Conference Proceedings

ASES National Solar Conference 2016

San Francisco, CA, USA July 10-13, 2016

# Solar Thermal Collection with Seasonal Storage

**Gaylord Olson[1], Yao Yu[2]**

[1] Temple University, Mech. Engr. Advisory Committee, Philadelphia, PA (USA)

[2] North Dakota State University, Fargo, ND (USA)

### Abstract

A system will be described which combines several different types of solar thermal collectors with a specific arrangement of valves to optimize the collection of heat and (if needed) the collection of cold. The collection of both heat and cold (dissipation of heat) is possible by using unglazed collectors as part of the system. The system may also include a type of seasonal underground thermal energy storage which is an extension of concepts already in use at Drake Landing Solar Community in Alberta, Canada and ICAX Limited in London, England. The results of simulating the underground heat transfer and thermal storage will be displayed. Factors that could impact the performance of underground heat storage will be discussed, including climate, building location, underground/soil thermal condition, building heating/cooling demands, heat dissipation/loss from the ground, etc. There will be a need to optimize many of the system parameters, such as dimensions, material properties, flow rates, etc. to get the best result for any specific building or set of buildings. It is our expectation that systems such as those described here could be significantly more cost-effective than systems in use currently.

Keywords: *solar, thermal, collector, underground, storage, seasonal*

## 1. Introduction

In the United States today the terms “solar energy” or “solar power” are nearly always assumed to be related to electricity generation. Other countries seem to have a broader view of the word solar, and have recently shown many interesting new ways to extend solar thermal technology (Good and Gora, 2016; Hesaraki et al., 2015). Pean et al. (2015) have shown the nighttime radiative cooling potential of the unglazed solar collectors and photovoltaic/thermal panels that are typically used for heat collection. Radiation cooling from an unglazed collector can be used on either a diurnal or a seasonal basis. Man et al. in 2011 designed a system that couples unglazed solar collectors located on the roof with underground heat exchangers. This system could be used during night to reject the accumulated heat from the ground heat exchangers to the outside mainly by radiation and convection through the collectors. An experimental and analytical study has been done by Xu et al. in 2015 to evaluate the performance of a radiative cooling system that consists of flat plate collectors. Seasonal thermal energy storage represents the storage of heat or cold with a long-time duration, such as several months (STES, 2016). An example for this is to seasonally store the summer heat in order to use it during cold seasons when heating is needed. An actual thermal energy storage project (Drake Landing Solar Community, 2016) in Alberta, Canada involves the seasonal storage of solar thermal heat collected through 800 solar thermal collectors during summer, which is transferred into the ground through 144 vertical boreholes with a depth of 37 meters for use during winter. It is reported that the ground temperature can be up to 80 ºC by the end of summer season, which is sufficiently high for the direct use of the underground heat during winter.

This paper is intended to show some additional new ways to use conventional (and some unconventional) solar thermal collectors to provide both heat and cold collection and to combine these with water source heat pumps for a more cost-effective method of space heating and cooling of buildings. It is also possible that the combination of some of these new methods along with seasonal underground storage and advances in low energy building technology such as passive house designs might allow for cost-effective Heating, Ventilating, and Air Conditioning (HVAC) systems without using heat pumps in the system. Another possibility is the extension of a flat plate solar thermal collector to include a modification which allows it to be used for efficient heat and cold collection using both radiative and convective thermal transfer for cooling. Many of the concepts described here are included in one or more recent patents or are patent pending.

## 2. Combining Multiple Collector Types

A large number of different products can be used for collection of solar thermal energy and air to liquid heat exchange (Table 1).

**Tab. 1: Multiple collector and heat exchanger types**

| Solar thermal collection | Air to liquid heat exchange |
|---|---|
| • Unglazed solar panels<br>• Glazed flat plate solar panels<br>• Evacuated tube or parabolic concentrator collectors | • Unglazed solar panels<br>• Fin-and-tube heat exchanger (using water or refrigerant)<br>• Cooling tower |

Another way to achieve thermal collection and heat exchange (although it is not a specific product) is to use a horizontal array of pipes that is buried just below the earth's surface. For example, this could be below a parking lot or road (Carder et al., 2007). This concept has been pioneered by a company in London, England: ICAX Limited (www.icax.co.uk).

