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Enhancing Thermal Performance of Hot Storage Tanks Through Chimney-Type Electric Heating and Natural Circulation

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ABSTRACT

This study goes on the enhancement of thermal performance of a chimney type electrically heated hot storage tanks (HST) in static mode. The different natural circulation areas (chimney areas) were used with different diameter of large (9.5 cm), medium (2.5 cm) and small (1.5 cm) to find the effect of natural circulation on HST performance. Being part of real system, the performance of chimney insulated and without chimney insulation was also studied. The experiments showed that the chimney significantly affects the thermal stratification within the tank. Different chimney contact diameters (9.5 cm, 2.5 cm and 1.5 cm) were tested giving varying degrees of thermal stratification. It was found that the smaller chimney contact diameters led to higher thermal stratification that gives a more rapid heating of the top layer temperatures. The impact of insulation on thermal performance was inconclusive as top layer temperatures of the tank were still rising, showing the need of a more effective insulation as well as further investigation into the dynamic mode of operation. It is also noted that the top outer layer had the higher rate of temperature rising to the larger diameter, giving the sign of the importance of the chimney type electrical heater in the hot storage tank.

Keywords: hot storage tank, static mode, chimney electrical heater, natural circulation, thermal performance, optimization.

INTRODUCTION

Hot water storage tanks (HWSTs) are considered an important part of engineering systems. The category of HST could be divided into hot water storage tanks and hot salt storage tanks. HSTs are integrated into solar water heating systems, solar power systems, thermal power plants, heat pump systems and space heating or cooling systems [1]. In addition, HWSTs are used predominantly in residential buildings, hospitals, hotels, and factories [2, 3]. The impact of hot water heating systems is reflected in their high energy use, noting that, HWHS consumed approximately 26% of all energy used in Europe [4]. Therefore, HSTs are one of the mostly investigated topic by researchers [5]. Some of the important aspects of HSTs that have been studied are their operation in static and dynamic modes, types that can be either vertical or horizontal, heating sources including electric, gas, spiral jacket, or mantle, effect of insulation, and location of inlet and outlet ports.

The high energy consumption of HWHS has been noted, and efforts have been made to find solutions [6]. Gasque et al. [7] investigated the impact of the thermal conductivity of inner lining materials on the performance of HST during charging and standby periods. They analyzed temperature versus time curves at varying heights and concluded that materials with low conductivity are preferred as inner lining materials for improved energy savings in HST. Additionally, they found that weak conductivity materials are favoured as inner lining material for better energy saving in HST. The HSTs operate in both static and dynamic modes. Fernández-Seara et al. [8] studied the thermal behavior of HWST experimentally in static operation mode, with a HWST aspect ratio of 1.81. They analyzed the energy and exergy efficiencies with thermal stratification in the tank. The dynamic mode performance of HWST, which is of higher concern in operation, has been studied by many researchers.

Hepbasli [9] performed exergetic modeling for a solar-assisted HWST with a ground-source heat pump for use in underfloor heating systems, analyzing the heat stored in the HWST. Abdelhak et al. [10] analyzed the thermal stratification evolution during charging and discharging of horizontal and vertical HWSTs using Fluent V6.3 with different parameters. They analyzed discharge efficiency, Richardson number, and stratification number, concluding on the low performance parameters of the horizontal tank. Furthermore, the dynamic mode of the HWST with a built-in heating coil was studied by Yang et al. [11] to ensure a correct design for special use, emphasizing the avoidance of oversizing and under-sizing of valves. Ievers and Lin [12] investigated the return loop on thermal stratification, concluding that a low return rate is preferable. Gao et al. [13] numerically studied the mixing characteristics inside the HWST for different fluid inlet velocities, using the entertainment factor as an indicator of the mixing effects. Additionally, González-Altozano et al. [14] proposed a multi-tank domestic HW solar plant as a solution for stratification, emphasizing the importance of stratification on solar collector efficiency. Fan et al. [15] developed a program to predict thermal stratification under different inlet conditions.

Phase change materials (PCM) have been experimentally tested within the HWST to intensify the energy stored in the system and maintain thermal stratification. Nkwetta et al. [16] examined the application of PCM in HST to increase energy storage and reduce space. Padovan and Manzan [17] also analyzed the potential of the PCM and its location for raising the quantity of energy that can be stored in the storage tank. Heat losses that occur at HST play a significant role in saving tank thermal distribution. Influence of HST heat losses on thermal stratification was conducted by Fan and Furbo [18] through CFD testing. The researchers applied variations in tank volume, height to diameter ratio, insulation and initial conditions. They concluded that side losses from 20% to 55% are generated by natural convection in the tank and proposed the removal factor of heat loss.

