HWST temperatures were recorded at different heights (2 to 62 cm). Even though all temperatures of the tank were recorded for energy balance and tank performance analyses, the water storage tank top layer temperature was the main target as it represents the tank supply temperature. As a first step the HWST dynamic mode was compared to static mode without and with chimneys, the tank top temperatures versus time are ploted in Figure 3.

Figure 3 shows the TTT versus time when the tank is used without a chimney, with 3 in the chimney, with 2 in the chimney and dynamic mode. It is clear from Figure 3 that using the tank without a chimney gives the lowest TTT and thus needs a long time to get hot water for use, whereas tank top temperature was improved using the 3″ chimney and better in the 2″ chimney case. The dynamic mode case for 3 in the chimney and 0.1 L/min flow rate is also shown in the figure and shows that TTT is much better

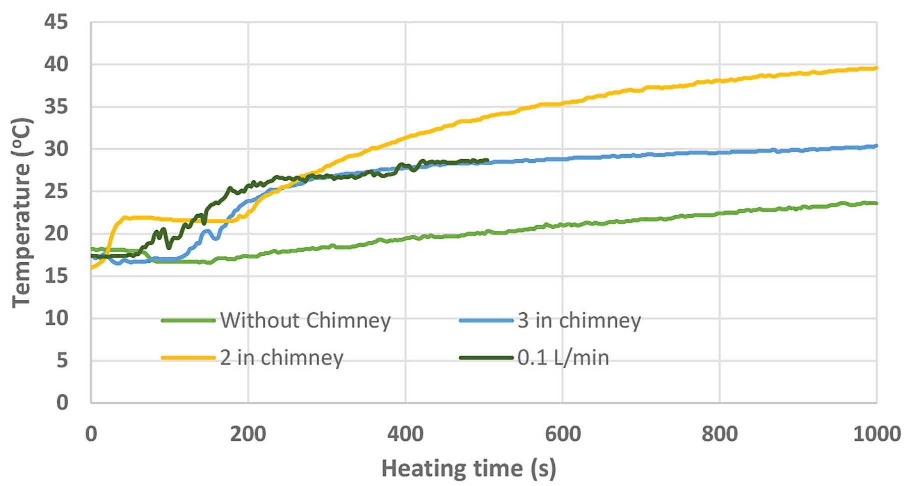


Figure 3. Tank top temperatures versus time (75 L tank)

than that without a chimney. The 3″ chimney type HWST dynamic behaviour has been investigated under variable flow rates from 0.1 l/min to 1.2 l/min. The temperature time behaviour is shown in Figure 4, where Tc is the temperature in the chimney, and To the temperature outside the chimney.

When the experiment is executed the temperature inside the chimney starts increasing rapidly and increases the TTT outside the chimney as both convection and displacement of water. In a short time, the TTT reaches 29 °C, which is a 12 °C supply temperature jump in 45 s, and then continues increasing with time, which means that the heating power is capable of supplying this flow rate with the recorded temperature. Applying the energy balance to the chimney only:

$$-\dot{W} \cdot \Delta t + \sum(\dot{E}_e - \dot{E}_i)\Delta t = = \frac{\pi D_i^2}{4} \cdot h \cdot 1000 \cdot C \cdot \Delta T \quad (6)$$

where: D – diameter [m], h – height [m], C – specific heat [J/kg K], ΔT – temperature change [K].

Substituting the values in the above equation an average ΔT = 1.7 °C is expected. This means that the heater can heat more water flow. The results for the other flow rates are indicated in Figure 4. It can be noted that the tank bottom temperature is kept unaffected at a low temperature, thermal stratification in the tank is well-suited. To understand the effect of the flow rate on the temperature change with