The products listed in Table 1 have been primarily used in systems where only one product at a time is in use. It is possible that several of the products above can be used together in a single system to give multiple functionality (both heat and cold collection) and also provide improvements in performance and cost-effectiveness.

As an example, consider the need to collect thermal energy with seasonal (very long term) storage. The project described before, Drake Landing Solar Community, uses glazed flat plate collectors exclusively. In this case there is a need for temperatures that are higher than can be obtained from the less expensive unglazed collectors. As a point of reference, glazed collectors are 5 to 8 times more expensive than unglazed collectors per unit area. This means that if low temperatures can be tolerated, the unglazed panels might collect more thermal energy per dollar per year than any other product.

A way to utilize the features of both glazed and unglazed collectors together is shown in Figures 1(a) and 1(b). These figures show a series connection between the two arrays of panels (collectors), however a three-port valve is used to bypass around the unglazed panels when this is called for. It is assumed that there are temperature sensors and a computer to automatically control the valve condition. The method of operation is such that on a calm, warm, sunny day the valve is set such that the water flows through the unglazed array to be preheated before being more completely heated with the glazed array. The term "array" here is intended to mean one or more panels connected in a series, parallel, or series-parallel arrangement. Figures 1(a) and 1(b) show nearly identical functionality. The optimum choice might relate to where the best physical locations of valves and pipes are in a given installation.

To be more specific about the operation of Figures 1(a) and 1(b), it is known that the efficiency of these collectors can be represented in Equation 1 and depends primarily on three parameters:

- incident irradiance on the collector
- inlet water temperature
- ambient air temperature

$$\eta = F_R\tau\alpha - F_R U_L\left(\frac{T_{in}-T_a}{I}\right) = \frac{m\cdot c_p(T_{out}-T_{in})}{A\cdot I}, \qquad \text{(eq. 1)}$$

where m (kg $s^{-1}$) is the mass flow rate of the fluid; $c_p$ (J $kg^{-1}$ $K^{-1}$) is the specific heat of the fluid; A($m^2$) is the collector glass cover area; I (W $m^{-2}$) is the intensity of solar irradiation; $T_{in}$ (°C) is the inlet fluid temperature; $T_{out}$ (°C) is the outlet fluid temperature; ηis the thermal efficiency of a collector; $F_R$is the collector heat removal factor (less than 1.0); $U_L$ (W $m^{-2}$ $K^{-1}$) is the collector overall heat loss coefficient; τ is the transmittance of the glass cover (the fraction of incoming solar radiation that reaches the absorber plate of the collector); α is the absorptance of the absorber plate (the fraction of solar energy reaching the plate surface and being absorbed); and $T_a$ (°C) is the ambient air temperature.

The efficiency goes down when the irradiance and the air temperature go down, and the inlet water temperature goes up. This relationship applies to all of the solar collector types listed above except for a parabolic dish type. An efficiency greater than zero means that the output temperature from a collector is greater than the input temperature. When this condition exists for the unglazed array, the water entering the glazed array is effectively preheated, thereby giving a net increase in energy collection for the system and more cost-effective collection. When this condition no longer exists, the efficiency might be effectively negative (meaning that the unglazed array is actually cooling the water rather than heating it). In this case the unglazed array needs to be bypassed (using the three-port valve) since it is doing more harm than good. It is to be noted from Equation 1 that the three parameters above do not need to be specifically known, as long as the inlet and outlet temperatures for the unglazed array are sufficiently known. This is now a system with two different collector types which allows for both high output temperature and a lower total cost for the collectors for a given amount of thermal energy collection.

