Seasonal Underground Thermal Energy Storage Using Smart Thermosiphon Technology

Kent S. Udell[1], Phil Jankovich[2], and Bidzina Kekelia[2]

[1]**Professor and Chair, Department of Mechanical Engineering, University of Utah**

[2]**Research Assistants and PhD Students, Department of Mechanical Engineering, University of Utah**

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ABSTRACT

In climates with hot summers and cold winters, it is thermodynamically possible to provide all heating and air-conditioning needs without significant fuel or electrical energy input if adequate thermal energy storage capacity exists. Because all buildings sit on massive volumes of soil, water and rock, capacity is not the problem. The obstacle in meeting that goal is the lack of technology to readily transfer heat to and from soil in a cost effective manner. Enhancement of heat transfer rates coupled with an order of magnitude drop in installation cost over current practices would likely lead to the widespread use of seasonal underground thermal energy storage (UTES).

Smart thermosiphon technology may be a path to those technical and economic goals. This technology uses conventional passive thermosiphon technology to transfer energy out of soil, and controlled rate transfer of energy into the soil. In this paper, we describe how smart thermosiphon technology can facilitate ample seasonal energy storage to meet air conditioning and winter heating needs. Simulations of soil freezing within an array of thermosiphons and the use of those frozen soils to provide air conditioning demands will be presented. A comparison of heat transfer from looped tubes inserted in vertical wellbores with the calculated heat transfer from thermosiphons shows that the same total heat transfer rate can be realized using 40% of the borehole length if smart thermosiphon technology is used.

Results of the testing of a lab-scale experimental smart thermosiphon demonstrate that uniform temperatures and heat fluxes can be maintained on the inside wall of the thermosiphon pipe, thus proving the potential for dramatic enhancements of heat transfer rates. Winter heating and summer air conditioning modes have been demonstrated. The first pilot-scale installation of smart thermosiphons for seasonal UTES has demonstrated the ability to install the devices using inexpensive direct push techniques.

Introduction

As we consider a future where we'll meet our energy needs in ways that don't produce emissions of carbon dioxide, we note that 25% of the CO_2 the US produces is from burning fossil fuels to meet residential energy needs, mostly for heating and air conditioning [1]. It is also known that conservation produces the greatest decrease in CO_2 production per dollar spent [2]. However, options for carbon-free heating and air conditioning are essentially non-existent.

Interestingly, some of the greatest home heating and air conditioning energy uses are found in climates where the winters are cold and the summers are hot. In those climates, there is no thermodynamic reason why summer heat can't be stored for future winter heating or winter "cold" stored to provide air conditioning in the summer - while using minimal fossil fuel or electrical energy. In essence, seasonal thermal energy storage heating and cooling can provide zero-carbon heating and air conditioning. The limiting technical problems in the way of the routine use of this approach are related to the huge energy storage needs, and the heat transfer limitations associated with energy transfer between the building, the ambient conditions and the storage medium. Thus, such concepts have not been explored to much of an extent. However, if the heat transfer and storage problems can be solved, there is huge potential for energy savings and CO_2 reductions using seasonal thermal energy storage.

This paper details the use of a new technology – Smart Thermosiphons - to effectively transfer heat to and from soils. Based on preliminary analysis and experimental data, it is clear that such devices will allow the transfer of sufficient thermal energy to and from the ground to facilitate seasonal thermal energy storage on a scale to provide all heating and cooling needs of a typical house or business. The goal is a 100% carbon-free heating and cooling system that is indistinguishable in simplicity of operation and comfort from conventional HVAC systems.

Soil for Energy Storage

If soil is used as energy storage medium, there is no restriction on the storage volume other than the potential constraint of keeping near-surface ground temperatures close to their natural values to avoid unwanted impact on surface soil flora and fauna. If heated and cooled in an optimum way, soil can provide not only a buffer for short term fluctuations in supply and demand, but can accommodate a complete annual heating/cooling load and serve a seasonal balancing function. Energy storage directly in the soil also reduces the cost sensitivity of reservoir depth on optimum capacity selection. So the storage system can be easily sized to maximum expected load by a simple increase of depth in most cases.

