A Thermal Design Strategy for Net-Zero Energy, High-Glazing Buildings in Temperate Climates

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Abstract—Green building standards like the Living Building Challenge promote the construction of net-zero energy buildings. In order to meet these standards, alternative heating and cooling methods become necessary, especially for designs with high glazing percentages in temperate climates, such as for aesthetic purposes or use in greenhouses. The design and analysis of a low-cost heating and cooling system is being investigated to address these scenarios. Air-source heat pumps are now commonly used in super-insulated, net-zero energy building designs, and we explore the possibility of augmenting this configuration with an inexpensive seasonal thermal energy store to address the increased heating and cooling loads. A high-glazing building scenario was modeled in Revit to establish monthly loads for a proposed building design, and a heat transfer model of a thermal store coupled to a heat pump was simulated in COMSOL Multiphysics to test feasibility of this idea. The results suggest this strategy has potential but may be limited in application due to its large size.

Keywords—Net Zero, Green Building, Passive Solar, Seasonal Thermal Energy Storage, Geothermal Heat Pump, Air-Source Heat Pump

1 Introduction

Architecture accounts for a large percentage of our energy footprint, with commercial and residential buildings consuming 40% of the total energy in the United States in 2013 [1]. In particular, heating and cooling accounts for one of the largest energy loads in most buildings [2], especially in environments where temperature and humidity differ significantly from the human comfort zone [3].

Green building design has the potential to address this challenge and green building standards have started to appear that are effective at promoting its use. Popular standards include the Living Building Challenge (LBC) certification program, the Passivhaus energy standard, and the Leadership in Energy and Environmental Design (LEED) rating system. Traditional heating, ventilation, and air conditioning (HVAC) systems account for over 50% of total home energy use [2]. Thus, we must move away from heating and cooling systems based on fossil fuels to using local renewable energy sources, such as available on-site solar insulation.

This research focuses on identifying a low-cost heating and cooling strategy to meeting these standards for small-scale buildings with high glazing percentages in temperate climates, such as to meet aesthetic demands or achieve greenhouse conditions. This work is informed by an initiative to develop a net-zero energy building at a small New England college located in Zone 6b [4], in the Northeast climate zone [5] in the United States. As part of this initiative, a variety of solar heating and cooling strategies were generated to enable potential designs to meet LBC certification.

We explore one of these strategies, the possibility that a seasonal thermal energy store (STES) could augment an air-sourced heat pump (ASHP) to effectively increase solar fraction by shifting excess summer heat gain to meet winter heating loads while maintaining costs. We suspect a low-cost energy store can be created using a large insulated block of soil with earth tubes [6] embedded to form a heat exchanger. An initial computer-based building model was created using Revit [7] to determine the seasonal thermal loads of a high-glazing building design while COMSOL Multiphysics [8] was used to create a heat-transfer model of an STES to test the feasibility of these ideas.

2 Background

Net-zero energy buildings are now commonly developed through a combination of traditional passive solar [12] [13] and Passivhaus [14] type design practices and the addition an ASHP powered by a photovoltaic (PV) array [16] [17]. These designs have relatively low amounts of glazing, and as techniques to manage the building envelope improve, the glazing percentage appears to be decreasing [14].

Higher amounts of glazing in temperate climates lead to larger heating and cooling loads as the effective insulation of the envelope decreases. For example, a 1200 m/2, well-insulated building may have a peak winter heating load of 2.9-4.4 kW (10,000-15,000 BTU/h), whereas a similar building with a high glazing percentage may have a peak heating load of 11.7 kW (40,000 BTU/h) or more [15]. While shading and direct ventilation can reduce cooling loads dramatically [16], the heating loads become too large to address through diurnal temperature variation alone or additional PV arrays. Large heating and cooling loads can be addressed through seasonal thermal energy storage (STES) [18] of solar energy [19] or with the use of a geothermal heat pump (GHP). The appropriate system will depend on the particular building configuration, site conditions, occupancy needs and local costs.