Notice in Table 1 that the unglazed solar collectors can also be used as air to liquid heat exchangers. This means that a system similar to Figures 1(a) and 1(b) might also serve to collect cold for use in summer season air conditioning. Seasonal storage of cold has been done at various places in Europe such as ICAX and others. The glazed panels in Figures 1(a) and 1(b) will not be very useful for the collection of cold, since the glazing over the panels is specifically designed to prevent this. The cold collection might best be done with the use of a second bypass valve as shown in Figure 1(c). This valve (V2) serves to bypass around the glazed array when cold collection is being done. It is assumed that there will be multiple temperature sensors and a computer to control the two valves.

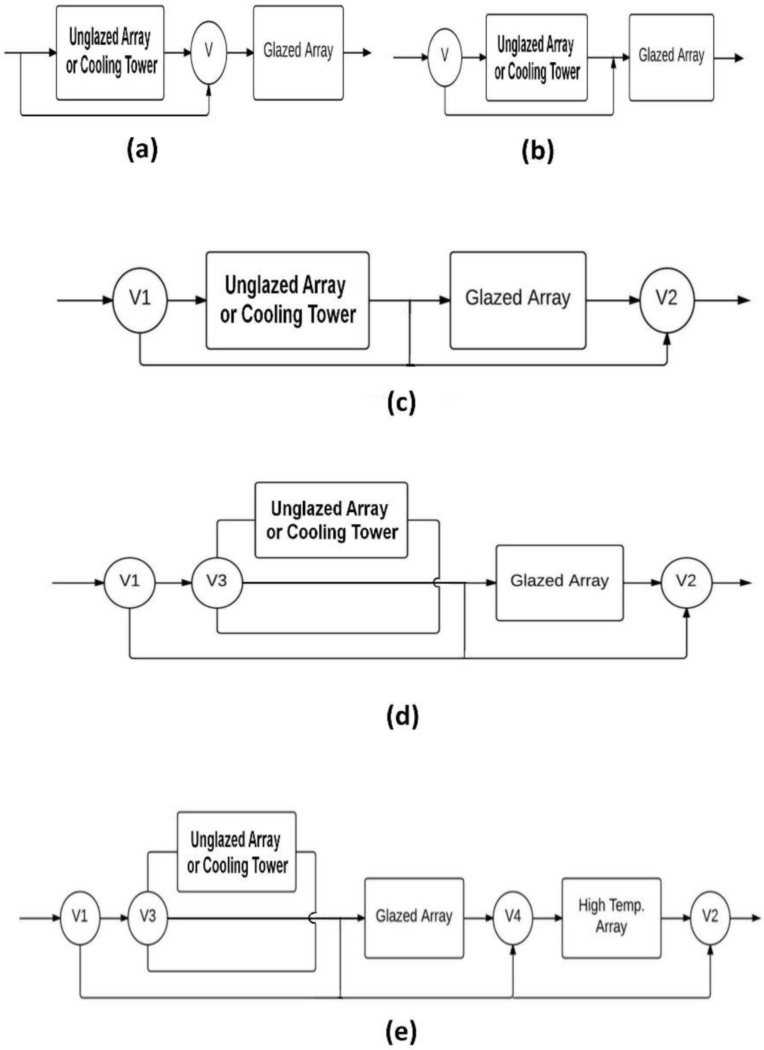


**Fig. 1: Multiple Collector Types for either Heat or Cold Collection**

Although the discussion up to this point has been about seasonal storage of heat and cold (possibly underground), the system of Figure 2(c) could also be useful on a more short term (or diurnal) basis. For example, for use during the cooling season, a water source heat pump could use cold water stored in a tank and cooled by the unglazed panels at night. This saves energy by boosting the efficiency of the heat pump. Even without a heat pump, there are examples where diurnal cold storage in hydronic floor slabs is used (SolarLogic, LLC in Santa Fe, NM - http://www.solarlogicllc.com/). Another option is to use the unglazed panels with a chiller at night to generate ice. The ice can be stored in an insulated container and will provide space cooling during the following day. Short term storage for space heating is also possible, such as with hydronic floors.

The unglazed panels are unique in that they provide four different ways to exchange energy with the environment:

- Direct collection of heat from solar irradiance.
- Convective exchange with the surrounding air.
- Radiative cooling into the night sky.
- Conductive cooling when covered with snow in winter.