Relationship to Ground-Coupled Heat Pump Applications

Rather than heating or cooling the soil for future energy use, in this application, the primary intent of ground-coupled heat pumps is to take advantage of the earth's relatively constant temperature. Thus, energy dissipation rather than storage is sought. But in most cases, ground coupling is not very effective, too complex, or too costly. An improvement in means to improve heat transfer to and from the soil would dramatically increase the market for ground-coupled heat pumps.

When plastic pipes are used in heat pump systems to exchange heat with the soil, the generally accepted assumption of negligible thermal effects in plastic pipes may not be an accurate representation of the thermodynamic coupling with the ground. Plastic (PVC and Polyethylene) pipes were introduced for economic reasons, justified by the argument that resistance to heat transfer is much greater in the soil than to the working fluid. However, in [3] it is shown that heat flows are substantially reduced (nearly half) due to high thermal resistance of the pipe walls and contact resistance between pipe and soil. Also, for vertical boreholes with closed loop tubing, "short circuiting" of heat from the hot tube to the adjacent cold tube decreases the amount of heat that can be transferred to the soil. This problem likely worsens as the tube spacing decreases. The installation cost for vertical borehole installation is also high, requiring dozens of large (8 inch) diameter boreholes to be drilled to depth for loop insertions. In such commercial installations, an improvement in the heat transfer between the ground and the heated space is of great importance and enormous potential economic value. Application of smart thermosiphons as a means of coupling heat pumps with the ground seems to be a very simple and effective step forward.

Heat Transfer Enhancement Using Thermosiphons

The heat pump systems described in the previous section can be replaced with a mostly passive system operating on much more effective natural convection and latent heat capture/release phenomena. If borehole piping is replaced with pump-assisted thermosiphons and connected directly to a heat exchanger in the heated or cooled space, then there would be no need for intermediary heat transfer fluids. Indeed, with the right configuration and operation, thermosiphons can eliminate the need of the heat pump, its electrical energy consuming compressor, and additional intermediary heat exchangers and pumps to move working fluids (Figure 1).

Passive Soil Cooling Mode

The two-phase thermosiphon considered for system performance improvement operates on a simple heat pipe principle (Figure 1). Heat from the soil vaporizes the thermosiphon's working fluid inside of the sealed pipe. The resulting vapor moves up and carries its latent heat to the heat exchanger where it condenses as heat is removed. That heat exchanger would be placed in the cold winter air if the intent is to cool the soil for future use as an air conditioning heat sink, or, if taking energy from heat soils for winter heat, in the HVAC ducting to heat air. The condensate liquid then drains back down the thermosiphon and repeats the cycle.

Soil and water in the vicinity of the thermosiphon cool down, giving up the energy. This creates water convection in the soil, with colder water sinking downwards and bringing fresh warmer water towards the thermosiphon, which increases the heat flux from the soil.

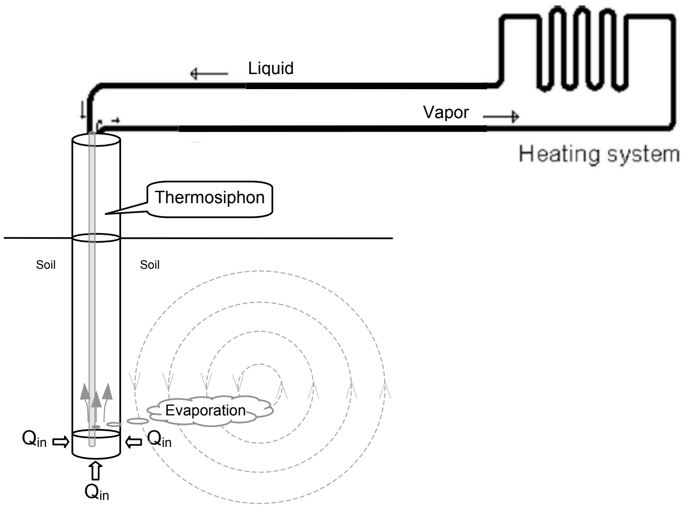

Figure 1. Passive space heating with thermosiphon (heat extraction from the ground).

It should be noted that the above described passive mode of operation for space heating will work satisfactorily only if soil is heated in summer to above 25-28°C. If soil temperature drops below 24-25°C there will be a need for a "booster" small heat pump in order to supply the room heat exchanger with the working fluid saturated vapor at approximately 30-35°C.

