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Micro-article

Numerical approach and experimental investigation of a stratified hot water storage tank for domestic hot water production

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ABSTRACT

Thermal stratification within storage tanks plays a critical role in the efficiency of thermal energy storage systems. In this paper, one-dimensional numerical model of a stratified storage tank is developed to simulate the thermal stratification process within a storage tank during the charging and the discharging processes, capturing the temperature distribution inside the storage tank over time. This work investigates the evolution and transient behavior of stratified flows during the heating and cooling process within sensible-heat energy storage systems under Re_D=167 and Re_D=616 for heating process. For that purpose, an experimental campaign was performed in an instrumented water storage tank to measure the stratification process when a hot water round jet was injected into a slender cylindrical tank filled with an initially uniform hydrostatic water field stabilized at a lower temperature. This information was used to develop a simple 1D model able to be applied during long-term charging/discharging transients of these kind of systems. The 1D model developed was validated against the experiments performed following prototypical charging/discharging tests according to the standard EN16147 and can be used to describe the energy performance of this kind of systems during long-term charging/discharging sequences. The present model provides a reduction of about 5 % of the error of the time of the water cooling process with respect to other models in the literature.

1. Introduction

Thermal stratification is a fluid flow mechanism that promotes the formation of horizontal strata at different temperatures. This process occurs naturally in thermal storage tanks due to gravity and the buoyancy generated by the variation of the fluid density with temperature. The terms "cold region" and "hot region" in a stratified storage tank refer to these two distinct strata at various temperatures [1,2]. In thermal storage tanks, thermoclines prevent temperature mixing, which is an energy-saving benefit. Thermal stratification generally plays a major part in the production of domestic hot water because it may improve the system's overall performance in addition to the thermal and energy efficiency of the tank. In fact, as the stratification promotes the higher temperature levels at the top of the tank, where the demand outlet is located, the promotion of this mechanism permits to reduce the duty cycle of the heaters. This is of major importance as thermal energy used for heating space and water represents 78.4 % of the final energy consumed by households in the EU [EU, 2022]. Thermal energy used for heating space and water represents 78.4 % of the final energy consumed by households in EU [EU, 2022]. As residential sector represented 25.8 % of final energy consumption, this means that the thermal energy consumed by households represented over 20 % of the total final energy consumed in the EU in 2022. Thus, the proper characterization and promotion of the stratification in thermal energy storage tank is key to improve the energy efficiency of these systems. When the storage tank is at rest, stratification takes place. Once the liquid moves, the stratification gradually disappears until the temperature inside the storage tank becomes homogenous. There is not only the water instabilities that can destroy the thermal stratification within the storage tank, but also various parameters as the tank shape, the inlet and the outlet position, etc. [3]. Moreover, many researchers concentrate on how the stratification behaves inside the storage tank used to produce hot water for domestic purposes [4]. A summary of experimental and numerical investigations on Thermal Stratified Storage Tanks was provided by Saïf Ed-Dınş Fertahi [5]. Many parts of a stratified storage tank were emphasized, including the auxiliary heater, mechanisms with various geometries and designs to improve the stratification inside the storage tanks. Baffles, separators, and controlled variable jet intake are also