All of these methods could apply to the system of Figure 1(c). One shortcoming of Figure 1(c) relates to the situation where the panels are mounted at an angle to the horizontal so that the solar radiation can be perpendicular to the panels at some time in the year. In this case the direction of flow though the unglazed panels should be switched between cooling and heating. For the heating mode, the relatively cool water should enter the panels at the bottom and warmer water should leave at the top (this relates to buoyancy flow due to density changes with temperature). For cold collection, the relatively warm water should enter at the top and the colder water taken from the bottom. This can be accomplished by adding a reversing valve (V3) as shown in Figure 1(d). In some cases (such as a large flat roof) the unglazed panels might be placed flat down on the roof. In this case the reversing valve is not needed.

As a modification of Figures 1(a) through 1(d), the use of other types of solar collectors could be considered instead of the glazed flat panel type. For example, the evacuated tube collector type might give higher temperatures at little added cost. Parabolic concentrator collectors could give even higher temperatures, but with the need for moving parts and perhaps shorter lifetimes.

Another possible improvement in the system would be the use of three collector types rather than two. An example of this is shown in Figure 1(e). The reasoning behind Figure 1(e) is that there will be some conditions of temperature and irradiance such that both the glazed and unglazed panels will have zero efficiency for heating. In this case, one of the other higher temperature collector types (evacuated tube or concentrator) could be used and the flat glazed and unglazed panels bypassed. This is accomplished with one more valve (V4).

The solar thermal panels discussed above are not specifically designed for air to liquid heat exchange. It just happens that the unglazed panels offer this as a secondary use. On the other hand, cooling towers are specifically designed and optimized for this type of use. Considering the major categories of cooling towers, most use water evaporation to assist in the cooling function however one type does not. In the application considered here, the cooling tower should function in a reverse mode in summer (heat transfer from air to liquid), so that water evaporation is not desired. This means that the appropriate cooling tower for use in systems described above will be the dry type. A dry cooling tower (or dry cooler) is functionally similar to an automobile radiator and fan, but on a much larger scale. One or more dry cooling towers can take the place of the unglazed panel arrays in any of the previous figures. A dry cooling tower will be suitable for both heat collection and cold collection. A side benefit of doing this would be a much larger thermal power transfer in a much smaller footprint. This is especially important for installations in cities with limited areas on rooftops or elsewhere. The relative performance and cost of the dry cooling tower approach versus the unglazed solar panel approach will require further study, although both could be used in a single system.

Although all of the flow control elements discussed and shown here are valves, this control could also be done with pumps (preferably positive displacement types). It is assumed that the collection and exchange of thermal energy is a part of a larger system which would require one or more pumps (not shown in the figures), and perhaps one or more thermal storage elements. It is also assumed that there would be sensors of various types such as temperature, pressure, flow rate, etc. along with a computer for control and optimization.

### 3. Flat Plate Collector for Heat and Cold

As a simplification of the concepts above, it may be possible to modify a flat plate solar thermal collector so that it is efficient for collection of both heat and cold. In this way the separate blocks for unglazed and glazed collectors in Figure 1 could be combined. A specific way to do this is shown in Figure 2.

Figure 2 shows the addition of a second pane of cover glass with a hollow space in between the panes such that fluid such as water or antifreeze solution can flow in this space. This sandwich of panes can be made stronger and able to withstand moderate pressure with the addition of spacer strips in between the panes. The spacer strips would be oriented in the flow direction (generally from top to bottom for cold collection) and would be small enough so that the obstruction of flow is minimized. Figure 2(a) shows a simplified cross-sectional view, and Figure 2(b) shows an exploded view. Figure 2(b) also shows the use of two check valves to control the flow direction for either heating or cooling. These two valves allow for a single pair of pipes to transfer fluid from the collector to the point of use. Without valves of this sort three or four pipes may be required. The concept of Figure 2 is similar to research on windows for buildings in Europe with a project called Fluidglass (www.fluidglass.eu). This project is supported by the European Union and has contributors from many different countries. Optimization of dimensions and material for the Fluidglass project may also apply to the modified solar collector described above.

