Performance analysis of novel thermal storage integrated heat pump system in a residential building at the hot climate for demand flexibility

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ABSTRACT

A novel thermal energy storage integrated heat pump system was proposed to reshape the electricity load profile of residential buildings while maintaining thermal comfort. High-fidelity computer simulations are needed for evaluating the feasibility of the proposed system. This study investigates the annual performance of the proposed system through Modelica-based system simulations. A rule-based control strategy was developed to shift the electric demand of a typical single-family house in Atlanta, GA from peak to off-peak hours to utilize the Time-of-Use electricity rate to lower the energy costs for conditioning the building. For comparison, a conventional air-source heat pump system serving the same building was also developed. Simulation results indicate that the proposed system is capable of shifting around 90% of the building's electricity consumption for meeting the thermal demand from peak to off-peak hours on a daily basis. In addition, the annual power consumption and operating cost for running the HVAC system can be reduced by 6% and 34%, respectively, compared with the conventional air-source heat pump.

INTRODUCTION

The increasing penetration of intermittent renewable power raises challenges to the existing electric grids due to a mismatch between the supply and demand sides. Buildings consume 74% of all U.S. electricity, space heating and space cooling account for 34% and 27% of the electricity consumed in residential and commercial buildings (Schwartz et al., 2017). Space heating/cooling contributes to an even higher proportion to the peak demand of electric grids (Neukomm et al., 2019). Therefore, high efficient building thermal systems with greater flexibility are in need to address the challenges.

Novel thermal energy storage (TES) integrated heat pump system was proposed to meet the residential building's thermal demand while reshaping its electricity load profile. This system consists of two innovative components: a dual-source heat pump (DSHP) and a dual-purpose underground thermal battery (DPUTB). The DSHP utilizes either the ambient air or the ground as its heat sink or heat source to ensure the heat pump's high operating efficiency. The DPUTB functions as both a ground heat exchanger (GHE) and TES. The DPUTB can be installed in a vertical borehole much shallower than typical vertical bore GHEs to reduce installation costs.

High-fidelity computer simulations are needed for evaluating the feasibility of the proposed system. In this study, Modelica was used for developing the computer simulation model. Modelica is an objective-oriented, multi-domain modeling language especially suitable for dynamic simulation. It has libraries like 'Buildings Library' (Wetter et al.

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2014) and 'IDEAS building energy simulation library' (Jorissen et al. 2018) developed. They include validated component modules that are specific for building energy system simulation.

The current study predicts the annual performance of the proposed system through Modelica-based system simulations. It calls for a computational effective system model with acceptable accuracy. A dynamic model of the DPUTB was developed and validated using experimental data obtained from lab tests of a small-scale DPUTB prototype. The model was further implemented in Modelica as a reusable module for long-term simulation. The DSHP was modeled as an air-source heat pump module and a water-source heat pump module from the Modelica Buildings Library. Given a time-of-use (TOU) tariff, a rule-based control (RBC) strategy was developed to shift the electric demand of a typical single-family house (SFH) while ensuring indoor thermal comfort. Modelica simulations were also developed for a conventional air-source heat pump (ASHP) serving the same residential building. A case study was implemented in a warn humid location (Atlanta, GA), and the annual performances of the two systems were compared.

SYSTEM DESCRIPTION

The configuration of the innovative DPUTB tank is shown in Figure 1. The tank is installed in the subsurface (around 6 meters/20 feet deep) of the ground. It diameter is 0.8 m (2.6 ft). The inner tank of the DPUTB works as a TES. Phase change material (PCM) is applied to enhance its storage capacity. Multiple cylindrical cans filled with salt hydrate PCMs are immersed in the inner tank. The total volume of the PCM is determined by the desired energy storage capacity and the volumetric energy density of the selected PCM. The inner tank is structured as a stratified thermal storage tank to have better energy storage and heat transfer performance. PCM cans are installed layer by layer with limited space in between. Diffusers/collectors are installed at the top and bottom of the tank to ensure uniform and steady flow of the water vertically and the tank's height. The water flows through the gaps among PCM cans to freeze or melt PCMs. Proper flow direction is selected to maintain thermal stratification within the tank. The main advantage of incorporating TES in the DPUTB is that it does not occupy any floor or roof space of the building. The outer tank of the DPUTB works as a GHE. A helical heat exchanger is installed in the outer tank that connects the DPUTB to the source side of the ground source heat pump (GSHP) system. The strong natural convection induced by the helical heat exchanger will keep the outer tank water well mixed. So that the temperature changes of the outer tank water and the helical heat exchanger leaving the water, in response to the heating/cooling input, are buffered by the entire water body in the outer tank.