In the case of small, well-insulated buildings, an ASHP system, including the PV array, can be significantly cheaper than a GHP to install and operate [20]. ASHPs are now available that maintain output even at outside temperatures well below freezing with a COP above 2 at temperatures as low as -26°C, although the trade-off is lower efficiencies at higher temperatures [21]. Thus, it may be possible to augment an ASHP with a low-cost STES to create a cost-effective solution to address high heating and cooling loads while achieving net-zero energy performance.

Effectively, the excess heat gain resulting from a higher glazing percentage would be utilized by an ASHP to charge an STES during the extended cooling months, which it would then discharge during the heating months. This arrangement may have the potential to hold down costs by substantially increasing the energy available and the efficiency of a heat pump, because the COP of an ASHP depends highly on its inlet temperature [25]. These gains would need to reduce the size of the required PV installation sufficiently and the installation cost of an STES would have to be low enough to warrant using this strategy.

Earth tubes [6] using air as a working fluid can be inexpensive to construct, especially if installed during new construction. Traditional earth tubes bring outside air indoors, which can have potential health implications if mold or other contaminants enter the system, a problem that the use of an ASHP eliminates.

3 METHODOLOGY

The main two components of the system studied are an insulated, soil-based STES with earth tubes and air as the working fluid coupled to a reversible air-to-air heat pump, as shown in Figure 1.

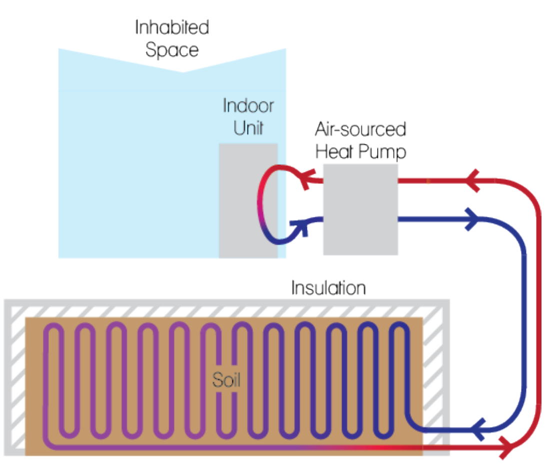

Fig. 1: A conceptual system diagram of the STES-augmented air source heat pump

The design is such that during the summer months, the heat pump exhausts hot air into the STES inlet, where the air is cooled to near soil temperature as heat is absorbed by the soil block. The cooled air existing the STES tubes is then recovered at the inlet of the heat pump where it is heated as energy is rejected from the building to reach the desired indoor cooling set point. In the winter months, this process is reversed. A thermal store that is too large will not be able to heat up effectively during the summer months, whereas one that is too small will run out of heat before the end of winter.

Steps were taken to initially size the system components and determine operating parameters before running simulations in COMSOL and making subsequent adjustments. A proposed 115 m^2 building configuration with 74% glazing percentage and planned occupancy patterns was created and explored in Revit to establish monthly heating and cooling loads for the system. These loads were used to calculate an initial estimated volume of 835 m^3. A nominal value of 1 $\frac{kJ}{kgK}$ for specific heat, 1750 $\frac{kg}{m^3}$ for density, and 1 $\frac{W}{mK}$ for thermal conductivity for soil were assumed [22][23][24]. The operating characteristics of a high-performance air-to-air heat pump [25] were used, including an air flow rate of 1.67 m^3/s. The initial temperature of the soil was chosen to be 10 °C. All six faces of the block were assumed to be perfectly insulated.

Using this information, a thermal model of the STES was created in COMSOL including its three-dimensional geometry consisting of an insulated block of soil with linear air tubes passing through it. The model was set to run for a 4 month cooling period, followed immediately by a 4 month heating period and so on for a total of 12 months representing 1 year of operation. The 2-month transition periods between the heating and cooling seasons was not modeled given the assumption of perfect insulation. The average soil temperature, as well as the average outlet temperature of the tubes, was plotted for each run. Adjustments were made to the number, diameter and spacing of the tubes and the simulation was re-run until effective use of the entire volume of the block was established. The final block size was 750 m^3 in size with 7 linear air tubes 15.2 cm in diameter and spaced 2 m apart between centers as shown in Figure 2.

