European Geothermal Congress 2013
Pisa, Italy, 3-7 June 2013

Soil-Borehole Thermal Energy Storage Systems for District Heating

John S. McCartney[1], Adam Reed[1], Shemin Ge[1], Ning Lu[2], and Kathleen Smits[2]

[1] University of Colorado Boulder, UCB 428, Boulder, CO, U.S.A., 80309

[2] Colorado School of Mines, 1500 Illinois St, Golden, CO, U.S.A., 80401

john.mccartney@colorado.edu

Keywords: Soil-borehole thermal energy storage.

ABSTRACT

This paper presents details of a new project involving an investigation into a new soil-borehole thermal energy storage (SBTES) system constructed in partially saturated soils. The system stores heat collected from solar thermal panels in borehole arrays for subsequent use in district heating of housing communities or buildings. This paper will discuss the heat transfer mechanisms involved in this system, which are different than those in water-saturated soils. In addition to details of the research thrusts, the economic, energy market, and policy issues associated with developing such systems are discussed, using information from two installations North America, the Drake Landing Solar Community and the Delta-Montrose Electric Association, for illustrative purposes.

1. INTRODUCTION

A new collaborative research project between the University of Colorado Boulder and Colorado School of Mines, Colorado, U.S.A., involves an investigation of the injection and storage of heat generated from solar-thermal panels into above the water table through a strategically designed array of closed-loop borehole heat exchangers, as well as the efficiency of withdrawing heat at a later point for direct use in building heating or for low-grade electricity generation through binary cycle power plants. SBTES systems have several key advantages in providing a sustainable energy pathway, including a renewable energy source (solar-thermal), low cost compared to other energy storage systems, space efficiency (they are underground), functionality in many locations, low environmental impact (closed-loop system), no requirement for long-distance energy transportation (localized energy storage), incidental electricity grid benefits in load levelling and the provision of demand response services to grid operators, and scalability from residential- to community- to utility-scale applications. Further, the low environmental impact of these systems compared to other energy storage approaches emphasizes the sustainability of this energy storage approach.

Borehole storage of thermal energy could provide a key element in balancing the cost and efficiency of renewable energy technologies such as solar-thermal systems as well as energy system-level benefits as grid operators seek ways to level demand throughout the day and align renewable energy generation with load. Other renewable energy technologies that generate excess heat, such as fuel cells, could be incorporated into a SBTES system. The storage of thermal energy in the ground may help determine the fate of these renewable energy technologies and help justify their implementation on a broader scale.

The unique aspect of the SBTES system investigated in this study is an engineering design built around the natural processes of coupled heat, water and vapor flow in the vadose zone, with the intention of transferring and storing heat in a similar manner to that in a heat pipe. The basic concept and flow processes in the borehole array are shown in Figure 1. By incorporating a surficial insulation and hydraulic barrier, water vapor will evaporate from the drying front and rise through dry soil layers. If the water vapour cannot escape into the atmosphere due to surficial insulation, it will condense near the surface, forming a saturated layer, thus forming a convective cell (e.g., Lu 2001).

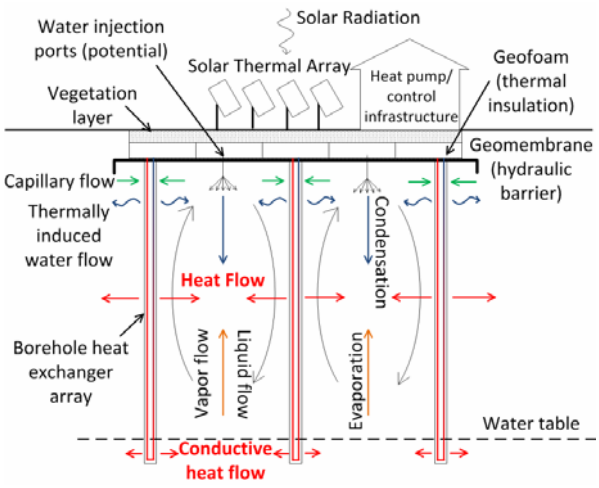


Figure 1: Physical processes in partially saturated soils in SBTES systems

Novel research opportunities arise in exploring how latent and sensible processes associated with phase change enhance soil-borehole heat transfer and augment the thermo-hydraulic properties of partially saturated soils. Preliminary analyses indicate that the rate of heat transfer may be up to 10 times faster when accounting for the coupled heat-mass transfer in partially saturated soils than when assuming that conduction is the only means of heat transfer (e.g., Lu 2001; Zhang et al. 2012).

The inter-related thermo-hydraulic properties of partially saturated soil also play a critical role in this approach. Although the distributions of water content and other soil thermo-hydrologic properties may vary with depth in natural conditions, the convective cell will lead to a relatively uniform distribution of water content in the vadose zone during operation, in which case the soil will have nearly constant hydraulic and thermal properties with depth. Schematics of the unsaturated soil properties before and after starting heat injection are shown in Figure 2. The uniform soil properties are expected to facilitate heat transfer into the borehole array. Further, the lower thermal conductivity of the partially saturated soil in the vadose zone surrounding the SBTES system will help minimize lateral loss of heat.

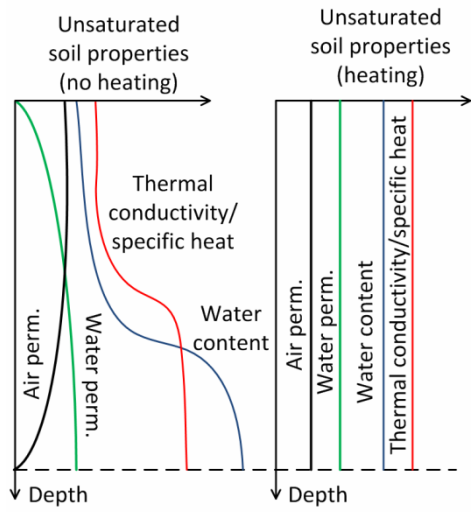


Figure 2: Partially saturated soil properties during heat injection into SBTES systems in the vadose zone.