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some techniques utilized to improve the thermal stratification of the storage system [4,6]. A numerical study of laminar natural convection in horizontal cylindrical storage tanks was presented by Darci et al. [7]. They came to the conclusion that the presence of the baffle plate permits the production of temperature profiles with a better thermal stratification. They also concluded that the inlet jet at the top of the tank has an important role. A one-dimensional transient heat transport model of a storage tank was presented by Nelson et al. [8] for both static and dynamic modes, they examined geometrical characteristics such as length, diameter, and wall thickness of the storage tank. According to their findings, a lengthy storage tank is ideal for better thermal stratification, and the mixing phenomena causes thermal degradation to increase as the Peclet numbers increase. The same author conducted an experimental investigation resulting in the same outcomes under identical conditions [9]. Audrius et al. [10] investigated numerically the stratification phenomenon using CFD, they created a model of conjugate heat transfer in two phases natural convection. A theoretical and experimental investigation of a domestic CO_2 heat pump for space heating and domestic hot water generation was presented by Jørn Stene [11]. He demonstrated that, in order to reduce the mixing and the conductive heat transfer between the hot and cold water during the dynamic periods, a specific tank design is required. Rejane et al. [12] compared various models of hot water storage tank simulations, including one- and two-dimensional models. They also demonstrated the significance of introducing the entire phenomenon into the computational domain and came to the conclusion that the multi-node model is a more effective and efficient tool for the stratification analysis within storage tanks. Al-Najim et al. [13] predicted the temperature distribution within a stratified vertical storage tank by theoretically analyzing a mathematical model of the thermo-hydraulic dynamics inside the tank. They came to the conclusion that the presence of a convective heat-transfer boundary at the tank walls causes the temperature to have a radial variation, and that the turbulent mixing factor significantly affects the temperature distribution. For this reason, having well-insulated walls is essential to maintaining optimal storage performance. More recently, Ali H. Abdulkarim et al. [14] presented a novel geometry guide within the storage tank that has the advantage of enhancing the thermal stratification. Their results showed that the proposed conical guide inside the thermal storage system benefits in terms of improved thermal stratification. Adrian Riebel et al. [15] compared three thermal storage tank models for modelling the transient behavior of stratified storage tanks. Their results showed that the analytical model maintains its accuracy even in the case of larger time steps meanwhile, the numerical models exhibit comparable performance at small time steps. A.M. Jodeiri et al. [16] presented a numerical and experimental investigation of stratified water storage tanks based on a novel approach model. The approach is based on an improved adaptive-grid model. Their model examines the analysis of energy balance and mixing, adopts a spatial discretization technique for water diffusivity, and provides a lumped mixing factor that correctly replicates the complicated impacts of inlet jets mixing. Aowabin Rahman et al. [17] developed a 10-nodes model that considers heat transfer and a node-mixing model that represents buoyancy within the tank to create a one-dimensional transient model of a thermal storage tank. Furthermore, many researchers focused on the numerical analysis of stratified storage tank using one-dimensional numerical models and CFD [18–20]. Jesus Lago et al. [21] presented a one-dimensional numerical model of a stratified storage tank using a continuous function to identify the mixing and the buoyancy dynamic within the storage tank. Their results shows that the presented function for mixing, and buoyancy dynamic gives good results in comparison of real-time model. Freerk Klasing et al. [22] presented three distinct numerical models with varying levels of complexity and a FEM model to evaluate the thermal stress of a molten salt in thermal storage tank. They revealed that the critical tank diameter is considerably influenced by the hydrostatic pressure and temperature differential. And they also determined that while raising the working temperature, additional attention should be given to the selection of the right material when using molten salt in thermal storage tank. The literature has a number of stratified thermal storage tank models that simulate and evaluate heat transfer and hydrodynamic distribution inside the tanks. Charging/discharging transients of these kind of systems are of the order of hours or days. For characterizing these types of long-term transients' systems, CFD models are available but also simple models with low computational cost are required. In this paper a one-dimensional numerical model of a stratified storage tank is developed and analyzed. The numerical model is based on the finite difference method including the heat transfer behavior within the stratification layers and the heat transfer surrounding the outer surface of the stratified storage tank. There are several models available in the literature to analyze stratification in storage tanks. For example, TRNSYS presents some models that can be used in the analysis of the stratification in the charging and the discharging processes. However, the models presented by TRNSYS consider the heat transfer losses and the heat transfer coefficient as a constant input. Meanwhile the presented numerical model in this paper considers the variation of the thermophysical properties of the fluid in function of time and also the variation of the heat transfer coefficient and the heat losses in function of the local temperature and its evolution with time.

2. Numerical model

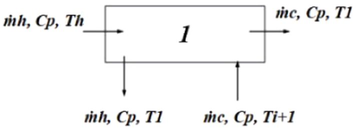
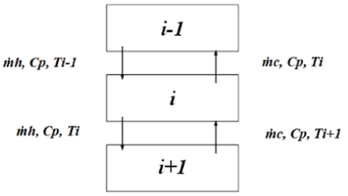
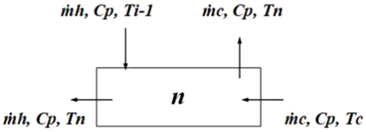
Stratification in storage tanks is frequently modelled numerically in order to optimize the tank design and measurements control. This numerical modelling aids in the development of thermal energy storage systems that are more dependable and efficient in terms of energy saving. A one-dimensional (1D) numerical model of the hot water storage tank was developed. The numerical model takes into account the convective and conductive heat transfer that occurs inside the tank's inner walls, the heat transfer between the tank's wall and the fluid, as well as the heat transfer between the fluid layers. The current numerical model is based on the finite difference approach. To account for the heat losses in the tank, free convective heat transfer between the surrounding air and the tank outside walls is also taken into consideration meanwhile, the thermal radiation is neglected in the presented model. The current model's hot-water storage tank is divided into N horizontal segments. The flow stream assumption is used in the model to support a high level of stratification. The model assumes that during the charging and discharging processes, the fluid streams at the inlet and outlet will uniformly mix the fluid inside each layer (node). Based on these hypotheses, the model considers a mass and energy balance between each layer and the walls. Table 1 presents the mass and energy equations that govern the fluid flow inside the hot water storage tank as well as the energy and the mass transfer between the stratification layers.