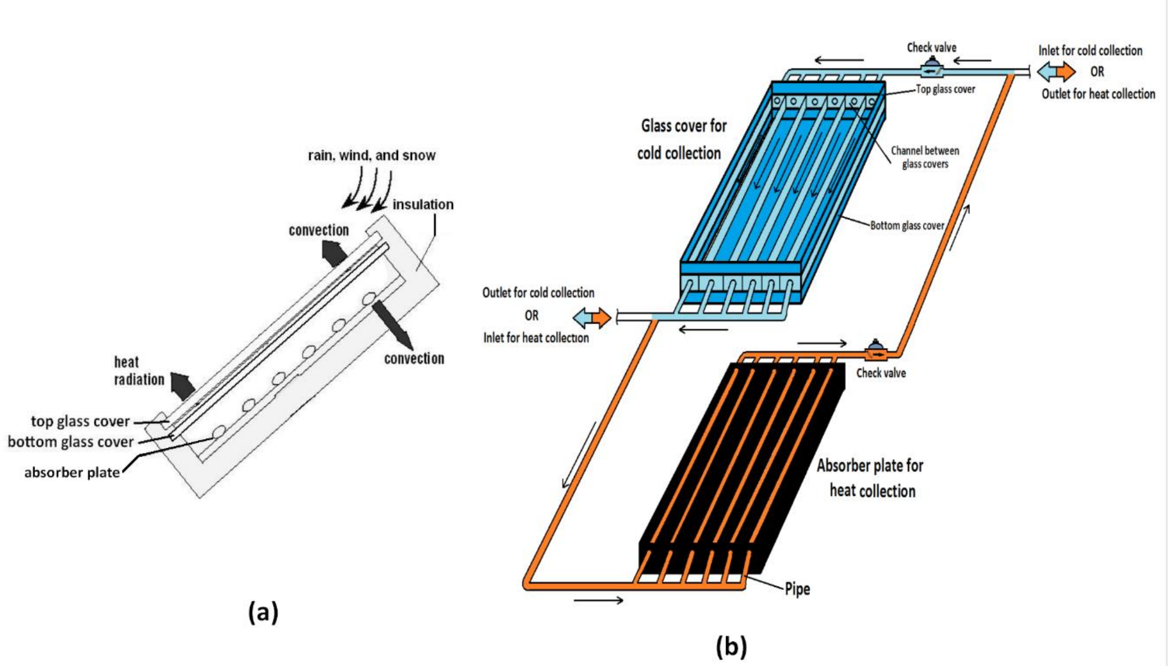


**Fig. 2: Flat Plate Collector for Heat and Cold**

Another consideration is how to use this collector design for maximization of solar heat collection. Two options for this are as follows:

- Option 1: when solar heating is desired, drain all of the cold collection liquid out of the collector so that the glazing becomes a double pane insulator.
- Option 2: keep the cold collection liquid (possibly water) in the collector at all times, including times for solar thermal collection.

There are pros and cons for each of these options. Option 1 gives a higher efficiency for very high temperature entrance water and low solar irradiance. Option 2 gives a higher efficiency for the opposite situation because of fewer glass to air reflective surfaces, and it avoids the extra cost and complexity of a system to control the drainage and subsequent replacement of water in the collectors. In any case, there may be some advantage to at least have these two choices, which are not present with any other type of solar thermal collector.

### 4. Hybrid Heat Pump Systems

Hybrid (or multisource) heat pump systems typically use a single three-port valve to improve the performance of ground source systems as shown in Figure 3. The valve allows for a series connection of two elements of heat exchange and it also allows for one of these elements to be bypassed.