Fan and Furbo [19] analyzed the influence of buoyancy driven by heat losses on thermal stratification. Additionally, researchers have analyzed various types of HSTs available in the market to assess their performance, including the analysis of horizontally oriented HSTs. Helwa et al. [20] examined the impact of water consumption on the temperature distribution of a horizontal storage tank and recommended the provision of an electrical heater to meet the required load. Jannatabadi and Taherian [21] studied horizontal tanks, where heat transfer to the tank was achieved through a mantle around 90 cm of the 110 cm long tank. They analyzed the effects of water consumption on the thermal stratification within the tank and found that turbulent mixing or short-circuiting of the cold water impaired the thermal stratification. Reindl et al. [22] investigated the spiral-jacketed HST and suggested that this type is suitable for small-sized HWST. Mantle type HSTs have garnered significant attention from researchers. Kenjo et al. [23] developed a numerical model for the HST and proposed a zonal model to analyze the system with variable performance parameters, including the mixing coefficient.

Dehghan and Barzegar [24] performed numerical analysis on HST performance using a mantle type with different Grashof, Richardson, and Reynolds numbers. They noted that high Grashof numbers resulted in deeper fluid penetration through the tank, causing a mix-and-disrupt nature that destroyed the thermal stratification. Additionally, they also noted the suitability of low Reynolds numbers in having good thermal stratification in the tank. A mantle type of Reynolds number study was also done by Arslan and Igci [25] who also had a similar conclusion with Dehghan and Barzegar. These studies show a variation in HST tank thermal stratification where, from the current literature, the inlet port configuration and location were observed as influencing factors. As a follow-up note after these observations, different industrial and academic sectors had an interest in the exploration of the inlet port inlet configurations and location. Moncho-Esteve et al. [26] came up with a simple elbow structure facing downward, whereas Beithou [27] explored the use of a modified electrical heated HWST. The use of a small spherical segment, which was likened to a coffee saucer on the cold-water inlet provides resultant turbulence in thermal stratification.

There are other researches that investigated a water deflector from a side supply of cold water. Issa and Kodah [28] used an obstacle to harass the stratification inside the tank. They studied the ratio of obstacle height to tank height (*f/H*) and the ratio of obstacle diameter to tank diameter (*g*/*D*). They said that the larger the ratio of *f/H*, the less hot water is used. They also mentioned that the larger ratio of *g*/*D* is better, as the natural circulation inside the tank will be restricted in small ratio of *g*/*D*. Andrews [29] later proposed a moving baffle to separate the hot water zone from the cold-water zone. This baffle works by simple buoyancy; it floats on cold water and sinks into hot water. Li and Sumathy [30] tested a partitioned HWST for a solar absorption system to achieve higher cooling loads. In this system, the upper part of the tank is used in the morning, and the rest of the tank is used in the afternoon. García-Marí et al. [31] studied three cases for improving thermal stratification in HWST: partitions, thermal diodes, and a coiled heat exchanger using ANSYS. They predicted an improvement in thermal stratification efficiency between 30 and 60% throughout the year. The most convenient design for the researchers is two partitions and each of them has four diodes. These thermal diodes were proposed by Rhee et al. [32] and they were experimentally tested for this work. They improved the thermal stratification by carrying hot water to the top of the tank and the cold water to the rest of the tank. Wang et al. [33] later proposed a novel inlet, the boxed equalizer structure, which carries the cold water supplied to the HWST distributed to the bottom layer of the tank without a disturbance to hot water.

This research article studies the chimney-type electrically heated HWST's operation in static mode. The aim is to improve the heated water's upward movement to the upper layer of the tank and simultaneously ensure that the bottom layer's temperature is at its lowest. The simplicity of this novel proposition makes it affordable, reduces mixing, and ultimately reaches high-temperature upper layers in a short amount of time. This reduces the heating time needed for boiling water, which in turn saves energy. The experimental setup was implemented in the lab with different types of sensors and a data acquisition system to test different heating contact areas with and without insulators.