In the above equations, T_i is the water temperature of the node, the superscripts $j+1$ and j denote the time steps, $S_{i,w}$ is the wall surface of the tank in contact with the node i, T_w is the wall temperature in contact with that node. Cp is the specific heat of the water at constant pressure, k is thermal conductivity. Finally, $\dot{m}_h$, $\dot{m}_c$ are respectively hot and cold-water mass flow rates entering and leaving the hot-water storage tank. Note that in the model Cp and k are temperature dependent functions.

3. Experimental procedure

Two experimental processes have been performed in order to realize the heating process and the colling process of the hot water storage tank. During the tests, the experimental procedure provided by the standard EN16147 was followed [23]. This standard EN16147 specifies the test procedure to realize the tests under controlled operating conditions. The European Standard EN16147 is a standard that outlines the test procedures for evaluating the energy efficiency and overall performance of DHW systems that use heat pumps with electrically powered compressors. The test procedures for this standard consist of many stages. the stages considered for the characterization of the water heating process

Table 1
Fluid flow governing equations.

Node 1 (top node)		$m \cdot Cp\,\frac{\left(T_1^{j+1}-T_1^j\right)}{\Delta t}=h \cdot S_{1,w}\left(T_w^j-T_1^j\right)+k \cdot S_{1,i+1}\left(T_{i+1}^j-T_1^j\right)+\begin{cases}(\dot{m}_h-\dot{m}_c) \cdot \left(T_{i+1}^j-T_1^j\right), & \dot{m}_h \geq \dot{m}_c \\ (\dot{m}_c-\dot{m}_h) \cdot \left(T_h^j-T_1^j\right), & \dot{m}_h<\dot{m}_c\end{cases}$
Node 2 to n-1		$m \cdot Cp\,\frac{\left(T_i^{j+1}-T_i^j\right)}{\Delta t}=h \cdot S_{i,w}\left(T_w^j-T_i^j\right)+k \cdot S_{i,i+1}\left(T_{i+1}^j-T_i^j\right)+\begin{cases}(\dot{m}_h-\dot{m}_c) \cdot \left(T_{i+1}^j-T_1^j\right), & \dot{m}_h \geq \dot{m}_c \\ (\dot{m}_c-\dot{m}_h) \cdot \left(T_{i-1}^j-T_1^j\right), & \dot{m}_h<\dot{m}_c\end{cases}$
de n (bottom node)		$m \cdot Cp\,\frac{\left(T_i^{j+1}-T_i^j\right)}{\Delta t}=h \cdot S_{1,w}\left(T_w^j-T_1^j\right)+k \cdot S_{1,i+1}\left(T_{i+1}^j-T_1^j\right)+\begin{cases}(\dot{m}_h-\dot{m}_c) \cdot (T_c-T_n), & \dot{m}_h \geq \dot{m}_c \\ (\dot{m}_c-\dot{m}_h) \cdot (T_{i-1}-T_1), & \dot{m}_h<\dot{m}_c\end{cases}.$

and the water cooling process are as follow:

- Stage A: Stabilization
- Stage B: Fill the accumulation tank and prepare the test set-up.
- Stage C: Determination of the water heating time.
- Stage D: Determination of the water cooling time.

Stages A and B correspond to the test preparation. Stage A includes the time required for the instrumentation and the system to warm up. During stage B, the storage tank was filled with cold water at 10 °C.