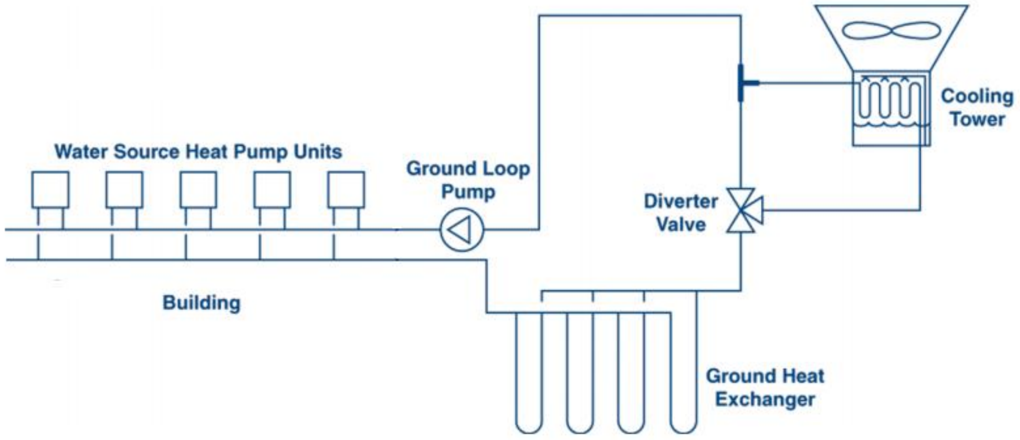


**Fig. 3: Typical Hybrid Heat Pump System (DOE/EE, 2001)**

Figure 3 shows a cooling tower as the above-ground heat exchange element, however this could instead be an array of solar collectors for either heat or cold collection. Notice that the direction of pump flow is from right to left in this example, which indicates a counterclockwise flow around the loop. There may be reasons to have the cooling tower placed ahead of the ground exchanger in the flow path (depending on climate zone or temperature conditions). This is not possible in Figure 3. It may also be desired to place the cooling tower in parallel with the ground exchanger or perhaps use the cooling tower in the system without any flow in the ground exchanger. These various modes are not allowed in Figure 3 however they are enabled with the use of more valves as shown in Figures 4 and 5.