METHODOLOGY AND EXPERIMENTAL TEST

To examine the HWST with static mode of operation, a hot storage tank was equipped with thermocouples inside and outside the chimney. The chimney was designed with a specific height and heat transfer contact diameter, and it was positioned over the electrical heater as depicted in Figure 1. The system was connected to a data logger t to a data logger to capture the thermocouple temperatures.The static operation mode of the HWST was tested without the chimney to establish reference data for comparison. With the 2 kW electrical heater activated, time and thermocouple readings were recorded until the top sensor temperature reached 60 °C. Subsequently, the chimney, with the appropriate height and contact diameter (as detailed in Table 1), was positioned over the electrical heater, and data was collected while the heater was in operation.

It is important to note that the thermocouples were arranged such that one column was placed inside the chimney and the other outside as depicted in Figure 2. Various contact diameters (large 9.5 cm, medium 2.5 cm, and small 1.5 cm) were utilized, and the time-temperature data was recorded. The chimney was then tested with insulation to observe the impact of insulation o on the thermal performance of the system. The results were assessed using different performance parameters.

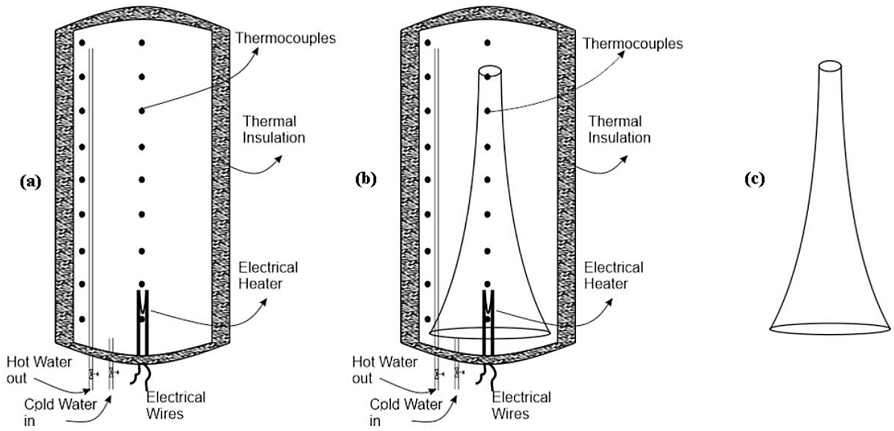

Figure 1. Schematic of the original tank (a), the modified tank (b) and chimney (c)

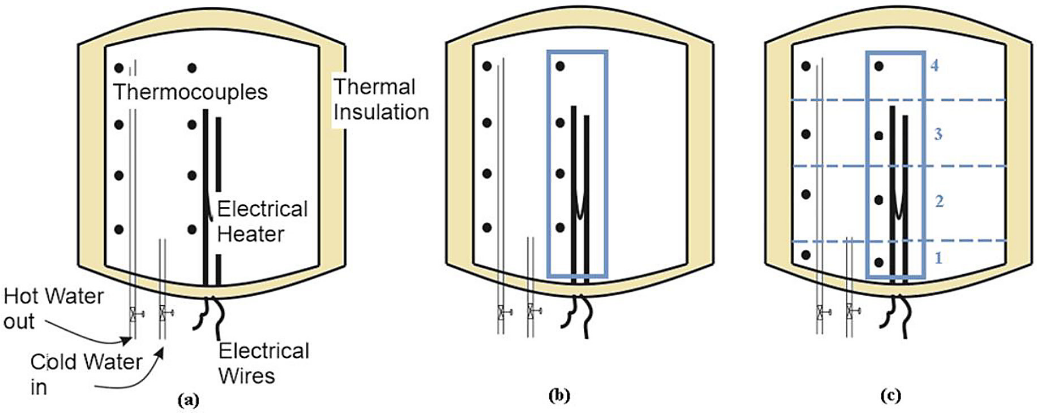

Figure 2. Schematic of the experimental tank (a), empty tank (b)modified with chimney and (c) control volumes of the water in the tank

Table 1. Technical dimensions and specifications

Parameter	Value
Tank inner height	34 cm
Tank inner diameter	39 cm
Chimney height	26 cm
Heater height	25 cm
Chimney inner diameter	9.5 cm
Chimney contact diameters	9.5, 2.5, and 1.5 cm
Heater power	2 kW