Despite their potential benefits, such localized, thermally-based renewable energy storage systems have not seen widespread implementation (Gao et al. 2009). Study of the experience from recent community-scale SBTES systems may help better understand the lack of implementation, although Hughes (2008) postulates that it is due to lack of objective data and research to validate and optimize system performance, high capital costs for individual building owners, low visibility of the technology at the community decision-making level, and the structure of the existing socio-technical energy system with its dominant centralized-generation and electrification paradigm. While the capital costs of a loop field and heat pump system are far lower than those associated with large-scale electricity generation and transmission to serve the same load, they are typically borne by a single owner who not only carries the investment burden but also receives no compensation for the broader energy-system benefits of reduced peak loads and energy efficiency. Absent policy changes, the owner also loses out on opportunities to provide potentially valuable demand response services to the energy grid. If this is shifted to a community-scale or utility-scale application, its implementation may be accelerated. Lessons learned concerning the application of community-scale ground-source heat pumps by rural electric cooperatives and public utility companies have not been analyzed to identify usage trends, barriers to implementation, or the vast opportunity space of market and policy strategies that may be relevant to subsurface thermal energy storage.

2. BACKGROUND

2.1 Overview

Many storage technologies have been considered in the context of utility-scale energy storage systems, including electrical systems (pumped hydro, compressed air, batteries, superconducting magnetic energy storage, flywheels, fuel cells, and capacitors), phase change materials, water or brine tanks, and underground thermal energy storage systems (aquifer, pit, or borehole systems). Advantages of underground thermal energy storage systems are that they can be installed anywhere in the world, have a good balance between efficiency and installation cost, and have the technical maturity to be implemented on a large scale (ECES 1997). Most underground thermal energy storage systems involve storage of heat at temperatures between 50 to 95 °C (High Combi 2008). Direct use of hot water for heating requires lower temperatures (50 °C), while a temperature difference of at least 35 °C must be maintained between the storage medium and the above-ground temperature to operate an efficient binary cycle power plant. The higher the temperature of the stored energy above ambient conditions, the more valuable it is for thermo-electricity generation.

One of the earliest studies to investigate underground thermal energy storage was by Meyer and Todd (1973), who proposed to store heat generated as a by-product from power plants operations in aquifers (temperatures up to 171 °C) to balance electrical supply and demand. Aquifer thermal energy storage systems involve extracting water from the subsurface, transferring heat, then re-injecting to the subsurface. Aquifer systems have been primary underground thermal energy storage method investigated in the U.S. (Molz et al. 1978, 1979; Molz et al. 1983; Guven et al. 1983; Dickinson et al. 2009), and have been implemented on a utility scale in Turkey, Greece, and the Netherlands for direct cooling (Paksoy et al. 2000; Snijders and Bakema 1997). However, aquifer heat storage is not feasible in many US states because of

water rights issues, issues with mass balance of water extraction and injection, and concerns of groundwater contamination or thermal mobilization of contaminants. Further, another major issue with aquifer systems is spreading of thermal energy away from the point of injection, making it difficult or impossible to extract at a later time.

2.2 SBTES

Most SBTES systems in operation are installed in saturated soil profiles and rely upon closed-loop heat exchangers to shed or absorb heat from the ground through conduction (Bakema et al. 1995; Gabrielsson et al. 1997; Sanner and Knoblich 1997). High-Combi (2008) performed a thorough study of existing underground thermal energy storage systems in Europe and found that SBTES systems that rely upon conduction for heat transfer require a larger underground volume than aquifer systems. Although they have lower installation costs than aquifer energy storage systems when normalized by energy storage, the larger volume required negates this benefit. Another issue with SBTES systems is that there is a shortfall of field performance data and validated numerical simulations of long term performance even though they have been implemented in Europe since the 1980's (Sanner and Knoblich 1997).

The governing parameter regarding the suitability of using SBTES is the annual energy extraction efficiency. In general, the efficiency depends on the volume and geometry of the SBTES space, number and dimensions of the boreholes, injection/withdrawal scheme, and soil and rock's mechanical, hydrological, and thermal properties (Ohga and Mikoda 2001). The typical heating and cooling capacity of a SBTES is 50-250 kW using 10-50 boreholes drilled to a depth of 100-200 m (Andersson 2003). Heat pumps used in conventional ground-source heat pump (GSHP) applications have a maximum coefficient of performance (COP = Thermal output / Electricity input) of 4.5, though their average COP is closer to 3 (Sanner and Knoblich 1997; Ohga and Mikoda 2001). For SBTES systems where the heat pump is used to move heat from a storage tank at constant temperature to the ground, the COP is expected to be higher.

2.3 Solar Thermal Panels

In addition to injecting waste heat from industry, SBTES systems may also store solar thermal energy, a readily available and free source of heat (Nussbicker et al. 2000, 2004; Mangold and Schmidt 2006; Bauer et al. 2007; Mangold 2008; McDowell and Thornton 2008). A schematic of the different closed-loop heat exchange processes involved when injecting heat from a solar thermal array to a SBTES systems is shown in Figure 3. Water heated by the solar thermal panels (which can be as much as 80 °C above ambient air temperature) is first stored within an insulated storage tank. This hot water is used to preheat refrigerant within a heat pump loop before the refrigerant enters the compressor cycle. The compressed refrigerant is then used to heat the fluid circulating within the closed-loop array of boreholes. Although ground-source heat pumps use an antifreeze solution in the closed loop system so that heat can be absorbed from the ground under ambient temperatures, these fluids often suffer from high viscosity and low thermal conductivity, indicating that alternative fluid should be investigated. The return temperature of the fluid reflects the amount of heat injected into the ground, which depends on the site characteristics as well as the routing of tubes within the borehole array. Hypothetical temperatures for the different phases are shown in the loops in Figure 3 to highlight the flow processes, and the electricity requirements for operation are shown on the left-hand side of the figure. The main energy costs for a SBTES system are associated with the electricity required for the circulation pumps and heat pump compressor.

