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System and Component Model Development of a Secondary Loop System with Buried Thermal Energy Storage Tank

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Abstract

Heating Ventilation and Air Conditioning (HVAC) represents the largest share of residential buildings' final energy consumption. Storage of thermal energy can facilitate renewable electricity generation by providing a way to mitigate renewable's intermittent nature. In this research, we are researching integration of a buried and stratified thermal energy storage tank with a residential-scale water-based secondary loop system providing cooling. Simulations are conducted to compare the performance of an Above-Ground (AG) thermal energy storage (TES) tank vs a buried-in the-ground TES tank. The in-tank model is validated with our experimental data for charging, storage, discharging and adverse feed temperature scenarios. Case studies are presented for Stillwater, Oklahoma and Chicago. Results show that a buried tank of volume 2 m^3 with insulation thickness of 13mm can provide a round-trip efficiency of 93 and 101% for single-family houses in Stillwater and Chicago respectively. This is 14 and 22% higher than an AG tank with the same insulation.

Keywords: Thermal Energy Storage (TES), buried-in-the-ground TES, Above-ground TES, Secondary loop

Introduction

The intermittent and non-dispatchable nature of renewable electrical energy generation is a key challenge to maintaining electrical grid stability. Grid-scale electrical storage is not currently feasible, but a potential solution is the use of load-side TES. Given the increasing interest in TES solutions, efficient numerical models are needed for accurately modelling TES systems as a new component of buildings' HVAC system.

While residential heating and cooling distribution systems are commonly air-based in the USA, water-based secondary loop systems integrated with TES offer many benefits - low-cost, no intermediate heat exchanger between the TES and distribution system; easy zoning of the house. Outdoor air-to-water heat pumps can use flammable refrigerants, and allow plug-and-play installation, so that the unit can be swapped out and serviced in shop. Review of the literature shows that integration of the TES with an HVAC system can help reduce peak energy consumption and cycling of the system, yet there is the risk that total energy consumption can be increased due to TES losses. If this increased energy consumption occurs while renewable electricity is available, the TES may still lower carbon footprints. Also, taking the advantage of low-cost time-of-use utility pricing during off-peak hours can compensate for higher initial cost of the system (Alghamdi and al., 2022). However, extra space needed for an AG storage tank may be undesirable.

In this research, we are studying the feasibility of an alternative solution: a buried-in-the-ground and fully stratified tank made from HDPE (similar technology to ground heat exchangers). Design guidance will then be needed for this novel approach in selection of the optimum tank design (shape and aspect ratio), burial depth, insulation thickness, etc.

In this presentation, we model a buried TES integrated with other components of a secondary loop system serving a residential building. Model validation is discussed. Storage efficiency of the tank will be compared for buried vs AG tanks with different insulation levels during the cooling season.

Methodology

Overview

Firstly, we developed a 1-Dimensional (1D) model for in-tank simulations. Our goal was to develop a comprehensive, yet simple model capable of modeling the TES in all operation scenarios: charging, discharging, and storage during the time between charging and discharging. Our experimental facility is used to examine the model's predictive capabilities for these scenarios. This model is also used as the AG TES model. To model a buried tank, this model is coupled to a 2D cylindrical model of the surrounding ground. The two models are coupled by assuming that the soil temperature remains constant for a given time step (dt_{soil}), calculating heat losses from the tank to soil for a given number of tank time steps ($N = dt_{soil} / dt_{tank}$) and updating soil boundary conditions for the next soil time step calculations. Typical time steps are 60 s and 600 s for the tank and soil, respectively. Additionally, a system model is developed for integrating the TES tank with other components of a secondary loop system for charging and discharging the tank. Here, we will examine the system performance for the cooling mode during summer. Comparisons will be made for AG vs buried TES tanks that are fully charged and discharged daily during this period.

In-tank Model

Accurately modeling a stratified tank is the first step in our simulations. We assumed that for a well-designed inlet and outlet diffuser design, the temperature profile in the radial direction of the tank will be uniform (this assumption is examined later in results). Hence, the temperature changes along the tank's height in the *z*-direction (Figure 1, left). The finite volume method (FVM) is used for numerical modeling of the problem.