In this study only two tests are taken into account in order to perform the experiments and validate the numerical model of the storage tank. The two steps considered are the water heating process (stage C) and the water cooling process (stage D). The heating process consists of heating the hot water storage tank that initially has a temperature of 10 °C until the temperature of the upper part reaches 60 °C. A preparation step just before the heating process is realized (stage A and stage B) and it consists of circulating the cold water in the storage tank until the temperature between the inlet and the outlet of the storage tank is 10±0.2 °C. Once this condition is reached the heating process begins. The cold water is taken out of the bottom of the tank, heated in the gas cooler, and then returned to the top part of the same tank to complete the heating process. In the other hand, the cooling process consists of cooling down the hot water storage tank that has an initial temperature of 60 °C and determine the cooling time till the temperature to the user decreases to 40 °C. The test facility considered to perform the tests of the heating, and the cooling process consists of a trans-critical CO_2 heat pump and a hot water storage tank of 720 liters with a height of 1.63 m and an internal diameter of 0 .95m. The hot water storage tank is the key element of this installation, and it instrumented with 10 RTD Pt-100 sensors (RTD Pt-100 class A 1/10 DIN ±0.1 K) sensors installed on its central axis (Fig. 1c) to analyze the stratification and the fluid flow behavior during the heating and the cooling process provided by the standard [24,25]. Actually, an extra cold-water tank stores water at 10 °C and it permits feeding the hot water storage tank. The tank is also equipped with valves, pumps, flowmeters, and temperature sensors to simulate the DHW consumption during the tests. This tank is connected to the gas cooler (condenser) of a heat pump. The cold-water storage tank is controlled through a three-way valve and a PID controller and it is also connected to the water chiller tank to maintain it always at a specific temperature of 10 °C. Table 2 presents the specifications of the measuring devices used in the experimental facility.

4. Results and discussion

In order to validate the numerical model of the stratified storage tank presented in this study, a comparison of the data obtained from the numerical model and the data obtained from the experimental facility of the stratified storage tank. The centroid of each section of the numerical model is aligned with one of the ten temperature sensors that are placed along the hot-water storage tank's central axis of the experimental facility. The Type4a and Type60 s models from the TRNSYS library are also taken into consideration when comparing the current model. In order to realize the numerical simulation and validate the presented model, the temperature of the water coming out from the gas cooler towards the inlet of the tank and the flowrate of the experimental results are introduced as input of the model. Reynolds number (Re_D) of the heating process based on the tank diameter is considered for typical experimental flow rates ranging from Re_D=167 and Re_D=616. The TRNSYS software is used as a tool to implement the present model and to carry out the transient numerical simulations of the experiments and compare the results of the TRNSYS library models (Type60 s, and Type4a) and the presented model (Type 269).

Fig. 2 shows the temperature evolution of the storage tank numerical models in comparison with the temperature of the experimental storage tank in function of time during the heating process in the case of Re_D=167 (Fig. 2a) and Re_D=616 (Fig. 2b). The temperatures (Top) and (Bottom) refer to the highest and the lowest part of the storage tank of each model. The TRNSYS library models (Type4a and Type60 s) and the actual model presented by our laboratory (Type269) show a good agreement with the experimental results in the case of Re_D=616. In the case of lower Re_D number Re_D=167, the temperature of the bottom part of the storage tank is slightly far away from the experimental results, and it takes a straight line in the numerical model while in the experimental results show an evolution of "step-shaped" temperature at this region of the storage tank. Fig. 2c shows the evolution of the numerical prediction as the number of nodes in the present 1D model increases. As shown, the result of the numerical model converges towards the experimental data when increasing the number of nodes considered in the spatial resolution The heating time of the storage tank took place of 8.64 h and 6.69 h in the case of Re_D=167 and Re_D=616 respectively from the initial temperature of 10 °C till it reaches 60 °C.

In the other hand, the cooling process is also experimentally characterized and numerically simulated for two Reynolds numbers Re_D=782 and Re_D=1563. The cooling time and the temperature evolution within the storage tank were analyzed to show the validation of the numerical model.