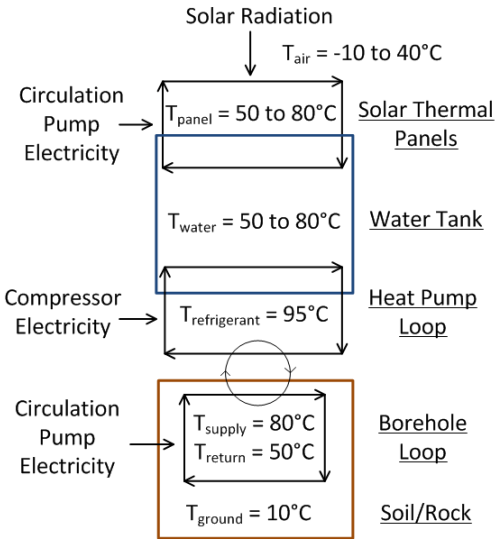


Figure 3: Schematic of solar-thermal heat injection processes in an SBTES system

The most common types of solar-thermal collectors for residential applications are flat plate collectors and evacuated tube collectors. In most climates, flat-plate collectors are the most cost-effective solution for providing domestic hot water (ΔT = 20 °C) and are easier to maintain. However, for a given solar radiation absorber area, evacuated tube collectors can reach higher temperatures and can maintain a higher efficiency of delivered solar energy (Walker et al. 2004; Trinkl et al. 2005). Evacuated tube collectors include a heat pipe that makes them act as a thermal one-way valve, so they are suitable for cold ambient temperatures and areas with low sunshine. They can collect thermal radiation from direct and reflected thermal radiation (top and bottom) and have lower wind drag (Walker et al. 2004). Walker et al. (2004) presented results from an evacuated tube collector in Philadelphia during a winter day in January that are shown in Figure 4. They observed that the panels produce heat for at least 7 hours of the day.

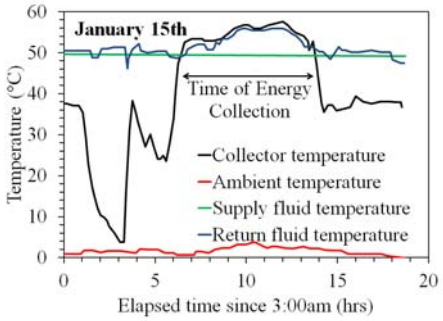


Figure 4: Evacuated tube solar thermal panel performance (Walker et al. 2004)

3. CASE HISTORIES

3.1 Overview

Two communities in North America have successfully implemented pilot programs, policies, and financing mechanisms to deploy borehole energy systems. They are the Delta Montrose Electric Association (DMEA), a rural electric cooperative serving towns in Western Colorado, and the Drake Landing Solar Community (DLSC), a Canadian government-funded pilot program near Calgary, Alberta. The programs are distinct, both in terms of technology and stage of commercialization. DMEA's program does not include a solar thermal component, using its borehole systems solely as heat sources/sinks for heat pumps. It is, however, fully commercialized and integrated into DMEA's business – the program pays for itself in the real world of energy procurement and delivery in which DMEA must operate. In contrast, the DLSC site is more technologically pioneering in its use of solar collectors in concert with a borehole field to provide seasonal energy storage and re-extraction in a cold, cloudy climate with very little reliance on natural gas back-up furnaces. However, DLSC is a pilot project of the Canadian Government, and does not represent a fully commercialized system within the energy utility paradigm. In other words, it is not clear whether a utility or community would undertake to re-create the DLSC concept on purely economic justifications.

Preliminary studies of these sites are useful resources for this project, as they demonstrate technological, policy, and market challenges that have arisen in their financing, construction, and operation. Additional communities have implemented utility-scale solar-thermal SBTES systems in Europe (Nussbicker et al. 2000, 2004; Schmidt and Nussbicker 2005; High-Combi 2008). These too, are important, but Europe's energy markets are rather different from North America's more balkanized systems. We expect to derive lessons and best-practices for policies, financing, strategy, and operation from all of these diverse sources.

3.2 DMEA

The DMEA developed a financing mechanism referred to as a "Loop Tariff" as a means of allocating capital costs for the installation of ground-source heat pump infrastructure (DMEA 2010). DMEA installs and pays for the underground loop systems, which comprise the vast majority of the capital cost of the system. Customers, in turn, purchase the heat pump unit and pay a monthly fee, or tariff, to DMEA for the use of the loop. DMEA reports that customers save substantially on monthly space conditioning costs, paying as little as 25% of the cost of electric space conditioning in some cases. This is true even when considering the additional monthly cost of the loop tariff, which is significantly lower than the monthly cost of self-financing the loop installation due to the cooperative's ability to procure lower interest rates on capital than individual customers could.

Nor do the benefits of the loop systems accrue solely to consumers. DMEA, for its part, uses the program to reduce its risk profile and costs on the wholesale energy market, because loop tariff customers use substantially less electricity at peak times than electric resistance heating and cooling would demand, resulting in lower demand charges (DMEA 2010; Nakagawa et al. 2011). In an interview in March of 2013, DMEA's loop tariff managers reported to us that its savings on demand charges, which are based on peak monthly demand, more than pays for the reduced electricity sales that it foregoes by promoting the more efficient ground source heat pump systems.

Further enhancements in the efficiency of energy recovery of SBTES systems will increase the attractiveness of this approach for communities, especially those governed by rural electrical cooperatives. These cooperatives, who generally do not own large electrical generation assets and whose sole fiduciary responsibility is to their own customers, often have more freedom to implement new solutions, and may be attracted to the possibility of storing free thermal energy near the point of collection, where it may be used locally when needed in order to reduce consumption of electricity and natural gas from distant wholesalers. The loop tariff approach proposed by the DMEA provides a baseline strategy for these communities to use in establishing the funding and policy mechanism for SBTES systems, as it solves the largest financial hurdle of the systems' higher first-cost. Interestingly, however, DMEA's loop tariff managers informed us that recent changes in the pricing structure for electricity by DMEA's wholesaler, Tri-State Generation and Transmission, have eliminated demand charges and moved to an energy-only rate, thus removing any incentive for DMEA to build further ground loops. This development poignantly illustrates how critical the nexus between market conditions, price structures, and energy-system-wide policies is to the economic viability of thermal energy systems under community financing schemes. DMEA, for its part, is optimistic that Tri-State's new rate structure will not remain, as a number of other cooperatives have threatened Tri-State with state regulatory agency appeals as well as outright lawsuits.