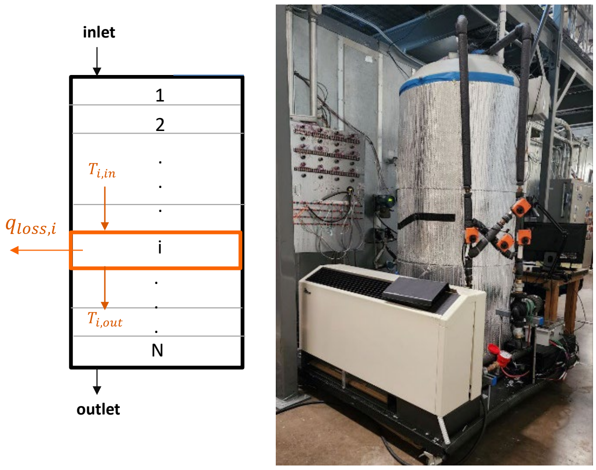

Figure 1: TES tank, left: Segmented numerical model and right: Above ground TES experimentation apparatus

We employed a hybrid scheme for numerical discretization of the governing equations (Versteeg et al., 2007). The hybrid scheme automatically selects between an upwind scheme (accurate in advection dominant flows: charging and discharging modes in our problem) or a central scheme (accurate in diffusion dominant flows: storage mode). Also, a simplified approach (Newton 1995) is used to account for buoyancy when thermal inversion occurs. The simplified approach checks for thermal inversion, and, when it occurs, mixes every two cells with a thermal inversion, and sets the temperature of these two segments equal to their average temperature. This procedure is repeated till no thermal inversion exists in that tank time step.

TES Tank Experimental Test Bed

A test bed capable of automatically replicating charging, storage and discharging modes is developed for validating the 1D tank model (Figure 1, right). A 5.3 kW (1.5-tons) heat pump is used for cooling/heating of the water in the tank. Four two-way valves allow the mode selection between charging and discharging based on the operation mode, e.g., in charging during cooling mode, cold water enters the tank from bottom diffuser and warm water is discharged from the top diffuser. Forty calibrated digital ds18b20 temperature sensors measure temperatures inside the tank with accuracy of ±0.5°C from -10°C to +85°C.

Twenty are located on a temperature tree close to the wall and the other half are located on a temperature tree in the middle of the tank at the same vertical locations. Additionally, temperatures at the inlet and outlet of the tank and heat pump are measured.

Ground Model

Heat transfer in the ground is modeled in 2D cylindrical coordinates. A grid with finer mesh in regions closer to the tank and coarser mesh in the far field is generated to save computational resources in the far field where temperature gradients are small (Figure 2). A modeled undisturbed ground temperature (UGT) is used to determine the initial and boundary conditions of the ground as a function of depth, location and day of the year. (Xing and Spitler, 2015)

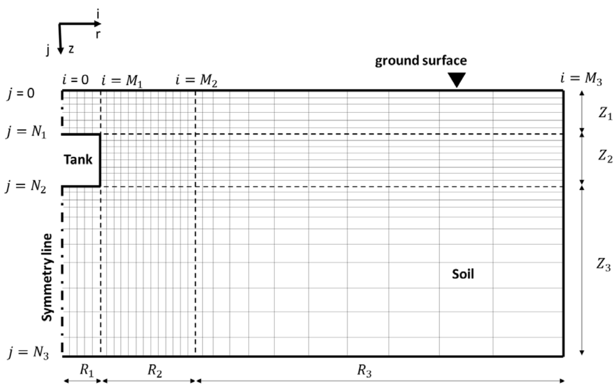

Figure 2: Problem domain-grid generation

Secondary Loop System Model and Control Strategy

The system model (Figure 3) incorporates the other components with separately calculated cooling loads. The system model consists of an Air to Water Heat Pump (AWHP), TES tank (buried or AG) and indoor hydronic coil. For the AWHP, we are using

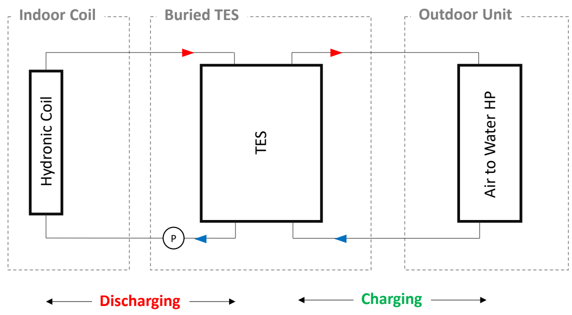

Figure 3: Secondary loop system with TES

performance data of a commercially available heat pump, with nominal 12.3 kW (3.5 tons) of refrigeration capacity.