Performance analysis

In order to analyze the performance of the HST, the governing equations are applied for each control volume throughout the HWST cylinder. The cylinder volume is subdivided into sub-control volumes for the HWST with a chimney. When considering the control volume depicted in Figure 3, the energy equations are formulated. The energy conservation equation is applied to every node within the control volume illustrated in Figure 2c and Figure 3 as follows:

$$\sum_{i=1}^{n} m * C * \frac{d\,T_i}{dt} = Q_{in} - Q_{out} - Q_{Loss} + Q_{gen} \quad (1)$$

where: i – the node number, n – the total control volumes in the tank, m – the mass of water in the control volume, C – the heat capacity of water, dTi/dt – the temperature variation of node i with time t, Q_{in} – the heat entering the control volume between the two water layers, Q_{out} – the heat leaving the control volume between the two water layers, Q_{Loss} – the heat losses from the sides of the surrounding surface area of the control volume, Q_{gen} – the heat generated within the control volume.

$$\sum_{i=1}^{n} m * C * \frac{d\,T_i}{dt} = U_{ws}A_{ws}(T_{i-1} - T_i) - U_{ws}A_{ws}(T_i - T_{i+1}) - U_{Ts}A_{Ts}(T_i - T_o) + \frac{\Delta L_e}{L_e} Q_{gen} \quad (2)$$

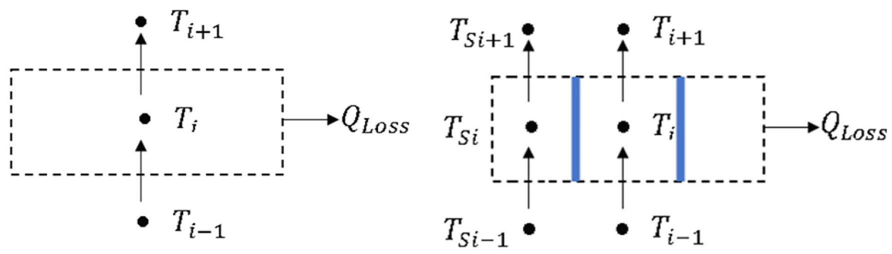

Figure 3. The control volumes of the water in the tank

The formula used to evaluate the heat transfer coefficient between the stagnant water layers is as follows:

$$h = \frac{C_t}{2^{4/3}} k \left(\frac{g\,\beta\,(T_i - T_{i+1})}{\nu\,\alpha} \right)^{1/3} \quad (3)$$

where: $C_t = 0.13$ for water.

As the water temperature within the tank remains below 80 °C, the variations in the physical properties are relatively minor. These estimated values are provided in Table 2.

The heat transfer coefficient between the layers can be determined using Eq. 3. Additionally, the heat transfer from the sides of the control volume can be calculated theoretically based on the properties of the tank material, dimensions, and insulation, or estimated from practical experimental tests.

The tank was allowed to cool down to assess its heat transfer resistance. The data for the cooling process of the water tank was fitted with time and the results are as follows:

$$T(t) = -0.0005 * t + T_{ini} \quad (4)$$

where: T_{ini} – represents the initial water temperature.

The accuracy of the fitted equation is determined as follows:

$$R^2 = 1 - \frac{\sum (T - T_{eq})^2}{\sum (T - T_{av})^2} \quad (5)$$

In this study, the value of R^2 is 0.978. Using Eq. 3, the heat transfer coefficient between the water layers was computed to be approximately $h \approx 9.55$ W/m^{2}K. Furthermore, employing Eq. 4, the thermal resistance of the tank is determined to be $R = \Delta x / kA = 0.0192$ K/W.

The experimental data was compared to the theoretical model and was observed to be highly consistent, as depicted in Figure 4. The performance of the HWST is assessed by employing the formula for the thermal stratification of the tank.

$$ST(n) = \frac{\sum_i^n (T_{i+1} - T_i)}{(T_{max} - T_{ini})} \quad (6)$$

As illustrated in Figure 5, the method employed enhances the thermal stratification within the tank, resulting in improved performance for solar systems and heat transfer.