3.3 Drake Landing Solar Community

The DLSC is the first community-scale SBTES system in North America, and was designed to supply more than 90% of the space heating requirements for 52 houses with solar thermal energy (Sibbitt et al. 2007; McDowell and Thornton 2008). The DLSC's SBTES system is shown in Figure 5.

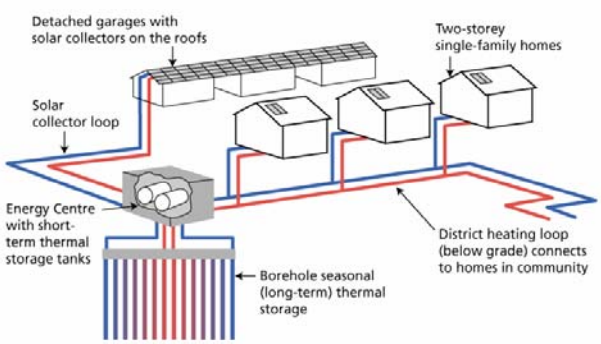


Figure 5: DLSC SBTES system (Sibbitt et al. 2007)

The system consists of an 800 panel garage-mounted array of solar collectors, an energy center for short-term thermal storage (STTS) tanks, and a SBTES system of 144 35 m-deep boreholes. Closed-loop polyethylene U-tubes in each borehole were interconnected in series. The SBTES site has plan dimensions of 30 m × 30 m, and is surrounded by an insulation-filled trench. However, the need for lateral insulation was not established through analysis.

To complement the analysis of the DLSC system by McDowell and Thornton (2008) a 3-D heat transfer analysis using TOUGH2 was performed by Zhang et al. (2012). This study used realistic heat injection and withdrawals rates measured at the site, and the predictions agreed well with measured time-dependent temperature distributions within the borehole region obtained over a 5 year period. The predicted energy recovery efficiency (defined as the heat extracted divided by the heat injected) approaches 27% after 10 years of operation as shown in Figure 6, which may improve through consideration of coupled heat and mass transport.

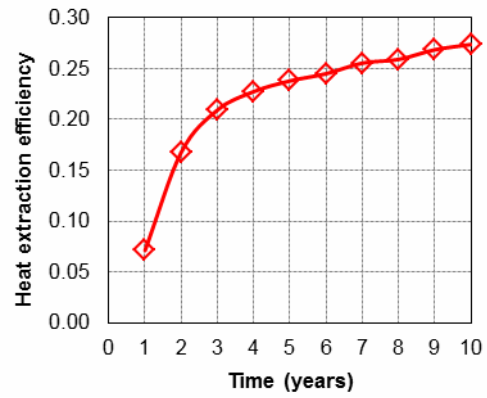


Figure 6: Simulated SBTES extraction efficiency (Zhang et al. 2012)

Although the energy recovery efficiency of existing installations may not be particularly high, this amount of energy recovery was sufficient to provide sustainable, year-round direct use heating for 52 houses at the DLSC site. It should also be noted that the heat injected was free except for the costs of operating the circulation pump.

While it is recognized that the Drake Landing case may be uneconomical in economies of scale with such a relatively small community, the proof of concept has been shown. The total cost of the subdivision was $7 million, but it is suspected that it could be repeated for half of that cost since around $3.5 million was required for design and modeling of the SBTES system. The project was heavily subsidized by the government at local and federal levels. With the energy savings obtained, a community model of Drake Landing would be economical in the free market on a larger scale and is closer in our future with the proven success of Drake Landing. The SBTES field cost estimation was broken down into the following components: (1) sub-grade excavation, borehole drilling, (2) the U-tube piping circuit, (3) special mix grouting of the boreholes, (4) the overlying insulating material, and (5) the overlying sand, and the landscaping of the field into a community park. The total cost for SBTES by our account is $500,400 to $562,800, including variable labor costs of $47,800 to $110,200. This estimation was close to the actual cost of $546,200, which is confirmed by Dr. Bill Wong of SAIC, Canada, who oversaw the Drake Landing project (Wong 2008). For the 52 houses at DLSC, this results in a cost per house of $9,615. Similar results are found for an SBTES system of similar size at Crailsheim, Germany, where the major sources of costs were drilling (52%), insulation (25%) and plumbing (17%) (High-Combi 2008). At both sites, the expenses are expected to be recovered in savings after 10 years.

4. RESEARCH APPROACH

4.1 Evaluation of the Role of Energy Policies

The concept of subsurface thermal energy storage suggests numerous potential applications to promote localized production and use of renewable resource-based thermal energy in residential and commercial buildings and at the community scale for several buildings. Indeed, two communities, DMEA and DLSC have pioneered innovative subsurface thermal energy programs and policies to promote and finance such systems based on their long-term cost savings, environmental benefits, and ability to reduce peak loads for local electric utilities. Despite their ingenuity and reported effectiveness, these programs are exploratory, rare, and poorly understood.

The DMEA and DLSC sites demonstrate both the basic technical feasibility of SBTES systems and the potential for innovative community programs and policies to drive installation without direct subsidies. The ultimate question, however, is whether such

systems can successfully scale to larger communities with highly variegated energy systems, decision-structures, markets, and regulations. Answering the scaling question satisfactorily requires both an objective and detailed understanding of existing programs that does not currently exist in the academic literature, and a comprehensive analysis of the exogenous socio-technical energy system factors that influence the development of such programs and policies. The academic literature is generally lacking in rigorous analysis of community energy governance dynamics, policy design, implementation, efficacy, and prospects for replication or adaptation in other communities.