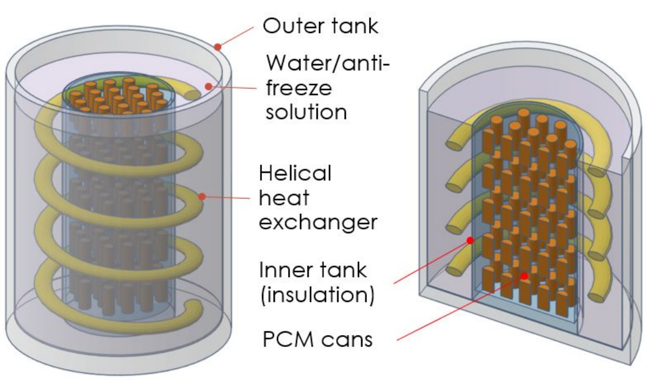


Figure 1 DPUTB tank configuration (not in scale).

The proposed system is targeted at SFHs. The mechanical system mainly consists of a DSHP and a DPUTB, as depicted in Figure 2. The DSHP is an electricity-driven heat pump using a vapor compression cycle, which utilizes either the ambient air or the ground as its heat source/sink. It runs as an ASHP when the ambient air temperature is favorable for the heat pump to run efficiently and switches to a ground source when the ambient air temperature is too high in summer or too low in winter. The source side of the GSHP connects to the helical heat exchanger submerged in the outer tank of the DPUTB. The helical heat exchanger extracts/rejects heat from/to the outer tank water, and eventually, the thermal load is rejected to, or extracted from, the surrounding soil of the DPUTB. The DSHP can reduce the seasonal imbalance of the building thermal loads imposed on the GHE (the outer tank of the DPUTB) and thus can reduce the needed size of the GHE. A fan coil works as the terminal that heats up or cools down the indoor air through forced convection at the room side.

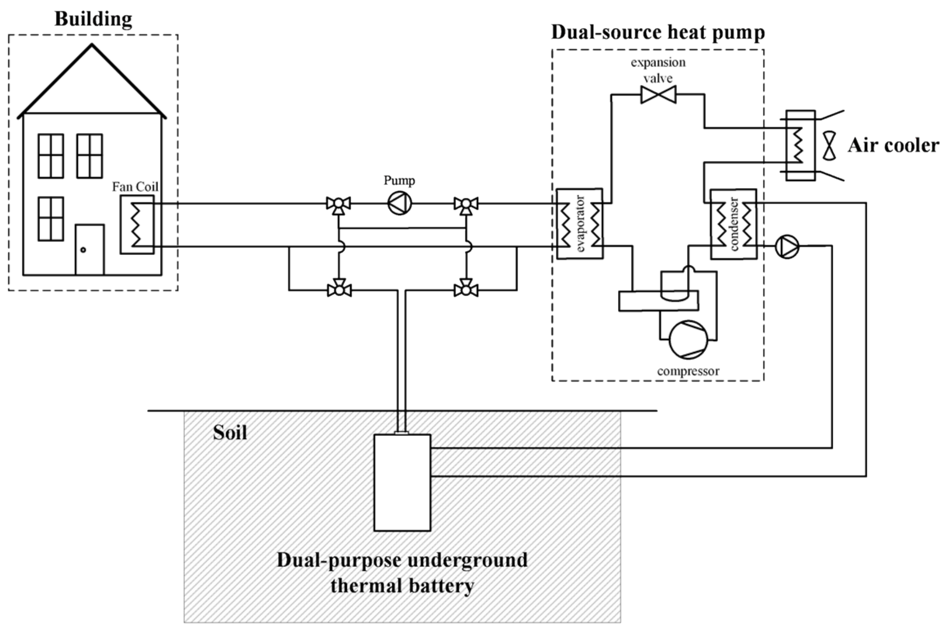


Figure 2 Diagram of an integrated DPUTB and DSHP system for a single-family house.