Smart Soil Heating Mode

Cooling of space can be achieved by reversing the working fluid flow direction in the system (Figure 2). In this case, the smart thermosiphon returns liquid from the bottom of each thermosiphons to the evaporator heat exchanger. Depending on the application (heat rejection to chilled soil in the summer or heating of soil for future winter heating) the evaporator would be different. For air-cooling purposes, the evaporator might be identical to the heat exchangers found in millions of homes using vapor compression central air conditioning. As in current residential installations, the liquid phase flows to the heat exchanger and the vapors leave to be re-condensed. With chilled soils and smart thermosiphons in place, the outside air conditioning units would be eliminated (as would their electrical load and their noise). Heat would thus move from the air-conditioned space to the chilled walls of the thermosiphon, giving up its heat to the surrounding soil. The Smart Thermosiphon returns liquid condensate to the heat exchanger at a rate determined by the mass flow rate of vapor entering the thermosiphon.

In the soil heating mode, natural convection is expected in permeable soils outside of the thermosiphon walls. Water near the bottom of the thermosiphon heats up and moves up towards the surface, bringing a cooler water stream in from the bottom and sides. This convection increases the heat flux to the ground and could be advantageous near the thermosiphon or harmful outside the heated volume if it leads to increased heat exchange with far field soils. If storing energy during the summer for future winter heating use, it may be possible to increase the thermosiphon wall temperature to over 100°C, initiating water "boiling" on the outside wall of the thermosiphon. If the water vaporized on the wall is replenished by capillary action in the soil, an extremely effective heat transfer phenomena called the heat pipe effect [4] can be exploited to overcome near wall heat transfer limits.

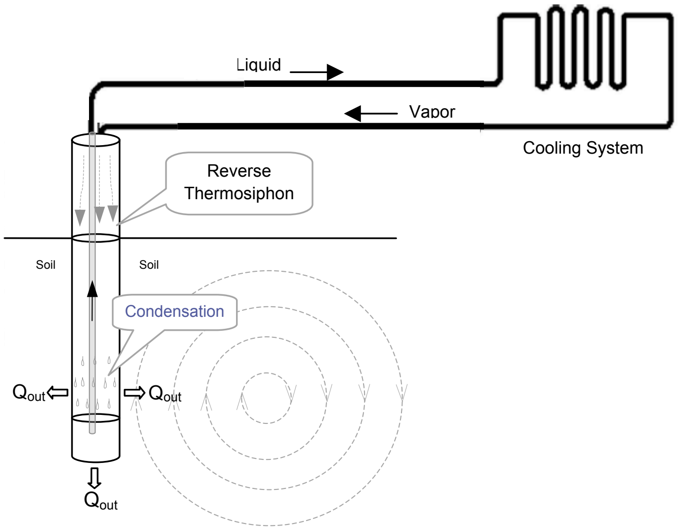

Figure 2. Space cooling using a smart thermosiphon (heat injection into the ground).

The cooling load (especially in southern United States) is normally higher than the heating load. If, in winter, sufficient heat is removed from the soil, then underground thermal storage can become an excellent way to create an energy sink for summer.

Modeling

The performance of a set of 7 thermosiphons for freezing soils and the use of frozen soil as an air conditioning heat sink was assessed using a two-dimensional model. The model was created using the commercially available software package COMSOL Multiphysics 3.3. The geometry chosen for the analysis was an array of six thermosiphons placed at the corners of a symmetrical hexagon with a seventh thermosiphon placed at the center of the hexagon. Utilizing the symmetry of the system, a quarter circle with a 5-meter radius was chosen as the domain of interest. Three thermosiphons were modeled in this domain: one positioned centrally and the other two placed 60 degrees apart with one of them on the axis of symmetry. The spacing between thermosiphons was 1.5 meters. Only conduction was modeled in this basic rendition.