EXPERIMENTAL RESULTS AND DISCUSSION

To investigate the effect of using chimney type electrical heater in the HWST, different experiments were conducted. The tank, with dimensions provided in Table 1, was initially tested without a chimney to establish reference data for comparison. Subsequently, different chimneys with varying contact area diameters (D = 9.5 cm)

Table 2. Water properties utilized in the assessment [34]

Property	Formula	Approximate value
Density (kg/m^3)	$\rho = -3.0115 \cdot 10^{-6}T^3 + 9.6272 \cdot 10^{-4}T^2 - 0.11052T + 1022.4$	994 kg/m^3
Diffusivity (m^2/s)	$\alpha = k/(\rho \cdot C_p)$	0.14558 mm^2/s
Thermal conductivity, W/(m·K)	$k = 4.2365 \cdot 10^{-9}T^3 - 1.1440 \cdot 10^{-5}T^2 + 7.1959 \cdot 10^{-3}T - 0.63262$	0.607 W/m·K
Heat capacity, kJ/(kg·K)	$C_p = 1.7850 \cdot 10^{-7}T^3 - 1.9149 \cdot 10^{-4}T^2 + 6.7953 \cdot 10^{-2}T - 3.7559$	4.182 kJ/kg·K
Viscosity (Pa·s)	$\mu = 3.8208 \cdot 10^{-2} \cdot (T - 252.33)^{-1}, \nu = \mu/\rho$	0.738 mm^2/s
Thermal expansion coefficient	$\beta = \Delta V/(V_o \cdot \Delta T)$	0.000345/K
Prandtl number, Pr	$Pr = -0.28661 + 276.20 \cdot (T - 253.31)^{-1}, 280\ K < T < 600\ K$	7