SYSTEM MODELING

The modeling of this study was conducted with Dymola 2019, a front-end interface developed for Modelica. Except for the DPUTB module, all other component modules were adopted directly from the Buildings Library 7.0. A new Modelica module was developed for DPUTB in this project due to its novelty. The system flow diagram is shown in Figure 3. Since the current study focuses on the mechanical system's response and performance, to reduce complexity, the building sub-model was simplified as an air volume with a pre-calculated hourly thermal load of the building.

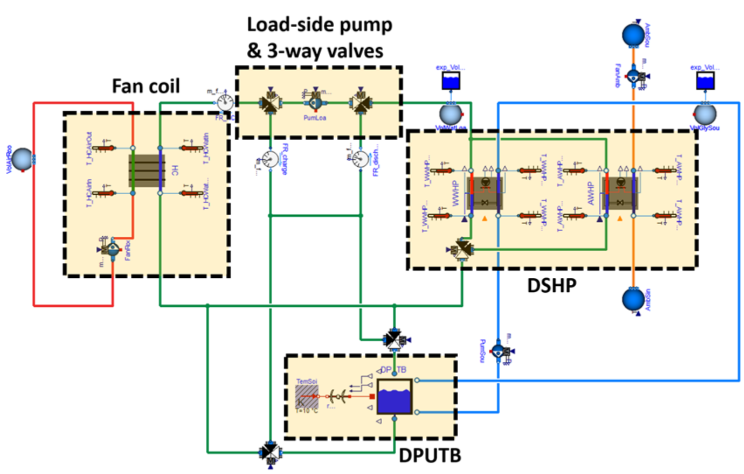


Figure 3 Diagram of the Modelica model for the integrated DSHP and DPUTB system.

DPUTB Model

A 2D numerical model was developed to simulate the dynamic performance of the components within and the soil surrounding the DPUTB. Inputs of the model include the mass flow rates and the inlet temperatures of both the inner tank and the helical heat exchanger in the outer tank and the weather conditions (ambient temperature, solar heat gain, etc.). The thermal mass of the inner tank water, PCM can, outer tank water, working fluid within the helical coil in the outer tank, and the soil was considered. This model has been validated against experimental data for a lab-scale prototype DPUTB. A detailed description of the DPUTB size, DPUTB modeling, and its validation results can be found in Shi et al. (2020), Wang et al. (2020), and Shi et al. (2021). The 2D model was further simplified to improve its computational efficiency without compromising its accuracy.

DSHP Model

A curve-fit method was adopted to predict the heat pump performance. Catalog data from heat pump manufacturers were used to generate performance curves for power and capacity prediction of the heat pump. Due to its novelty, there is not any catalog data available for the DSHP. Therefore, the DSHP is modeled as a combination of a water-to-water heat pump (WWHP) and an air-to-water heat pump (AWHP). The reversible heat pump module based on the equation fit method in the Buildings Library was adopted. The modeled heat pump uses a single-speed compressor. Catalog data of Trane's Axiom EXW0601 water-to-water heat pump was used for the current study to simulate the DSHP performance.

Control Strategy

Assuming a two-stage TOU tariff is applicable, an RBC strategy was developed for the DSHP+DPUTB system to reduce the electricity cost of the building by shifting the electric demand for HVAC from peak to off-peak hours.

The control strategy decouples the local thermostat control (for maintaining room temperature) from a supervisory control of the DSHP and the TES. The room temperature is maintained within user-specified setpoints by turning on/off the fan coil (FC) fan through a thermostat inside the building. The inlet water temperature of the FC, the status of the TES, and the peak and off-peak periods are used to control the operation of the DSHP. The TES is charged during off-peak period when the electricity price is low and the TES is not fully charged. The ambient air temperature determines the switch between the air source and the ground source. Detailed control strategy description can be found in Shi et al. (2020).