The indoor coil is a hydronic heat exchanger component adapted from ACHP (ACHP's documentation, 2011). For purposes of demonstrating the results, the AWHP starts to run at 2 a.m to charge the tank until the average temperature inside the tank reaches a target setpoint temperature. Discharging mode starts at 2 p.m to maintain indoor temperatures using the secondary loop until the tank reaches to a discharge setpoint temperature. Energy extracted from the tank divided by energy needed for charging the tank is used to calculate the round-trip efficiency (RTE) of the tank as a key performance indicator.

Results and Discussion

The 1D in-tank model has been validated with experimental measurements made in the test apparatus shown in Figure 1. Sample validation results for charging and storage modes are presented in Figure 4.

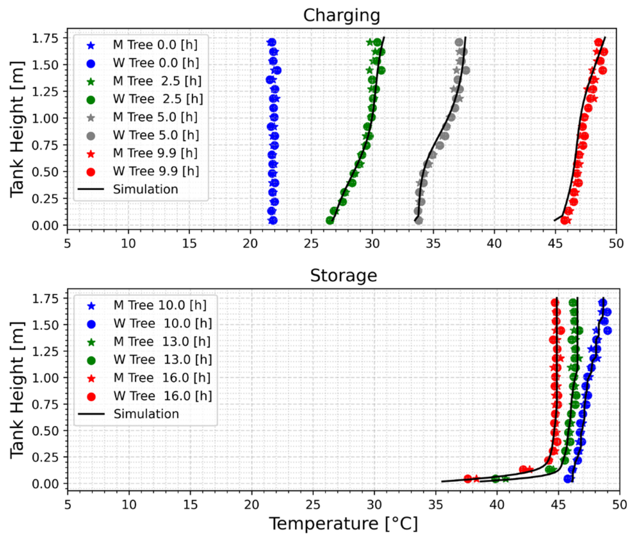

Figure 4: In-tank model validation-time in hours [h]

Temperature profile inside the tank as a function of time is shown where M Tree and W Tree represent the middle and wall temperature trees, respectively. The legend shows elapsed times since the start of charging. Maximum RMSE for the results is 0.46 ℃ for the data shown in Figure 4.

As can be seen, temperature in W and M trees are almost the same, indicating the validity of the 1D assumption. To examine the accuracy of Newton's (1995) simplified approach, tests with adverse feed temperatures were also conducted (e.g. feeding hot water from bottom). Model accuracy similar to that shown in Figure 4 is obtained, indicating the high performance of the simplified approach.

Sample results for the coupled ground-tank model are shown in Figure 5. Temperature contours show both in-tank and ground temperatures in ℃.

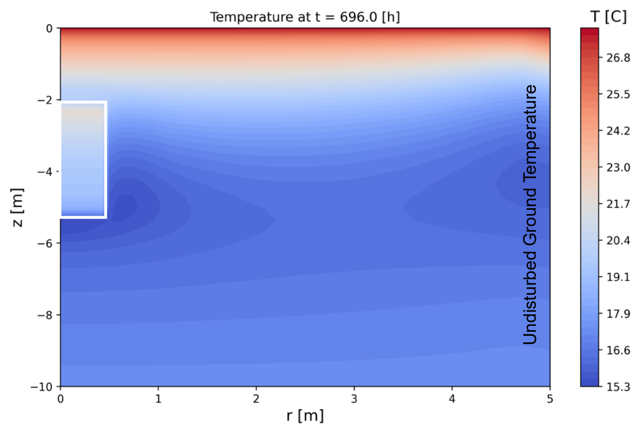

Figure 5: Temperature contour in the problem domain

System simulations are conducted for two locations in the USA: Stillwater, OK, and Chicago, IL. A buried tank with 13 mm insulation is compared with an AG tank with different insulation thicknesses. This is to see how much extra insulation is needed if the tank is installed above ground. Simulation assumptions are presented in Table 1.