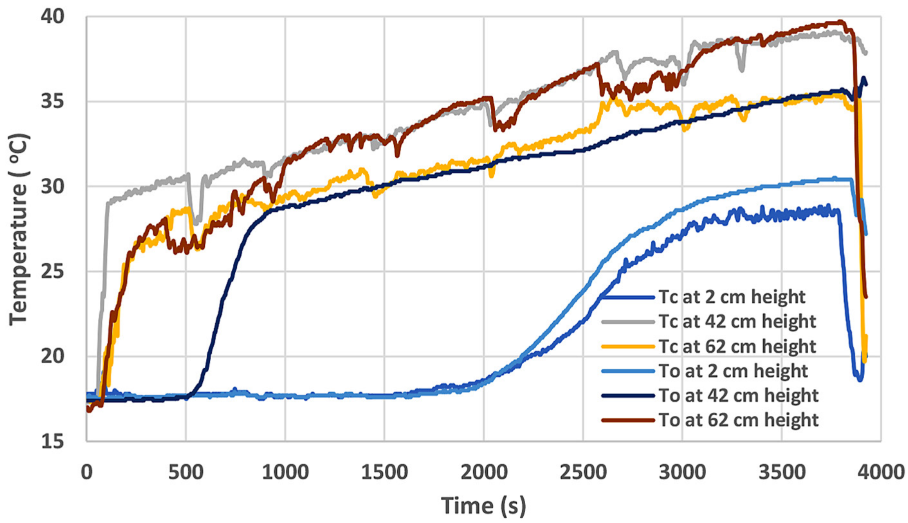


Figure 4. Temperature and time behaviour of 3″ chimney, 75 L tank (0.1, 0.45, 0.6, 0.8, 1.0, and 1.2 L/min)

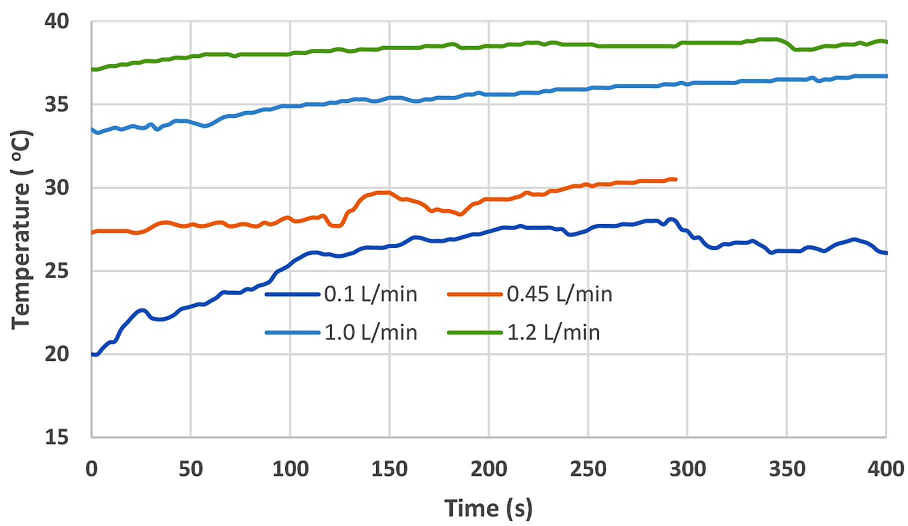
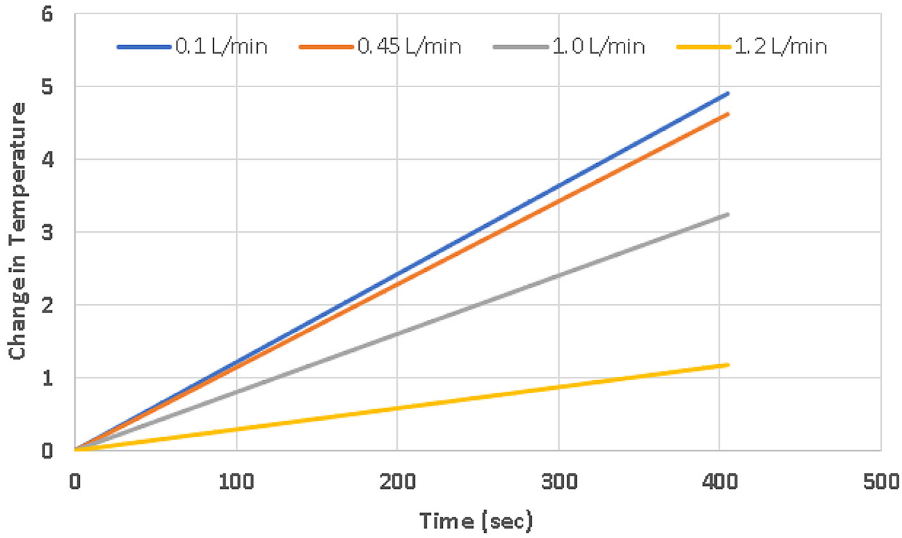


Figure 5. Temperature and time behaviour for each flow rate (3″ chimney, 75 L tank)