Conventional ASHP System Model

For comparison, a conventional domestic ASHP system with simple thermostat control to maintain the room thermal comfort has been developed. Except for the heat pump configuration, all other boundary conditions and inputs of the building are identical to the simulation of the DSHP + DPUTB system. The winter operation of the ASHP is modeled following the procedure described in ASHRAE standard 90.1 (ASHRAE 2004). Accordingly, the ASHP and the auxiliary electric heating operate together to meet the thermal load of the building when the outdoor air temperature is between 4.4 °C (40 °F) and -8.8 °C (16 °F). When the outdoor air temperature is below -8.8 °C (16 °F), all building heating load is met by the auxiliary electric heating only. Catalog data of Bosch BMS500 ASHP were used to simulate the ASHP performance.

SIMULATION RESULTS AND DISCUSSIONS

A case study was conducted to verify the technical viability of the integrated DSHP and DPUTB system operated with the above-introduced RBC strategy. Annual simulations were performed for both the DSHP+DPUTB

[1] Note: Rated in accordance with ANSI/AHRI/ASHRAE/ISO 13256-2.

system and a conventional ASHP system for conditioning a typical residential building in Atlanta, GA. It took 30 minutes to complete an annual simulation of the DSHP+DPUTB system using Dymola 2019 on a desktop computer with an Intel Core i7-6700 CPU.

Background Information

Prototype building and building thermal load profile. As mentioned in Section 3, instead of modeling the prototype SFH in detail, the building was modeled as an air volume of 1500 m^3 (52972 ft^3), accounting for both room air and building thermal mass. The hourly thermal load of a typical SFH in Atlanta, GA, was pre-calculated with the EnergyPlus program using a prototype building model for SFH (DOE, 2020) and the Typical Meteorological Year 3 (TMY3) weather data of Atlanta, GA. The hourly building thermal load profile is shown in Figure 4. As can be observed, the location is cooling-dominated.

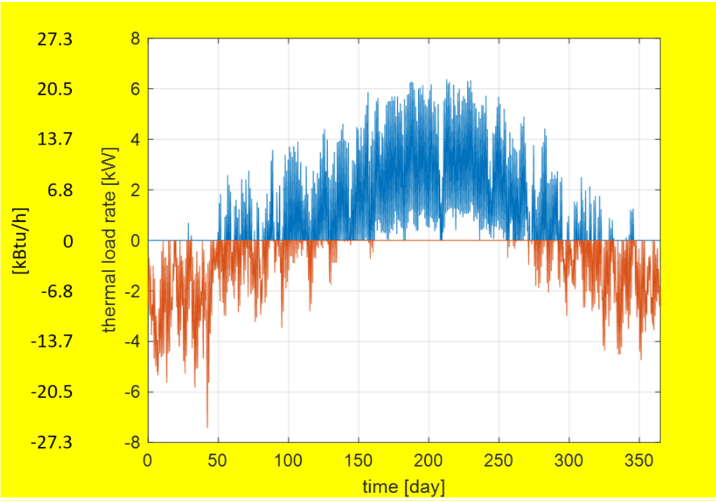


Figure 4 Hourly thermal load profile of the prototype single-family house in Atlanta, GA.

Electricity rate. A TOU electric tariff was used in this case study. This TOU electric tariff (named 'TOU-REO-12') was introduced by the utility company Georgia Power (Georgia Power 2021). According to this tariff, peak hours only occur during summer (June 1 through September 30) weekdays between 14:00 and 19:00. The retail electricity price is 0.2032 $/kWh. All other periods are off-peak times, and the electricity price is 0.0498 $/kWh. For simplicity, the current study assumes that the weekends have the same tariff as that of weekdays in summer.

System sizing. A full-size DPUTB alone can provide the heat sink and heat source for a GSHP with 0.5-1 ton capacity. As a TES, its capacity is a combination of the PCM latent heat and the water sensible heat. The total volume of the PCM is 0.168 m^3 (5.93 ft^3) and it occupies 18% of the inner tank volume. The volumetric energy density of the PCM used for simulation is 300 MJ/m^3 (8052 Btu/ft^3) and the total latent heat is 50.4 MJ (47770 Btu), which is equivalent to 1-ton cooling for 4 hours. The melting point of the PCM is around 9.5 °C (49.1 °F). Because the maximum building thermal load is around 2 tons, 2 full-size DPUTB would be needed. The thermal load of the building was divided by two to simplify the system simulation, and it is used to size the system. Thus only 1 DPUTB is included in the simulation.