Table 1: Simulation setup and assumptions.

Variable	Value	Explanations
Tank Volume	$2\ m^3$	Cylindrical tank with 0.5 m radius and 3.37 m height
Tank burial depth [m]	$2\ m$	Z_l in Figure 2
Operation Period	Summer	June 1 to Sept. 1
Charging Setpoint Temp.	7 ℃	Average temperature inside the tank
Discharging Setpoint Temp.	20 ℃	Average temperature inside the tank
Insulation	$k = 0.04\ \frac{W}{m.K}$	Polyurethane foam

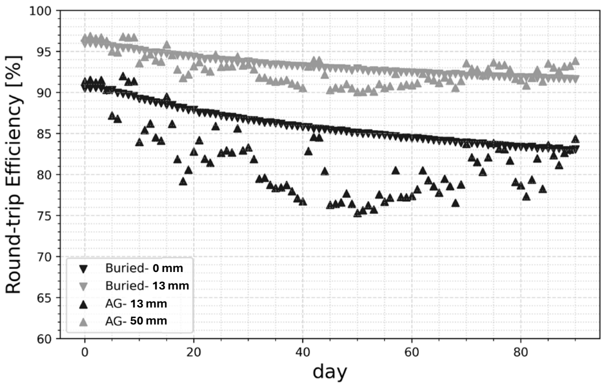

Figure 6: Daily RTE during cooling season, Stillwater, OK.

The daily variations of RTE during the cooling season are shown in Figure 6 for Stillwater for several cases. Both the buried tank and AG tank are subject to ambient temperature variations. The AG tank is exposed to outdoor air without solar radiation (e.g. located in a carport).

The buried tank, however, shows less fluctuation – the RTE drops as the cooling season progresses, due to an increase in UGT over the summer. Although we cool down the ground surrounding the tank during charging period, the far-field UGT increases its temperature leading to higher heat gains to the tank in summer. Table 2 summarizes the results for the entire cooling season for Stillwater and Chicago.

Table2: Summary table, RTE [%] for the entire cooling season.

	Buried TES		Above-Ground TES		
Insulation [mm]	0	13	13	25	50
Stillwater, OK	86%	93%	82%	88%	93%
Chicago, IL	102%	101%	88%	92%	95%

As can be seen in Table 2, the TES tank has higher overall RTE in Chicago in comparison with Stillwater, which is due to lower ambient and ground temperatures in Chicago. The Chicago system with buried TES has RTE exceeding 100% due to low ground temperatures in Chicago. This is for an idealized case where the tank is fully charged and discharged each day. This condition is nearly met for Stillwater with the 2m^3 tank, but not for Chicago. Therefore, the high seasonal RTEs may be considered an upper limit for the building loads and tank size. For Stillwater, burying the tank with 13mm insulation can provide the same RTE as an AG tank with 50mm insulation.

Conclusions

A system model capable of simulating the integration of buried or AG TES tanks with other components of a secondary loop is developed. With the validated in-tank model, a daily charging/discharging scenario is simulated throughout the cooling season. Results for Stillwater and Chicago show that:

- Burying the tank can save aboveground space and lower ground temperatures, compared to the ambient air, can result in lower heat gains to the tank in the cooling season.
- As a result, the buried tank has a higher RTE than an AG tank for the same insulation thickness. The trend of change in RTE is also more stable and predictable for the buried tank and this can be an advantage for predictability of the system and its charging/discharging controls.
- RTE for the AG tank fluctuates with ambient temperature. However, RTE drops for the buried tank as we go through the cooling season indicating that the increase in UGT is the dominant phenomena around the tank.
- Low ground temperatures in Chicago are favorable for the cooling performance of the tank, but these values depend on a daily cycle that fully charges and discharges the tank. Further investigation is planned to optimize the tank size, design, controls, and economics for a range of locations.

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