4.2 Characterization of Transport Properties

An efficient SBTES system involves multi-phase fluid flow and heat transfer processes. As this project is exploring the active heat pipe concept involving coupled flows of liquid and vapor associated with evaporation and condensation, interrelationships between soil material properties in the SBTES must be well characterized. The main material property functions and physical processes in SBTES systems in the vadose zone are presented in Figure 7.

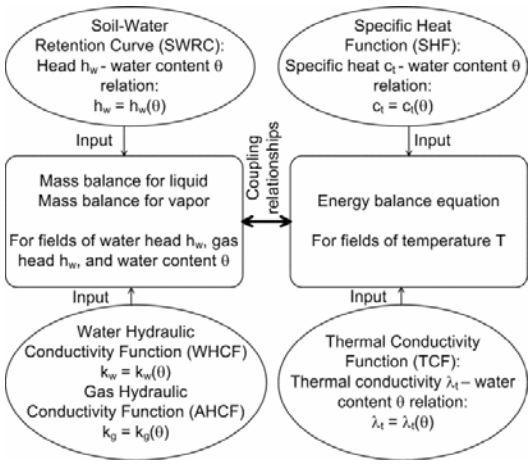


Figure 7: Illustration of coupled, multi-phase thermal-hydrologic processes and material property functions

Many of the properties noted in Figure 7 are highly non-linear, inter-related, and may be temperature dependent. An example of this coupling is shown in the thermal conductivity data for partially saturated sands shown in Figure 8 (Smits et al. 2012). The data show that sands have a higher thermal conductivity under dry conditions while under elevated temperatures. An improved experimental quantification of the material property functions and their inter-relationships for soils in SBTES systems will provide a foundation for rigorous modeling of the coupled, multi-phase thermal-hydrological processes in the vadose zone. Development of advanced measurement techniques to capture these inter-relationships will involve combinations of existing techniques, e.g., McCartney and Zornberg (2010), McCartney and Znidarcic (2010), Jougnot et al. (2011), Revil et al. (2011), Parks et al. (2012), and Wayllace and Lu (2012) for measurement of the SWRC and WHCF, Lu (1999) for measurement of the AHCF, and Smits et al. (2010, 2012) for measurement of the SHF and TCF.

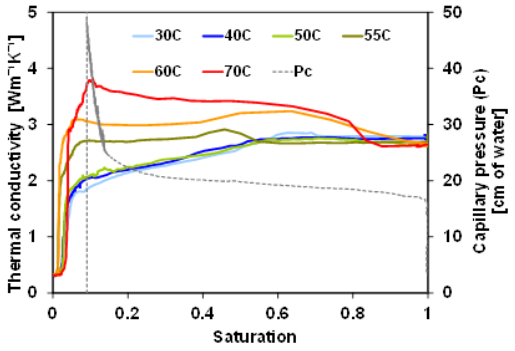


Figure 8: Thermal conductivity and capillary pressure as a function of saturation for dense sand (Smits et al. 2012)

4.3 Simulations

Most conventional SBTES systems have been studied using analytical solutions to the heat conduction equation (Carslaw and Jeager 1959; Lee 2008). This approach makes several limiting assumptions, including injection of a constant heat flux into a borehole, homogeneous thermal and hydrologic soil properties, a zero-diameter borehole, and constant initial and boundary temperatures. However, SBTES systems in the vadose zone involve coupled heat transfer and multi-phase fluid flow processes, shown schematically in Figure 7. Pruess (1991) provides a thorough summary of the mass and energy balance governing equations, although coupling relationships between these phenomena are still being explored (Smits et al. 2011a).

A properly validated computer model is best suited for defining the geometry, boundary conditions, realistic heat injection and withdrawal patterns, for site-specific design or analysis of SBTES systems having different scales. In order to capture the heat pipe phenomenon expected in SBTES systems in the vadose zone, the model must simulate coupled water, gas and heat flow processes in partially saturated porous media considering the effects of sensible and latent heat transfer. Although there are a variety of commercial and in-house numerical tools suitable for simulation of these processes, TOUGH2 (Pruess 1991; Pruess et al. 1999) may be best suited for modeling SBTES systems based on previous experience on coupled gas, liquid and heat transfer in partially saturated porous media (Lu and LeCain 2003; Zhang et al. 2012). Further, the source code of TOUGH2 can be modified, so the governing equations, coupling relationships, and material properties can be improved to capture the phenomena observed in the field and laboratory physical models. As all of the investigators have experience in different aspects of computer modeling of these flow processes, collaboration on

strategies to simulate different effects is expected. For example, heat, liquid water and water vapor flow under varying boundary conditions will be explored based on a concept that allows non-equilibrium liquid/gas phase change with gas phase vapor diffusion (e.g., Smits et al. 2011a, 2012b). Specifically, in the mass balance equations of liquid water and vapor, a source term describing a finite liquid-gas phase change rate with gas phase vapor diffusion can be included. This non-equilibrium phase change approach will be compared to the traditional equilibrium approach that assumes the water vapor concentration in the pore air is always in equilibrium with liquid water (i.e. vaporization occurs instantaneously). This new approach has been validated by Smits et al. (2011a, 2011b, 2012b), who evaluated heat and mass transfer in both 1- and 2D column and bench scale apparatuses equipped with a network of temperature and dielectric sensors with well-defined surficial thermal boundary conditions. The field and laboratory physical modeling results generated in this project will be used to further validate this approach and its significance in heat transfer for capturing 3-D transient conditions expected in the convective cells forming within the borehole arrays.

The model will also be used to design laboratory- and field-scale physical modeling experiments discussed in the following sections using the material property functions using the calibrated lab-scale data. Both forward modeling with TOUGH2 before construction, as well as inverse modeling with iTOUGH2 (Finsterle 1993) after data collection will be conducted for various field-scale scenarios. The inverse modeling will address uncertainties associated with up-scaling, material heterogeneity and boundary conditions. The well-calibrated model is expected to predict the energy storage efficiency of the SBTES under different testing conditions and will then be used to predict community-scale SBTES at other sites such as DLSC and DMEA and to perform parametric analyses.