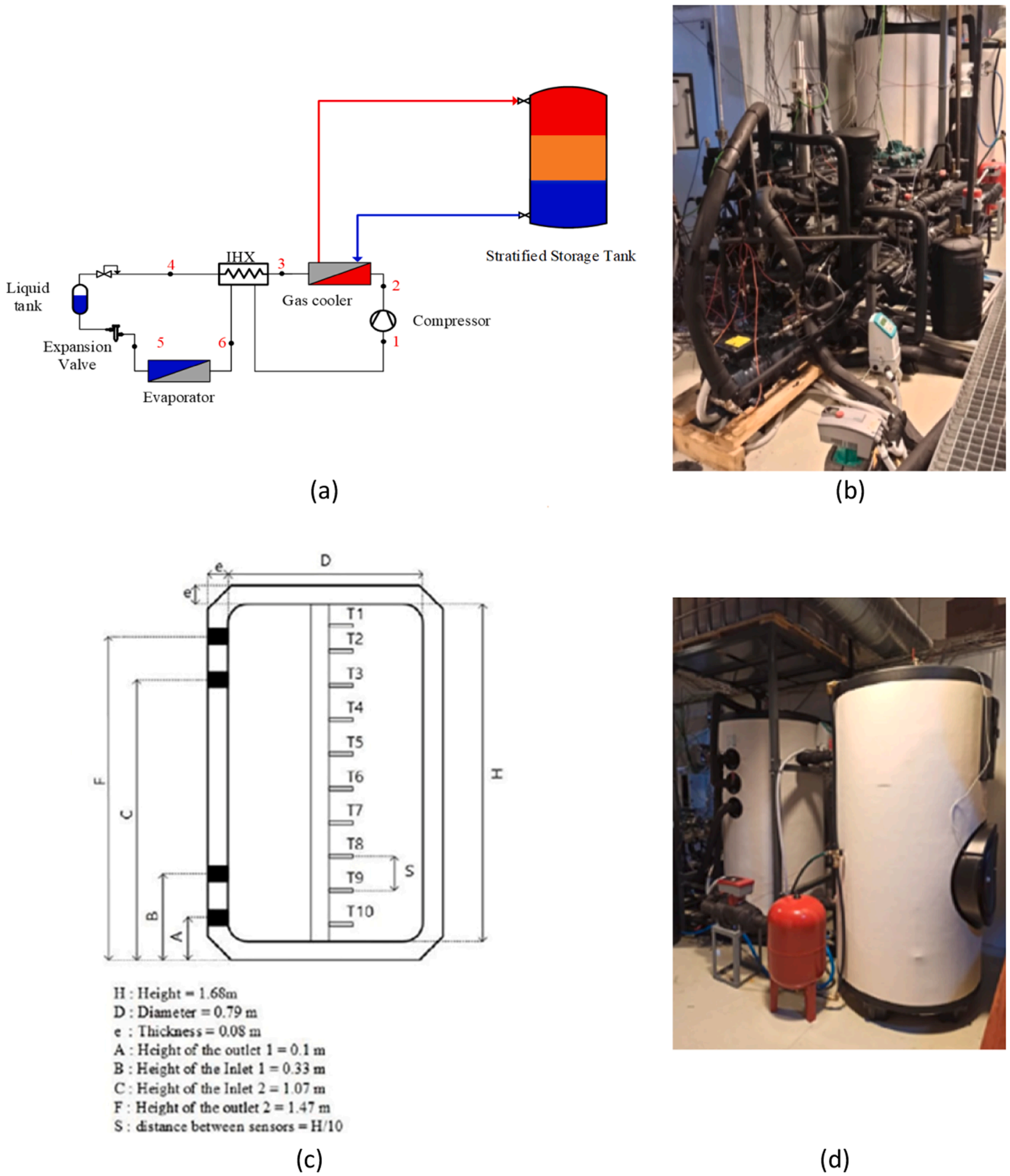


Fig. 1. (a) Sketch of the experimental facility. (b) CO_2 heat pump. (c) Schematic diagram of the hot water storage tank with the 10 RTD pt-100 sensors. (d) Hot water storage tank of the test facility.

Table 2
measuring device specifications.

Sensor	Characteristics	Measurement accuracy	Range of measurement
Temperature sensors	RTD Pt-100 class A 1/10 DIN	±0.1 K	223- 523 K
Water Flowmeter (flow rate at the water side of the gas cooler)	Siemens fm magflo mag1100 // Sitrans fm mag 5100w.	$\pm 4.91 \cdot 10^{-7}\ m^3 \cdot s^{-1}$ ± 0.2 % of the measured value in $m^3 \cdot s^{-1}$	0 – $0.1111 \cdot 10^{-2}\ m^3 \cdot s^{-1}$
Clock (time measurement)	Ni-DAQ system	0.001 s	–

The comparison of the temperature evolution of the storage tank in the case of the cooling process between the experimental data and the numerical model as a function of time at the top (T1) and the bottom (10) of storage tank for $Re_D=782$ and $Re_D=1563$ is presented in Fig. 3.