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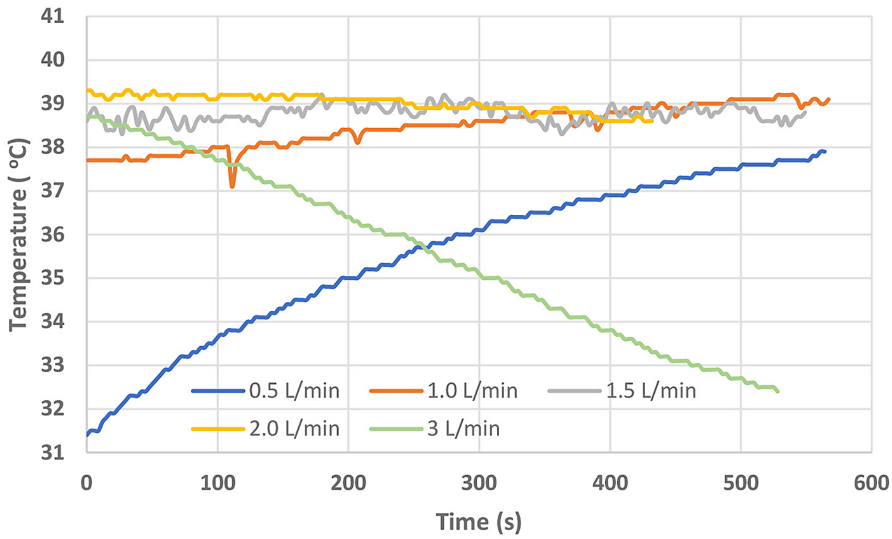

Figure 7. Temperature change versus time for various flow rates (2″ chimney, 75 L tank)

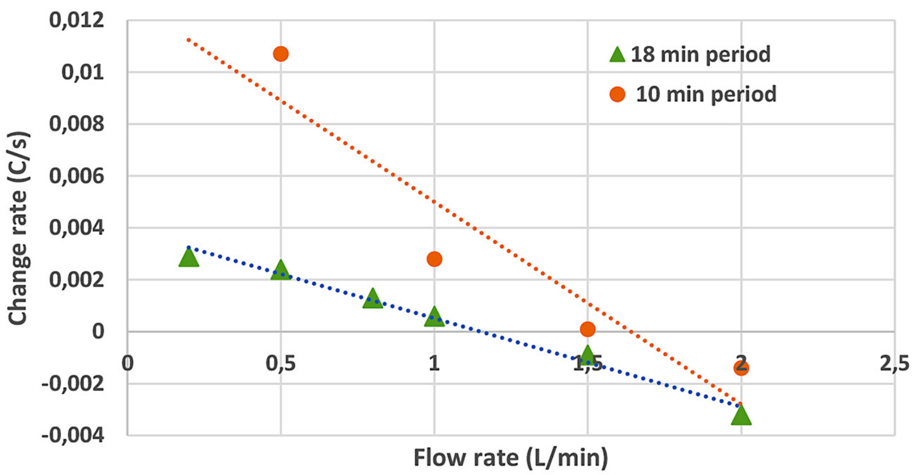

Figure 8. Temperature change versus time for various usage periods and flow rates (2″ chimney, 75 L tank)

time the temperature variation versus time plotted for various flow rates (Figure 5). It can be observed that temperature changes with increasing flow rate. Another point which is important, that the tank top temperature did not exceeds the 40 ^{o}C. The data from each flow rate were fitted linearly and the change of temperature was plotted (Figure 6).

From Figure 6 as the flow rate increases, temperature change decreases, but up to 1.2 l/min flow rate the temperature change in the 3″ chimney HWST is still positive. To improve the system more and achieve higher temperatures the 2″ chimney was tested. As shown in Figure 7, higher working temperatures have been achieved in a short time, when the water flow rate is low as in 0.5 l/min. A steep increase in water temperature is achieved, if the water flow rate increases over 1.5 l/min the temperature change start declining, higher heating loads will be required. Next to optimize the performance of the chimney type HWST under dynamic load different usage intervals have been tested at 18 minutes and 10 minutes, respectively. Figure 8 shows the change in temperature versus time to locate the suitable flow rate of each case. It can be concluded that the lower period, the higher the flow rate, that can be used.

CONCLUSIONS

In this research the performance of the hot water storage tank was improved by adding a chimney. Chimney-type HWST supplies hot water in a shorter time, has better thermal stratification, and better efficiency in solar collectors' storage tanks. Variable chimney diameters were tested (three-inch and two-inch) – the smaller the chimney diameter, the faster and higher hot TTT achieved. At low flow rates, the tank top temperature increases continuously whereas at high flow rates, the TTT starts to decrease. Safe flow rate gradients (positive temperature change) of 1.2 and 1.5 L/min were registered for 18 min and 10 min usage periods, respectively. The proposed chimney type HWST provides high thermal stratification tanks, with fast hot tank top temperature, thus reducing the energy used in heating water for certain processes.

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