4.4 Laboratory Tank Testing

A set of laboratory-scale tests on SBTES systems will be performed in large tanks at the Center for Experimental Study of Subsurface Environmental Processes (CESEP) at Colorado School of Mines. An example of one of these tanks is shown in Figure 9.



Figure 9: Intermediate-scale tank for thermo-hydraulic flow analyses in soils layers

Preliminary work has established the capabilities of intermediate-scale tank testing for capturing coupled liquid water, water vapor, and heat flow processes (Smits et al. 2011a, 2011b, 2012). In addition to the 3-D tank shown in Figure 9, other tanks may be used to characterize the 1-D and 2-D flow phenomena shown in Figure 1. These test tanks can incorporate dense arrays of dielectric sensors, suction sensors, thermocouples, pore gas sampling ports, etc. The laboratory tank tests are expected to permit high-resolution observations of the coupled flow processes and to perform parametric evaluations of different variables. Intermediate-scale experiments offer a convenient and cost-effective means of testing a wide range of system configurations prior to field application, as well as to better understand phenomena that may be observed during field testing. The differences in local hydrogeological conditions and thermal properties in the vadose zone may result in a distinct pattern of water saturation and temperature in the direct vicinity of SBTES systems, which can best be captured in laboratory setting where it is easier to incorporate sensors and control the soil types and placement conditions.

4.5 Field Testing

To better understand the efficiency of injection, storage, and subsequent extraction of thermal energy, a full-scale field installation of a SBTES system will be constructed in Colorado, USA. A site has been identified that consists of primarily alluvial silty-sand deposits, and the water table is approximately 20 m below the ground surface. The construction goal is to provide a modular approach to assess different heat injection strategies and SBTES installation characteristics in a real-world setting. The primary variables under investigation include borehole spacing, solar-thermal loop circulation rate, and the inlet temperatures and circulation rates for the heat exchanger loops in the borehole field. The circulation rate is critical in terms of both heat exchange as well as in energy efficiency of the heat pump (Lambert and Kavanaugh 1999). Further, the rates and pressures of fluid injection into the space between the borehole arrays to enhance heat exchange through latent heat transfer will be investigated.

A series of evacuated tube collectors will be installed at the site, with the goal of collecting over 90% of the available solar thermal energy. The solar thermal collectors will be coupled with a water storage tank that will be used to temporarily store the heat. A heat pump will then be used to move the heat from the water tank to the boreholes. This differs from the approach used at DLSC, where the heated fluid from the solar panels was directly circulated in the borehole array. A nearby building will be coupled with the borehole array to provide a realistic sink for the heat extraction process.

Although the borehole pattern may be refined based on the results of the laboratory-tank tests, it is expected that 27-30 boreholes will be installed within a 30 m × 30 m plot of land (Figure 11). The boreholes will be installed beneath the solar-thermal array to

maximize the use of space, and will be drilled to a depth of at least 30 m (below the water table). Closed-loop polyethylene U-tubes will be installed into each borehole, along with a permanent tremie pipe used to fill the borehole with grout and to serve as long-term separator between the inlet and outlet heat exchanger tubes, as shown in Figure 10.

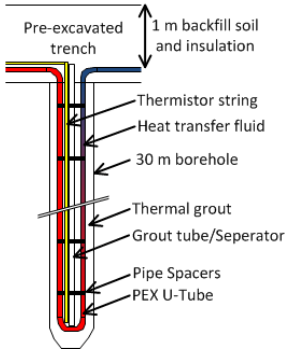


Figure 10: Heat exchanger layout in boreholes

Although typical ground-source heat pump boreholes are backfilled with sand-bentonite, this type of grout may not be suitable for use above the water table where thermally induced shrinkage may occur. Kavanaugh and Allan (1999) found that sand-cement provides the highest thermal conductivity of thermal grouts, and is not change in volume during heating and cooling. Accordingly, different sand-cement mixtures will be evaluated in the laboratory, and will be used to backfill the boreholes. Each borehole will incorporate a thermistor string, so when a borehole is not in use it will be used for monitoring. Additional boreholes may be installed to install thermistors strings, obtain soil samples, or monitor the location of the water table. The U-tubes they will be connected in series from the center borehole as shown in Figure 11, although the plumbing system will be arranged so that each borehole or the borehole group at each concentric location can be evaluated individually. The spacing of the boreholes in Figure 11 will be refined based on numerical simulations and laboratory physical modeling to ensure development of convective cells.

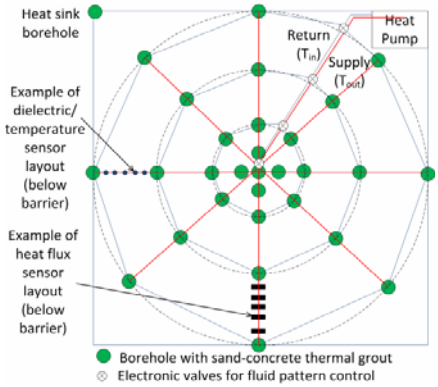


Figure 11: Preliminary borehole layout

It is critical to monitor the ground surface conditions, so an atmospheric weather station will be installed to monitor the air temperature, humidity, solar radiation, and wind speed at the site. Profiles of 5TE sensors from Decagon Devices (Sakaki et al. 2008) will be installed at strategic locations around the boreholes, to monitor changes in water content and temperature. Other variables to be monitored include the: (a) current consumption of heat pump (compressor), ground-loop circulation pump, solar-thermal circulation loop; (b) water tank temperature (inside and surrounding); (c) ambient ground temperature; (d) inlet/outlet temperatures for each borehole; (e) inlet/outlet temperatures for each solar/thermal panel (for a given orientation); (f) temperature profiles in the boreholes/observation locations.