The size of the DSHP was selected based on half of the maximum building load and the capacity of the heat pump at the expected worst operating condition when the full thermal load occurs. After several trials and errors, it was found that a heat pump with a 1.5-ton capacity at rating condition was large enough to maintain the room air temperature within setpoints for the whole time of the year. For the conventional ASHP system, an auxiliary electric heater (assumes its efficiency is 1) was applied to cope with the extreme cold weather. After trial and error, an ASHP with a 1-ton rated capacity and an electric heater with 3.5 kW (11942 Btu/h) output were large enough to satisfy the building thermal comfort at all times.

Simulation Results

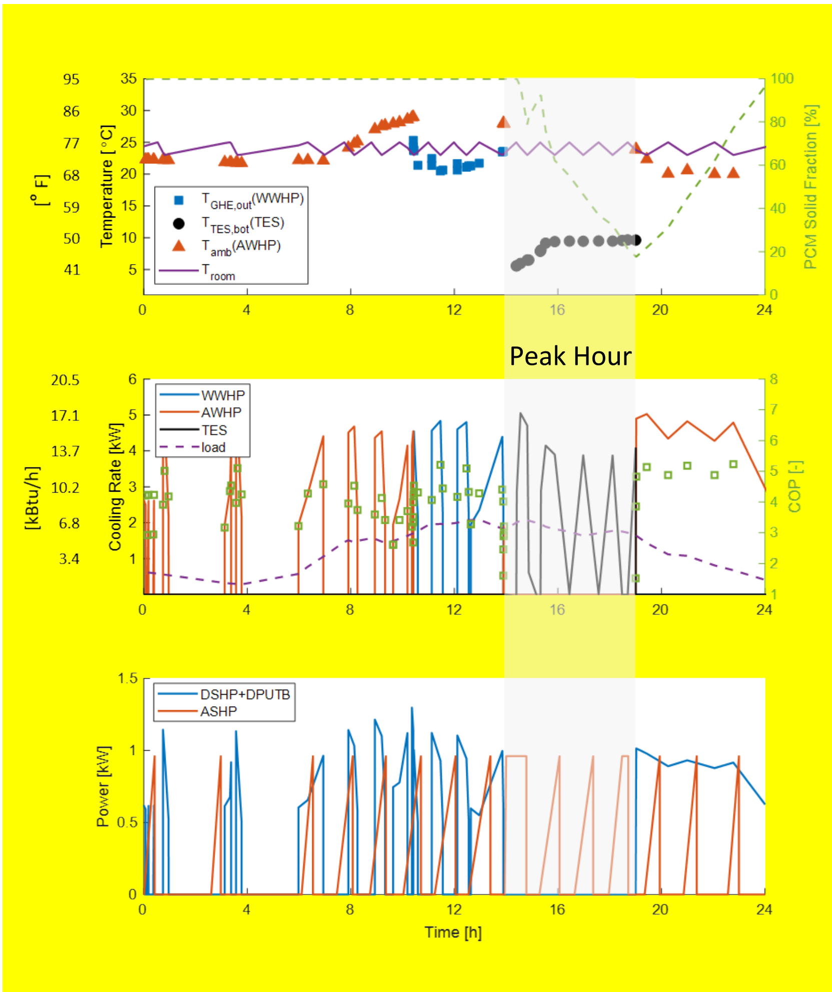
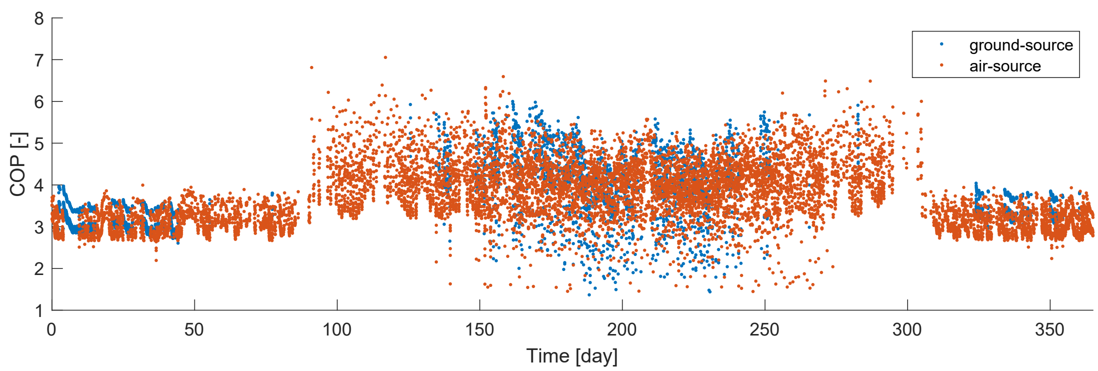