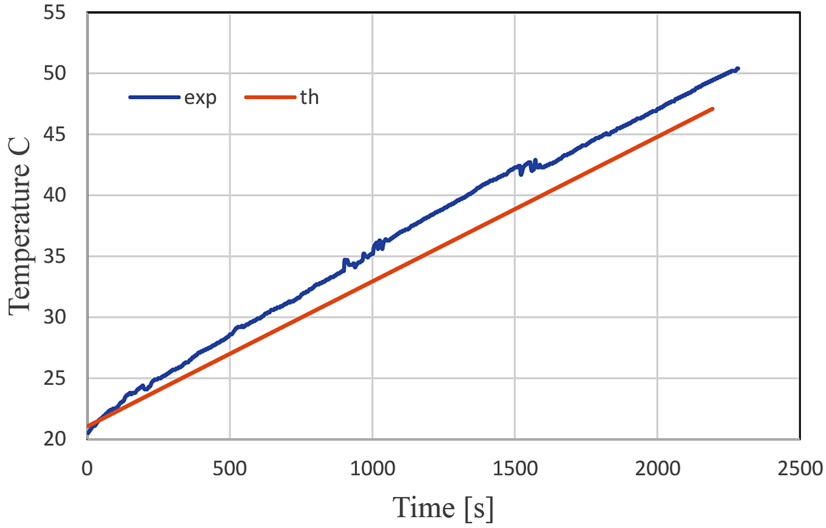

Figure 4. Time versus temperature from experiment and simulation

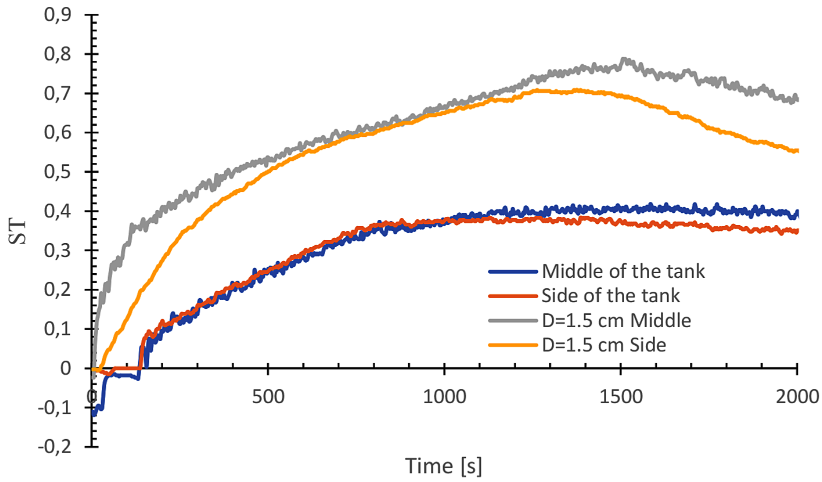

Figure 5. Thermal stratification of the water in the tank

were utilized (*D* = fully open, *D* = 2.5 cm, and *D* = 1.5 cm), and the effect of insulation was also examined through the experiments. The HWST was equipped with a data acquisition system to gather temperatures over time. Four thermocouples were positioned near the center of the near to the electrical heaters, while another four thermocouples were situated outside near the cylinder wall. The thermocouples are positioned at four specific locations within the tank to measure water temperatures. These locations are 2 cm from the bottom of the tank to measure the lowest water temperature, and then at 12 cm, 22 cm, and 32 cm to measure the temperature of the upper water layers, as illustrated in Figure 2. Figure 6 illustrates the performance of the heat storage tank (HST) without a chimney. The temperature readings from the four levels of thermocouples show minimal variation, indicating a low level of thermal stratification. The centered thermocouples and the outside thermocouples display nearly identical temperatures. To observe the impact of inserting a chimney with a diameter of *D* = 9.5 cm, the chimney was fully open to contact with the top layer of the tank. The temperature-time graphs are presented in Figure 7 and compared to those in Figure 6.

As observed in Figure 7, the thermal stratification within the chimney (center TC) is significantly greater than that for the standard configuration. The outer TC experiences lower thermal stratification due to the additional energy utilized in the chimney. The top two thermocouples exhibit higher temperatures and are closer to each other. This is attributed to the reduced heat transfer to the adjacent water layer, which is separated by the chimney. Figure 7 depicts a slight change in thermal stratification, resulting in a reduction in the contact area between the chimney water and the top layer to a 2.5 cm diameter. The result of this investigation is presented in Figure 8, which illustrates a larger area between thermocouples 1-4 and 5-8, indicating higher thermal stratification. This test yielded higher top layer temperatures compared to those of *D* =

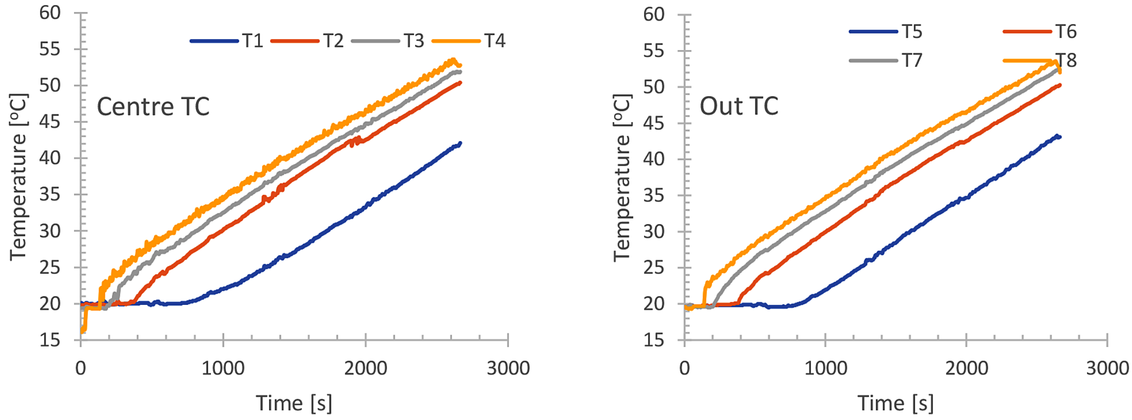

Figure 6. Temperature versus time for the centered and outside thermocouples, tank under standard operation (without chimney)

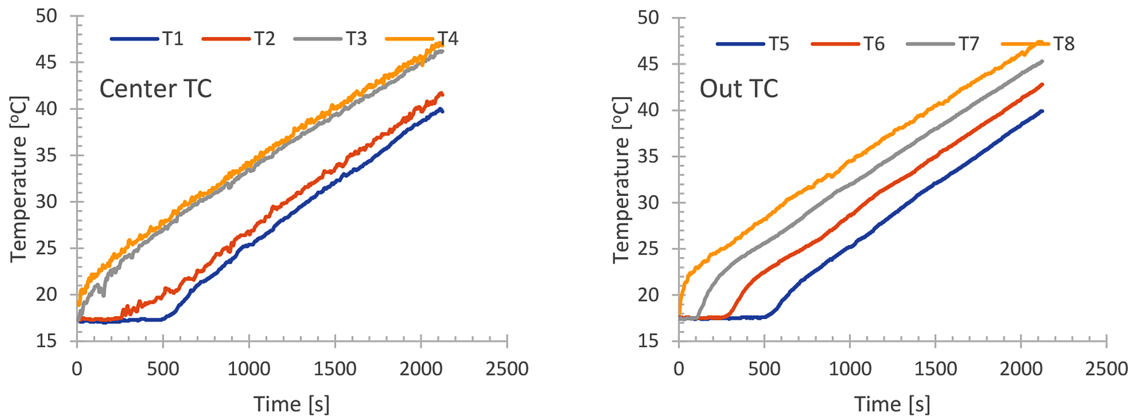

Figure 7. Temperature versus time for the centered and outside thermocouples, tank with 9.5 cm diameter chimney (without insulation)