5. CONCLUSIONS

This paper describes the details of a new project involving the evaluation of SBTES systems in the vadose zone. The experience with existing SBTES systems indicates that they will be an economical approach for thermal energy storage, especially with further research to refine operations and efficiency. The construction of this facility in the vadose zone may permit enhanced heat injection as well as greater storage of heat.

REFERENCES

Andersson, O. (1997). ATES utilization in Sweden – An overview. Proc. MegaStock'97. 7th International Conference on Thermal Energy Storage. Sapporo, Japan. June 18-21, 1997.

Bakema, G., Snijders, A.L., Nordell, B. (1995). Underground Thermal Energy Storage State of the Art Report 1994. Arnhem, The Netherlands: IF Technology.

Bauer, D., Heidemann, W. and Steinhagen, H. (2007). Central solar heating plants with seasonal heat storage. Renewables in a Changing Climate. Lausanne, Switzerland. September 2007.

Carslaw, H.S. and Jeager, J.C. (1959). Conduction of Heat in Solids. Oxford: Clarendon Press, 2nd Edition.

Choudary, A. (1976). An Approach to Determine the Thermal Conductivity and Diffusivity of a Rock In Situ. Ph.D. Thesis. Oklahoma State University. 1976

Delta Montrose Electric Association (DMEA). (2010). About Geoexchange. http://www.dmea.com/index.php?option=com_content&view=article&id=60&Itemid=64.

Dickinson, J.S., Buik, N., Mathews, M.C., and Snijders, A. (2009). Aquifer thermal energy storage: theoretical and operational analysis. Geotechnique. 59(3), 249-260.

ECES (Energy Conservation through Energy Storage). (1997). Annex 12: High-Temperature Underground Thermal Energy Storage. International Energy Agency. Paris, France.

Finsterle, S. (1993). iTOUGH2 User's Guide Version 2.2. Report LBL-34581. Lawrence Berkeley Laboratory, Berkeley, CA.

Gabrielsson, A. Lehtmets, M. Moritz, L. and Bergdahl, U. (1997). Heat Storage in Soft Clay Field Tests with Heating (70 °C) and Freezing of the Soil. Report 53, Swedish Geotechnical Institute. Stockholm, Sweden.

Gao, Q., Li, M., Yu, M., Spitler, J.D., and Yan, Y.Y. (2009). Review of development from GSHP to UTES in China and other countries. Renewable and Sustainable Energy Reviews. 13, 1383–1394.

Gehlin, S. and Spitler, J. (2003). Thermal response test for BTES applications: State-of-the-art 2001. 9th International Conference on Thermal Energy Storage, Warsaw Poland, 2003.

Guven, O., Melville, G., and Molz, F.J. (1983). An analysis of the effect of surface heat exchange on the thermal behavior of an idealized aquifer thermal energy storage system. Water Resources Research. 19(3), 860-864.

High-Combi. (2008). High solar fraction heating and cooling systems with combination of innovative components and methods. Report STREP. European Union.

Hughes, P. (2008). Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers. Oak Ridge National Laboratory, U.S. Department of Energy.

Jougnot, D., Revil, A., Lu, N., and Wayllace, A. (2010). Transport properties of the Calloxo-Oxfordian clay-rock under partially saturated conditions, Water Resources Research, 46, W08514, doi:10.1029/2009WR008552.

Kanoglu, M. (2002). Exergy analysis of a dual-level binary geothermal power plant. Geothermics. 31, 709–724.

Kanoglu, M. and Bolatturk, A. (2008). Performance and parametric investigation of a binary geothermal power plant by exergy. Renewable Energy 33, 2366–2374.

Kavanaugh, S.P. and Allan, M.L. (1999). Testing of enhanced cement ground heat exchanger grouts. ASHRAE Transactions. 105(1), 446–450. Chicago.

Lambert, S.E. and Kavanaugh, S.P. (2004). Operation performance of GSHP system pumping alternatives. ASHRAE Transactions, 111, Pt. 1, Atlanta.

Lee, K.S. (2008). Performance of open borehole thermal energy system under cyclic flow regime. Geosciences Journal, 12(2), 169-175.

Lu, N. (1999). Time-series analysis for determining vertical air permeability in unsaturated zones. Journal of Geotechnical and Geoenvironmental Engineering, 125(l), 69-77.

Lu, N. (2001). An analytical assessment on the impact of covers on the onset of air convection in mine wastes. International Journal for Numerical and Analytical Methods in Geomechanics. 25:347-364

Lu, N., and LeCain, G. (2003). The use of temperature data to estimate infiltration flux beneath a desert wash. Journal of Geotechnical and Geoenvironmental Engineering. 129(11), 1040-1053.

Mangold, D. (2008). Seasonal Heat Storage: Pilot Projects & Experiences in Germany. Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems. Stuttgart, Germany.

Mangold, D. and Schmidt, T. (2006). The New Central Solar Heating Plants with Seasonal Storage in Germany. EuroSun, Glasgow UK, June 2006.

McCartney, J.S. and Znidarcic, D. (2010). “Test System for Hydraulic Properties of Unsaturated Nonwoven Geotextiles.” Geosynthetics International. 17(5), 355-363.

McCartney, J.S. and Zornberg, J.G. (2010). Centrifuge permeameter for unsaturated soils II: results and analysis. ASCE Journal of Geotechnical and Geoenvironmental Engineering. 136(8), 1064-1076.

McDowell, T.P., and Thornton, J.W. (2008). Simulation and model calibration of a large-scale solar seasonal storage system. Third National Conference of IBPSA-USA, Berkeley, California, July 30-August 1, 2008.

Meyer, C.F. and Todd, D.K. (1973). Are heat-storage wells the answer? Electrical World, Aug. 15, 1973, New York, 42-45.

Molz, F.J., Waarman, J.C. & Jones, T.E. (1978). Aquifer storage of heated water: Part I – A field experiment. Ground Water. 16(4), 234-241.

Molz, F.J., Parr, A.D., Andersen, P.F., Lucido, V.D. & Warman, J.C. (1979). Thermal energy storage in a confined aquifer, experimental results. Water Resources Research 15/6, Washington, 1509-1514.