The temperature evolution of the 3 numerical models Type4a and Type60 s and the actual model presented by our laboratory shows a good tendency with the experimental data in the case of the two cases of the Reynolds numbers case of $Re_D=782$ (Fig. 3a) and $Re_D=1563$ (Fig. 3b). In the two cases of Reynolds number, the numerical model shows better results and the temperature of the top part (T1) of the storage tank in the case of the numerical model presented in this study is closer to the results obtained from the experimental data. Meanwhile the two models from the TRNSYS library are slightly far from the tendency of the

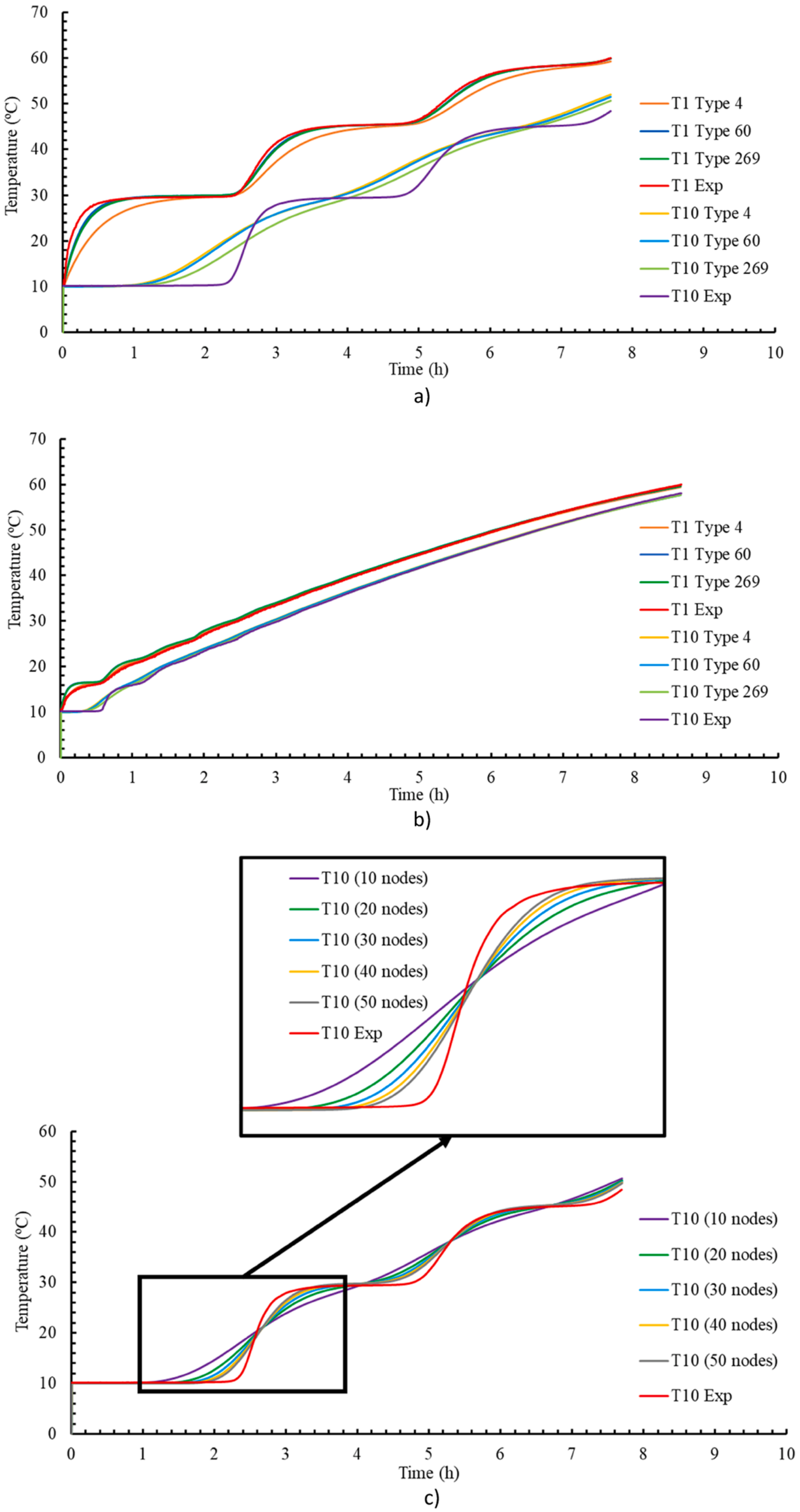
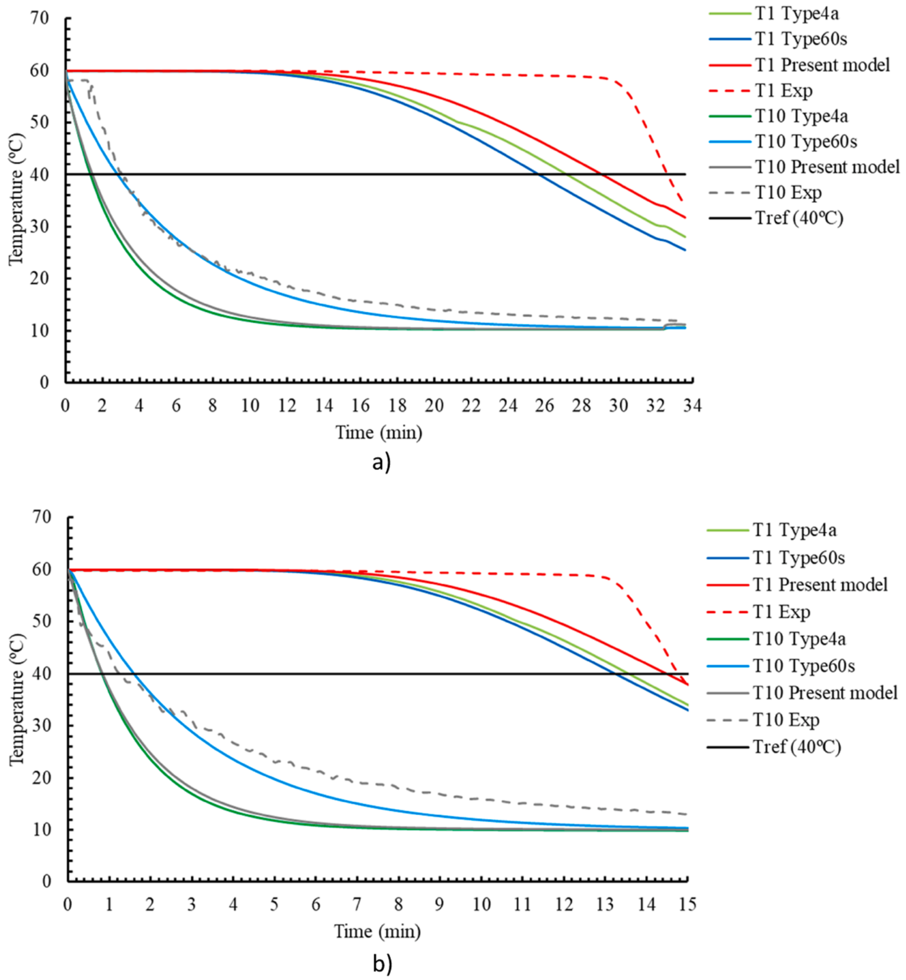