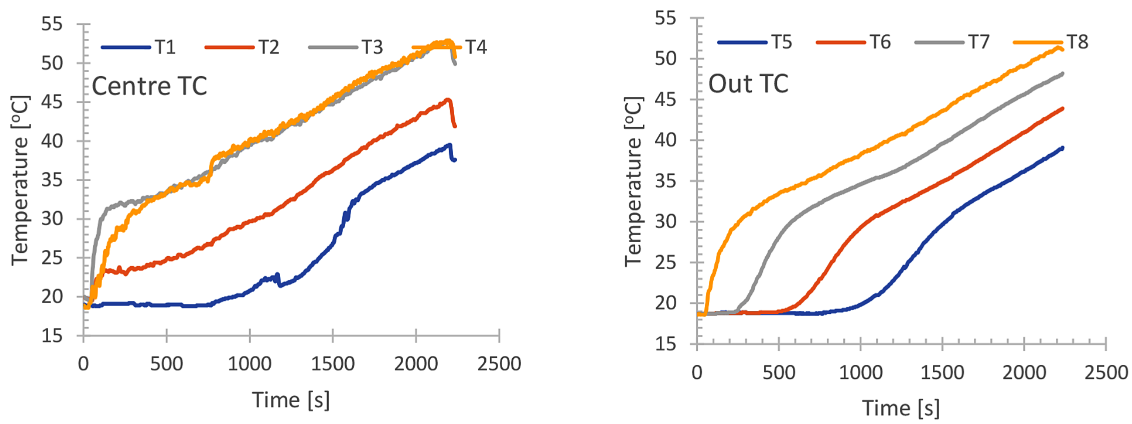

Figure 8. Temperature versus time for the centered and outside thermocouples, tank with 2.5 cm diameter chimney (without insulation)

9.5 cm, and a more rapid heating of the top layer temperatures. The outcomes depicted in Figure 8 prompt a query: Can the top surface temperature be increased even further and more rapidly? To address this, an experiment was conducted using a chimney with a contact area diameter of D = 1.5 cm, and the results are displayed in Figure 9. As expected, higher temperatures were attained in the top layer, resulting in a larger area between the thermocouples (indicating higher thermal

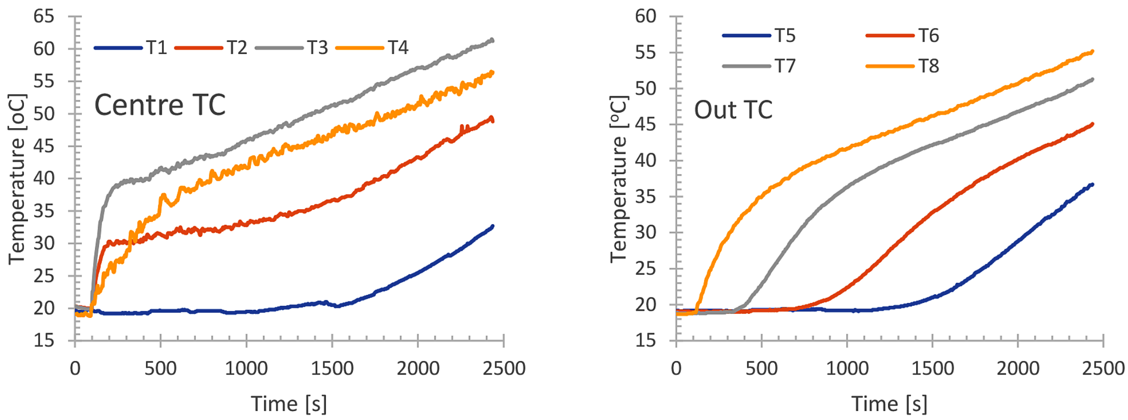

Figure 9. Temperature versus time for the centered and outside thermocouples, tank with 1.5 cm diameter chimney (without insulation)