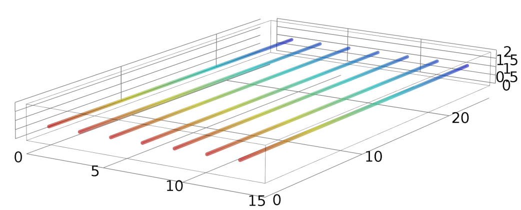

Fig. 2: COMSOL CAD geometry of the insulated soil block with tubes

Note that the amount of fan pressure needed to move air through this tube configuration was not taken into consideration. If an additional fan is found to be needed the COP would reduce accordingly.

4 RESULTS

The COMSOL heat transfer simulation of the proposed STES was used to look at the amount of heat that enters the storage system in the summer, how long that heat store will last when heating the building in the winter and whether this system is effective once it stabilizes after multiple annual cycles. The results for the first annual cycle are shown in Figure 3.

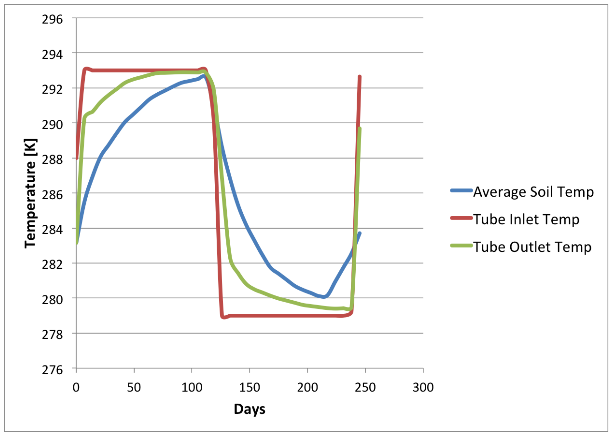

Fig. 3: Heating and cooling cycles with the tubes' inlet and outlet temperatures as well as the average temperature of the block of soil

The soil block is at 10° C (283 K) initially when hot exhaust from summer cooling begins to run through the tubes, heating the block.

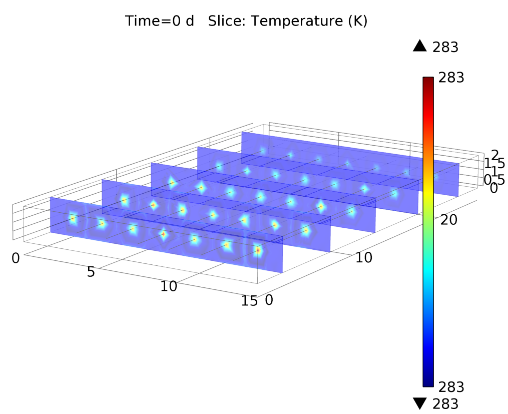

Fig. 4: Soil block temperature at day 0 of heating cycle

As shown in Figure 4, halfway through the summer the average soil temperature of the block begins to approach the inlet temperature of the tubes, 19.5 °C (292 K).

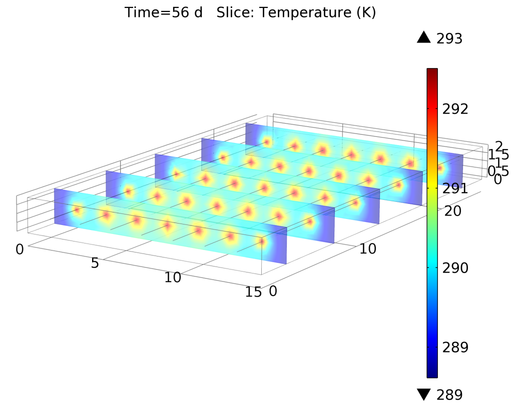

Fig. 5: Mid-summer soil block temperature

By the end of the summer, the soil block is hot at an average temperature of 17.85 °C (291 K) and the heat pump shifts to begin heating the building in the winter. This can be seen in Figure 5.