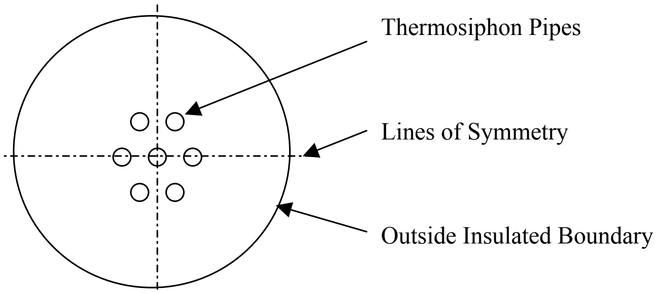

Figure 3. Plan view of thermosiphon pattern. Using the symmetry of the pattern of 7 wells, the two dashed lines are planes of temperature and heat flux symmetry. Only the top right quadrant is modeled and displayed.

Modeling Results

The model was run for the full year. The temperature distributions in the domain (in °F) are shown in Figure 4 on the 15th of each month. The maximum and minimum temperatures in the domain are also shown. The absolute minimum (17 °F) occurs in January next to the wall of the heat pipe. The maximum temperature that occurs next to the heat pipe during the summer season does not exceed initial conditions. As can be seen, the soil between the heat pipes freezes during the winter and remains frozen throughout the summer and into September.

A comparison of the results obtained in this simulation was made to results obtained for a design of a ground loop heat ex-

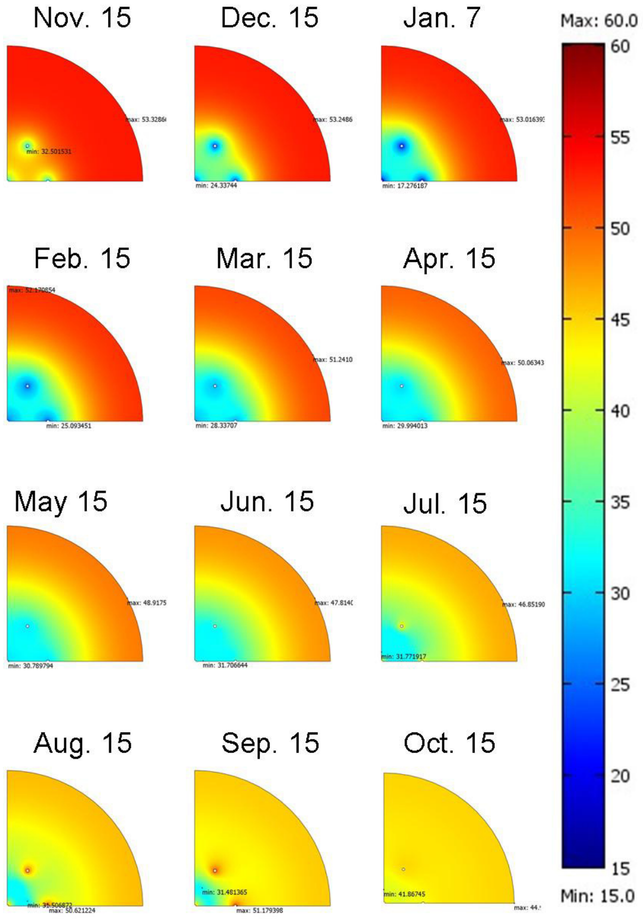

Figure 4. Results from COMSOL simulation. All temperatures have units of °F.

changer by Spitler in his software package GLHEPro [5]. The example that Spitler uses in this design tool has a total cooling load of 95.600 MW-hr, as shown in his Table 1. GLHEPro indicates that for this load, 3796.7 meters of borehole would be required. This corresponds to 25 kWh of load per meter of borehole. In comparison, the results obtained from this simulation shows a load of 62.4 kWh per meter of thermosiphon – a 250% increase in heat transfer. In other words, ground loop heat exchangers typical of common practice requires 2.5 times the amount of drilling depth of thermosiphon technology for the same heat transfer.

Smart Thermosiphon Prototype

An experimental smart thermosiphon (Figure 5), with capability of both winter (passive) and summer operation modes, has been built with an 11.5cm (4.5") diameter, 140cm aluminum tube with a welded flange on the top. The working liquid (R-134a) passes through a three-way valve (used to reverse the flow for winter or summer operation) and is supplied to the heat exchanger (operating as an evaporator or condenser, depending on the mode of operation) placed at the top of the experimental device. The smart thermosiphon is capable of reversing the heat flow direction by supplying working liquid to the heat exchanger (evaporator). The apparatus is capable of field-scale simulation of the dominant heat transfer mechanisms found in smart thermosiphons in contact with various media. Operation in subfreezing outdoor temperatures demonstrated uniform ice buildup on the outside wall of thermosiphon during passive operation (Figure 6).