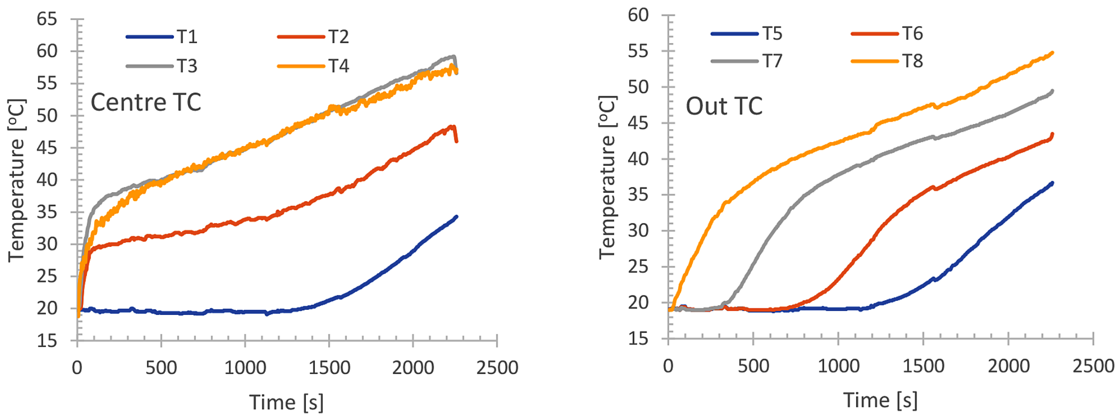

Figure 10. Temperature versus time for the centered and outside thermocouples, tank with 1.5 cm diameter chimney (with insulation)

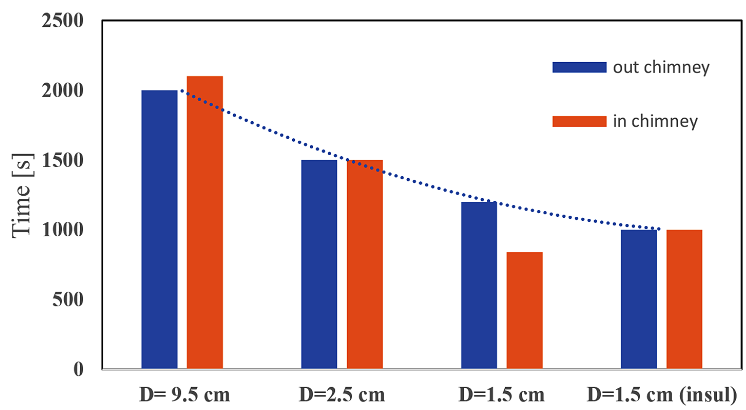

Figure 11. Time consumed to heat the outer layer to 45 °C for the various diameter's chimneys

stratification). Figure 9 illustrates that the temperature of thermocouple T3 is higher than T4, indicating that the rapid natural heat transfer in this scenario was not adequate. This observation may suggest a transition from the static mode to the dynamic mode of operation. Figure 10 presents the outcomes of enhancing the insulation of the utilized chimney and its impact on the temperature distribution of the HWST. The insulation did not appear to have a significant impact, which could be attributed to the use of a potentially ineffective or weak insulation material. More effective insulation should be employed to accurately assess its impact. Despite this, the thermal stratification remains high, suggesting the need to further investigate the impact of increased insulation and flow rate in a dynamic model. Figure 11 illustrates the time required to heat the outer layer and the top chimney layer to 45 °C for various chimney diameters. It is evident from the figure that the top outer layer heats up much faster, taking almost half the time of the larger diameter. These results underscore the significance of this application.

CONCLUSIONS

The impact of different chimney contact diameters and insulation on the thermal performance was investigated. It has been observed that the chimney-type electrical heater with a 1.5 cm diameter contact area with the top layer significantly accelerates the heating of the water compared to the standard HST. This results in higher temperatures in the top layer and an increase in thermal stratification throughout both zones of the tank (chimney inner and outer zones). This study suggests a more comprehensive investigation of the chimney-type electrical heater in a dynamic mode to maximize usable energy and potentially use the design as a rapid heating solution. More effective insulation should be considered to accurately assess its impact on thermal performance.

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