Monzo, P.M. (2011). Comparison of Different Line Source Model Approaches for Analysis of Thermal Response Test in a U-pipe Borehole Heat Exchanger. KTH School of Industrial Engineering and Management. Stockholm, Sweden.

Nakagawa, M., Reed, A., Fujiomi, H., and McCartney, J.S. (2011). Geothermal Academy: Focus Center for Data Collection, Analysis and Dissemination. Department of Energy. Report DE-FOA-0000116. 114 pp.

Natural Resources Canada. (2010). Drake Landing Solar Community. http://www.dlsc.ca/index.htm.

Nussbicker, J., Heidemann, W., and Steinhagen, H. (2000). Monitoring Results and Operational Experiences for a Central Solar District Heating System with Borehole Thermal Energy Store in Neckarsulm (Germany). Stuttgart, Germany.

Nussbicker, J., Mangold, D., Heidemann, W., and Steinhagen, H. (2004). Solar Assisted District Heating System with Seasonal Duct Heat Store in Neckarsulm-Amorback (Germany). EuroSun 2004, Freiburg Germany, June 2004.

Ohga, H. and Mikoda, K. (2001). Energy Performance of Borehole Thermal Energy Storage Systems. Seventh Int. IBPSA Conference. Rio De Janeiro, Brazil. August 13-15, 2001.

Paksoy, H.O., Andersson, O., Abaci, S., Evliya, H. and Turgut, B. (2000). Heating and cooling of a hospital using solar energy coupled with seasonal thermal energy storage in an aquifer. Renewable Energy. 19, 117-122.

Parks, J.M., Stewart, M.A., and McCartney, J.S. (2012). Validation of a centrifuge permeameter for investigation of transient infiltration and drainage flow processes in unsaturated soils. Special Issue on Advances in Experimental Characterization of Unsaturated Soils, Volume 2. ASTM Geotechnical Testing Journal. 35(1), 11pg.

Pruess, K. (1991). TOUGH2: A General-purpose Numerical Simulator for Multiphase Fluid and Heat Flow. Lawrence Berkeley Laboratory, LBL-29400, Berkeley, CA.

Pruess, K., Oldenburg, C. and Moridis, G. (1999). TOUGH2 User's Guide, Version 2.0. Lawrence Berkeley National Laboratory Report LBNL-43134, Berkeley, CA.

Revil, A., Woodruff, W., and Lu, N. (2010). Constitutive equations for coupled flows in porous media. Water Resources Research. 47, W05548, doi:10.1029/2010WR010002.

Sakaki, T., A. Limsuwat, K. M. Smits, and T. H. Illangasekare (2008). Empirical two-point alpha mixing model for calibrating the ECH2O EC-5 soil moisture sensor in sands. Water Res. Res. 44: W00D08, doi:10.1029/2008WR006870.

Sanner, B. and Knoblich, K. (1998). New IEA-Activity ECES Annex 12: high temperature underground thermal energy storage. Journal of Underground Thermal Storage and Utilization. 98, www.geo-joumal.stockton.edu.

Schmidt, T. and Nussbicker, J. (2005). Monitoring results from German central solar heating plants with seasonal storage. ISES 2005 Solar World Congress, Orlando Florida, August 6, 2005.

Sibbitt, B., Onno, T., McClenahan, D., Thornton, J., Brunger, J., Wong, B. (2007). The Drake Landing solar community project – early results. Canadian Solar Buildings Conference, Calgary, June 10-14.

Smits, K.M., Cihan, A. Sakaki, T. and Illangasekare, T.H. (2011a). Evaporation from soils under thermal boundary conditions: Experimental and modeling investigation to compare equilibrium- and nonequilibrium-based approaches, Water Resources Res., 47, W05540, doi:10.1029/2010WR009533.

Smits, K.M., Sakaki, T., Limsuwat, A. and Illangasekare, T.H. (2010). Thermal conductivity of sands under varying moisture and porosity in drainage-wetting cycles. Vadose Zone Journal. 9:doi:10.2136/vzj2009.0095.

Smits, K.M., A. Cihan, V. Ngo, T. Sakaki, and T.H. Illangasekare (2012). An evaluation of models of bare soil evaporation formulated with different land surface boundary conditions and assumptions. Water Resour. Res., 10.1029/2012WR012113

Smits, K.M., T. Sakaki, S.E. Howington, J. F. Peters and T.H. Illangasekare (2012). Temperature dependence of thermal properties of sands over a wide range of temperatures [30-70oC], Vadose Zone J., 10.2136/vzj2012.0033

Snijders, A.I. and Bakema, G. (1997). The successful introduction of aquifer cold storage in the Netherlands. Proc. MegaStock'97. 7th International Conference on Thermal Energy Storage. Sapporo, Japan. June 18-21, 1997.

Trinkl, C., Zorner, W., Alt, C., and Stadler, C. (2005). Performance of vacuum tube and flat plate collectors concerning domestic hot water preparation and room heating. 2nd European Solar Thermal Energy Conference. Freiburg, Germany. June 21-22, 2005.

Walker, A., Mahjouri, F, Stiteler, R. (2004). Evacuated-tube heat-pipe solar collectors applied to the recirculation loop in a federal building. Solar 2004 Conference. Portland, Oregon. July 11-14, 2004

Wayllace, A., and Lu, N. (2012) Transient water release and imbibitions method for rapidly measuring wetting and drying soil water retention and hydraulic conductivity functions, Geotechnical Testing Journal, 35(1), Paper ID GTJ103596.

Wong, B. (2008). The Drakes Landing Solar Community. Toronto & Region Conservation Authority, Alberta, July 30, 2008.

Zhang, R., Lu, N., and Wu, Y-S. (2012). Efficiency of a community-scale borehole thermal energy storage technique for solar thermal energy. In Proceedings of ASCE Geo-Institute Annual Conference, Oakland, CA.

Acknowledgements

Funding provided by NSF grant 1230237 is much appreciated. The views in this paper are those of the authors only.