(a) (b)

Figure 5. Smart thermosiphon in test tank (a) and removed (b) from tank to show scale and thermocouple array. The reversible thermosiphon was designed and built in the Department of Mechanical Engineering at the University of Utah.

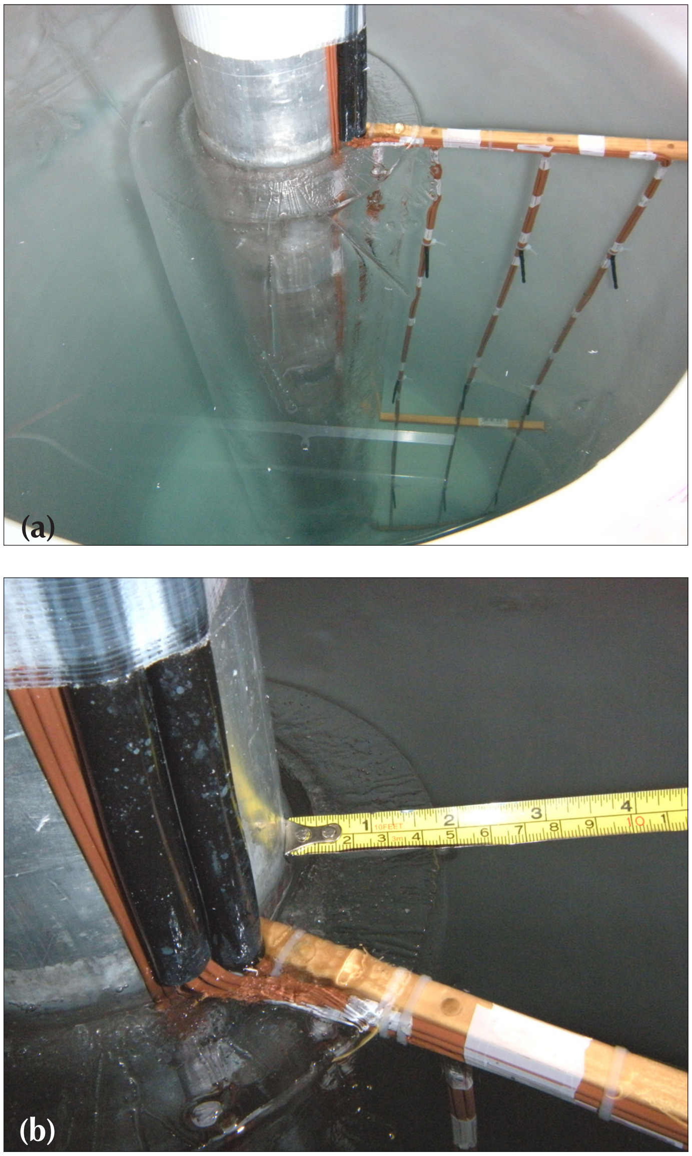

Figure 6. Uniform ice buildup on thermosiphon wall (a) measuring approximately 45mm (b).

Pilot Scale Implementation

A pilot scale demonstration of smart thermosiphons is underway. The thermosiphon pipes were installed using a direct-push method of drilling (Figure 7a). Based on commercial bids, GeoProbe installation costs are about one tenth the cost of drilling an 8" borehole. Direct push installation also eliminated the need for drilling mud and handling of removed soils. Seven pipes were installed to a depth of 10 feet in the configuration shown in Figure 3. Above ground heat exchangers were constructed of copper and are shown in Figure 7b.

Summary

Research to date has demonstrated the heat transfer enhancements, operation, and cost effectiveness of smart thermosiphons to transfer energy into and out of the ground. Simulations show that

(a) (b)

Figure 7. Direct punch drilling (a) and above ground heat exchangers (b).

clustered smart thermosiphons are capable of facilitating seasonal UTES without significant fuel or electricity input.

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