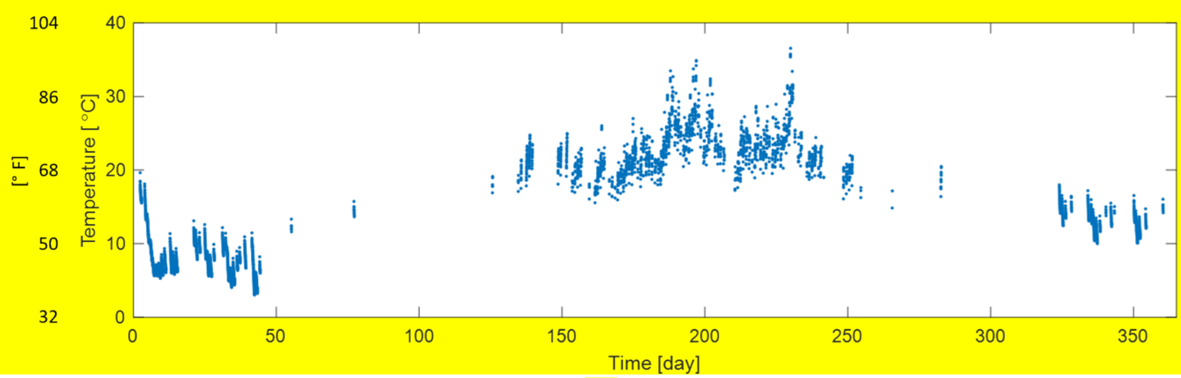
Figure 5 System simulation results on a typical summer day. Upper figure: temperatures of different equipment when they are in operation. Middle figure: thermal outputs of different equipment. Bottom figure: power load comparison between the DSHP+DPUTB system and the conventional ASHP system.

Figure 5 shows the simulation results that reflect the system operation on a typical summer day (July 1). The sub-figure on the top includes the temperatures of different equipment when they are in operation, the one in the middle shows the corresponding thermal energy outputs, and the one on the bottom compares the power load profiles of the DSHP+DPUTB system and the conventional ASHP system. The red-triangle and blue-square markers indicate DSHP running with the air source and the ground source, respectively. The yellow-circle markers indicate that the TES was activated to discharging the store energy to cool the building. The room temperature (purple curve in the top figure) was maintained within 23 to 25°C (73.4 to 77°F) as required. During the off-peak period (0:00-14:00 and 19:00-24:00), the single-speed DSHP was turned on/off intermittently to meet the building thermal load (purple curve in the middle figure). The DSHP ran with air-source in the early morning and late evening when the ambient temperature was moderate (less than 28.5°C/83.3°F) and ran with ground-source during the mid of the day. The coefficient of performance (COP) of the DSHP (green-square markers in the middle figure) was maintained at the same level no matter air or ground was used as the heat sink. During the peak period (14:00-19:00, shaded area), the stored cooling energy in the TES was discharged to meet the building's thermal load. The PCM was melted during this process (green dashed curve in the top figure), as indicated by the continuous decrease of the PCM solid fraction. As shown in the figure in the middle, TES was the sole cooling provider during the peak period. The sub-figure at the bottom indicated that the conventional ASHP system was turned on and off during the entire day to maintain the room temperature within the thermal comfort range. However, it was not able to shift the load from peak to off-peak period. The results showed that the DSHP+DPUTB system operated with the RBC shifted all the electric demand for meeting the thermal load from the peak to off-peak period on the summer day.