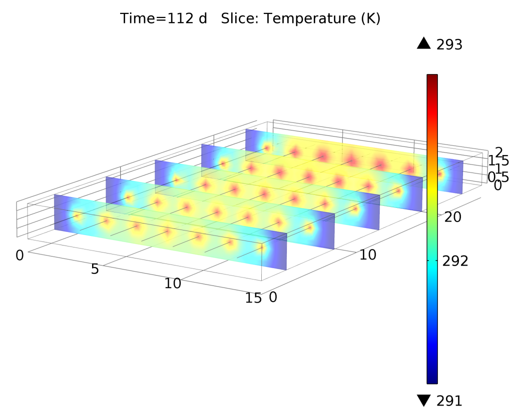

Fig. 6: At the end of the summer, the average temperature of the soil block has increased by 9.5°C

Halfway through the winter the soil block begins approaching the inlet temperature of the tubes, 6° C (279 K), as shown in Figure 6.

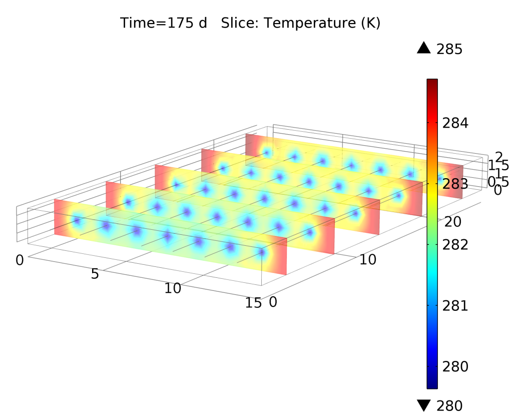

Fig. 7: Halfway through the winter, the block has again decreased in temperature, as the heat from summer charging is discharged into the building space

As shown in Figure 7, by the end of the winter the average soil temperature has decreased to 7.85°C (281 K) and is ready to cool air for the summer months. Finally, as can be seen in Figure 8, at the end of the winter the heat energy is depleted from the block of soil which prepares the system for cooling the building space in the summer.

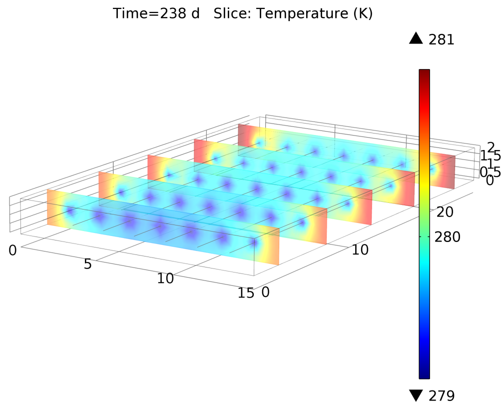

Fig. 8: At the end of the winter, the block is fully discharged for cooling in the summer

Note, the outlet temperature of the STES tubes (inlet temperature of the air-sourced heat pump) is lower than the outdoor temperature in the summer, and higher than the outdoor temperature in the winter. This correlates to a higher COP, as the higher the inlet temperature in the winter, and the lower the outlet temperature in the summer, the more efficiently the heat pump can run [25].

5 Conclusion

The preliminary results of this initial study suggest that a system consisting of an ASHP with a low-cost STES has potential to address the larger heating and cooling loads associated with higher glazing percentage building designs while increasing COP and overall efficiency. Given the chosen parameters, this model overestimates the performance of the system, and more modeling work is needed to obtain more realistic results, particularly relating to the amount and location of insulation used. Even so, these results suggest that STES systems using soil as the storage medium require considerable space to implement and will not be practical for all sites.

The model should be expanded to simulate the collection and loss of heat within the building envelope, including incorporating diurnal strategies, further increasing the efficiency and comfort of the system. Alternative storage media and working fluids with higher heat capacities and thermal diffusivities, such as water, should be explored but may not meet the objective of finding a low-cost alternative. Calculation of an overall COP for the system, along with a full cost analysis, should be undertaking in order to effectively compare this strategy with the option of using a GHP instead.

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