Fig. 2. Temperature evolution of the storage tank in the case of the heating process, (a) Re_D=167 (b) Re_D=616, (c) Impact of the node number in the resolution of the present model.



a)

b)

Fig. 3. Temperature evolution of the storage tank in the case of the cooling process, (a) Re_D=782 (b) Re_D=1563,.

experimental data. In the other hand, the temperature of the bottom of the storage tank coincides better with the experimental data in the case of the Type60 s and for Re_D=1563. The cooling time of the presented numerical model and the experimental tank are in good agreement, and a cooling time of 14.3 min and 14.7 min for the present numerical model and experimental results respectively in the case of Re_D=1563. A relative error of 2.72 % resulted. The cooling time of the TRNSYS library models Type4a and Type60 s are 13.6 min and 13.3 min respectively. A relative error of 7.48 % and 9.52 % is obtained for Type4a and Type60 s respectively.

At lower Reynolds number (Re_D=782), the cooling time resulted is 32.7 min, 29.2 min, 27.3 min and 25.8 min for the experimental data, the present model and the models of the TRNSYS library Type4a and Type60 s respectively. A relative error of 10,7 %, 16.51 % and 21.1 % for the present model and the models of the TRNSYS library Type4a and Type60 s respectively.

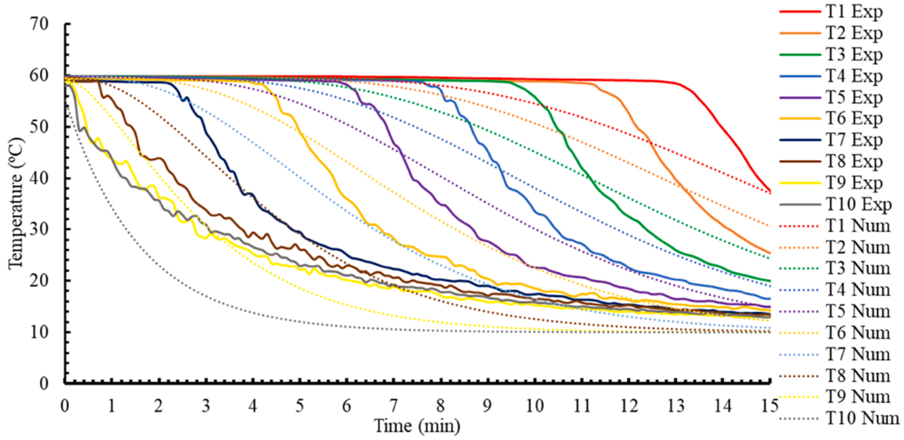


Fig. 4. Comparison of temperature evolution of the numerical model with the experimental data of the storage tank at different levels in the case of the cooling process of storage tanks.

The temperature evolution of the 10 RTD sensors installed in the central axis of the experimental storage tank and the temperature of the present numerical model at different levels of the storage tank is plotted in Fig. 4. The comparison of the numerical model and the experimental model shows a reasonable agreement in the case of the cooling process with a slight difference between the experimental and the numerical results in terms of temperature evolution. While the temperature starts to drop in the 7th minute in the numerical model, the temperature in the experimental data stays at the starting temperature of 60 °C for almost 13 min and then it begins to decrease. Meanwhile the cooling time of the numerical model and the experimental tank are in good agreement, and a cooling time of 14.3 min and 14.7 min for numerical model and experimental results respectively. A relative error of 2.72 % resulted. Comparing the temperature evolution of the lower part of the storage tank (T10), a slightly different is notable between the numerical results and the experimental data in the transitional range, but at the end of the cooling process the temperatures are almost equal.

5. Conclusions

A one-dimensional (1D) numerical model of a stratified hot water storage tank has been developed and validated with experimental data in order to show the accuracy of the model and analyze the fluid flow and the thermal behavior of the hot water storage tank during the heating and the cooling process provided by the standard UNE-EN16147. The numerical model has been discretized using the finite element method including the external and internal heat transfer phenomena influencing the fluid flow and the thermal behavior of the hot water storage tank.

- The heating (i.e. charging) process of the numerical model of the storage tank shows good agreement with experimental results for Re_D=616. While in the case of Re_D=167, the bottom part of the model of the storage tank is far away from the experimental data, but a closer temperature resulted at the end of the heating process. The increase of the number of nodes in the 1D model improves the convergence towards the experimental data.
- The cooling (i.e. discharging) process of the presented numerical model shows a good agreement with the experimental results with and error of the cooling time of 2.72 % for Re_D=1563, which makes the model accuracy better and the model can be used for further investigation of the fluid flow behavior with stratified storage tank.
- At lower Reynolds number Re_D=782, the temperature of the numerical models is slightly far from the results obtained from the experimental data. In general, the present numerical model of the stratified storage tank gives better results in comparison with the TRNSYS library models.

Future work will include the application of the present model to describe the dynamic behavior and energy performance of this kind of system during long-term operation with multiple charging/discharging sequences and the use of phase change materials.

CRediT authorship contribution statement

M. Reda Haddouche: Writing – review & editing, Writing – original draft, Methodology, Investigation. **F.J.S. Velasco:** Writing – review & editing, Visualization, Validation, Supervision. **F. Illán:** Writing – review & editing, Visualization, Supervision, Investigation. **J.R. García Cascales:** Writing – review & editing, Visualization, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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