Some featured results are plotted in Figure 6 to show the system's dynamic performance on an annual basis. Figure 6(a) shows the COP values of the DSHP. The DSHP uses air-source more frequently than the ground source, given the ambient temperature thresholds for switching from air-source to ground-source is above 28.5°C (83.3°F) in summer and below 2.5°C (36.5°F) in winter. These switching temperatures were chosen so that the COP of the DSHP can be maintained near the same level no matter air or ground is used as the heat source/sink. This method tends to make the best use of both the available air- and ground-source of the DSHP. Figure 6(b) illustrates the DSHP's source-side entering temperature when running with the ground source. The results show that the source-side entering fluid temperature was maintained not lower than 0°C (32°F) in winter and not higher than 35°C (95°F) in summer. It indicates that the heat exchanger in the outer tank of the DPUTB has enough capacity to maintain its leaving fluid temperature within the typical range offered by conventional GHEs.



(a)



(b)

Figure 6 Annual simulation results of (a) heat pump COP; (b) DSHP source side entering fluid temperature in ground-source mode.

Annual Energy Consumptions and Performance Comparison

The simulation results of cumulative power consumption and operating cost of the two systems in the summer and winter are listed in tables 1 and 2, respectively. While the ASHP meets the building thermal demand without any load shifting, the DSHP+DPUTB system shifted 89% of the electricity consumption for HVAC from peak to off-peak hours on a daily basis in the summer. However, due to thermal loss from the TES tank, the DSHP+DPUTB system has to produce more thermal energy than the ASHP to enable load shifting. Some of the thermal energy lost from the TES (the inner tank of the DPUTB) is recovered by the heat exchanger in the outer tank of the DPUTB to improve the operating efficiency of the DSHP. As can be seen in Table 1, the DSHP+DPUTB system produced 10612 MJ (10 MBtu) more cooling energy than the ASHP system in the summer. Thanks to the higher seasonal COP of the integrated system, this 32% thermal demand increase did not cause an increase in the total power consumption. Since there are no peak times for winter operation, the TES was not operated for load shifting in winter. Thus, the process of the DSHP and the ASHP was similar. They produced an equal amount of thermal energy to fulfill the building's thermal demand. However, the seasonal COP of the ASHP was lower than that of the GSHP system. This resulted in a slightly lower operating cost for the DSHP system in winter.

Overall, the annual power consumption of the DSHP+DPUTB system is 4356 kWh, and it is 6% less than that of the ASHP (4609 kWh). In addition, the annual operation cost of the DSHP+DPUTB system is $257 if a TOU tariff is utilized. The proposed system can cut energy bills by 34% compared with that of the ASHP ($390).

Table 1. Summer energy consumptions and costs.

	P_{total} kWh	$P_{on\ peak}$ kWh	Q_{total} MJ (MBtu)	COP -	Cost dollar
ASHP	2760	781	32832 (31.1)	3.31	301
DSHP+DPUTB	2719	85	43444 (41.2)	4.44	178

Table 2. Winter energy consumptions and costs.

	P_{total} kWh	Q_{total} MJ (MBtu)	COP -	Cost dollar
ASHP	1849	18936 (18.0)	2.84	89
DSHP+DPUTB	1637	19093 (18.1)	3.24	79

CONCLUSIONS

This study investigated the technical feasibility of using a novel integrated DPUTB and DSHP system to actively manage residential buildings' electric demand. A high-fidelity simulation model of the integrated system was developed using the Modelica program. A case study was conducted through computer simulations using the system model. Simulation-predicted performance of the integrated system was compared with a conventional domestic ASHP system. The main conclusions from this study include:

- The Modelica model of the integrated DPUTB and DSHP system operated with the proposed RBC is robust. It takes about 30 minutes to run an annual simulation of the integrated system.
- Due to the implementation of the underground TES, the integrated system is capable of shifting around 90% of the electricity consumption for space conditioning from peak to off-peak hours on a daily basis.
- The integrated system is more energy-efficient than the conventional ASHP system, and it can take advantage of available TOU tariffs. As a result, for a warm, humid place like Atlanta, GA, its annual power consumption can be reduced by up to 6%. Its operating cost is 34% lower than the conventional ASHP system.

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