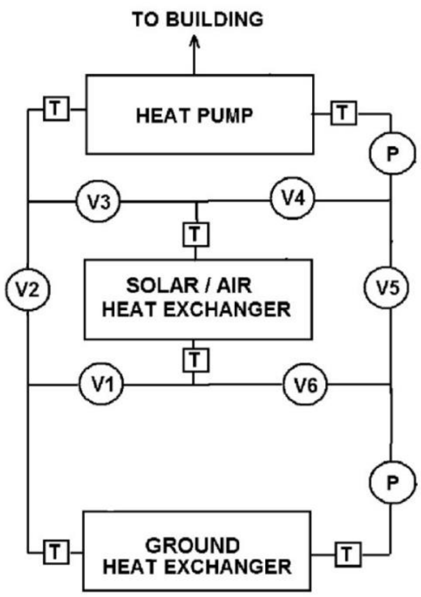


**Fig. 4: Six Valve Heat Pump System**

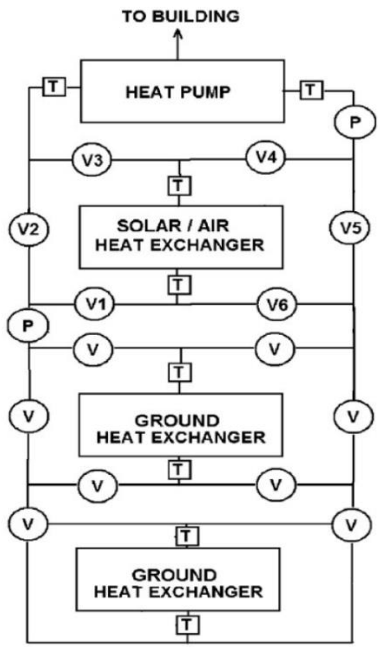


**Fig. 5: Dual Ground Exchanger HP System**

The six valve system in Figure 4 allows for 10 different modes of functionality, depending on which valves are open and which are closed. For example, if flow is excluded from the solar/air heat exchanger, the system is in a ground source mode. If flow is excluded from the ground heat exchanger, the system is in an air source mode with the possible added benefit of solar heating. Figure 4 also allows for the ground to be preconditioned seasonally either with or without flow through the heat pump. For cooling dominated climates, the coldness of winter nights can be used to cool the underground heat exchange region. For heating dominated climates, the summer sun can be used to place heat into this region. Figure 5 allows for two separate regions underground, each of them having the use of the 10 modes of Figure 4. The expectation is that if one region is kept permanently warm and another region permanently cold the heat pump will always be more efficient than for the case where the ground is at a single temperature all the time. Even worse is the case where the ground becomes either too hot or too cold to be useful for space conditioning. Figures 4 and 5 show the use of temperature sensors and pumps indicated with the letters T and P respectively. The concepts shown in Figures 1 and 2 could be used in the solar/air heat exchanger block of Figures 4 and 5.

The systems above can be used with any typical form of underground heat exchange method (boreholes, slinky systems, etc.) however for the case of long term thermal energy storage, better designs are possible. Perhaps the best design is a modified form of the horizontal array mentioned with respect to ICAX in England. There are at least three improvements that might be used: a spiral shape for the pipe array, a highly conductive material around the pipes, and a "soaker hose" perforated pipe array to add moisture to the ground. Three versions of horizontal spiral pipe arrays are shown in Figure 6. Figure 6(a) is the simplest concept with just a single flow path from center to edge. Figure 6(b) shows two flow paths in parallel from center to edge, which could reduce the pump power required. More than two paths could also be considered, this being one of many parameters to be optimized. If the array is to be placed under a building, a rectangular shape could be used as in Figure 6(c), to match the dimensions of the building.

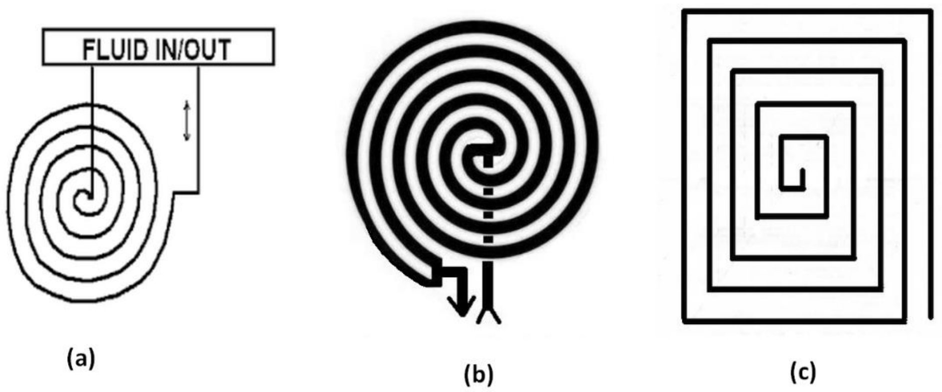


**Fig. 6: Horizontal Spiral Pipe Arrays**

The reason for the spiral shape is to always have the most extreme temperature at the center of the thermal storage region. This leads to an approximate hemispherical shape for the isothermal surfaces underground. A hemisphere with insulation at the surface gives the maximum possible ratio between volume and surface area, and also gives the maximum ratio between energy stored and rate of heat loss to the surroundings. Another assumption (for cost reasons) is that insulation is only at the top, not along the sides or the bottom. This is consistent with the Drake Landing Solar Community design and the designs from ICAX in England. A second improvement to be considered is to cover the pipes in the array with highly conductive material such as grout or concrete. For purposes of heat exchange, concrete around horizontal pipes has been used by Enercret GmbH in Rothis, Austria (www.enercret.com). The reason for this is the same reason that grout is used in boreholes. It gives a more complete and effective thermal transfer from the pipes to the ground below in comparison to dry dirt or sand. A third possible improvement is to purposely introduce water into the ground just below the pipe array to keep the ground permanently damp and thereby more thermally conductive. This will be a replacement for the normal moisture from rain that is diverted away by the insulation at the top. Also, there will likely be an impervious plastic cover at the top surface of the insulation to assure that the insulation performance is not degraded by moisture. The array to introduce water may be similar to the perforated pipe drain fields in septic systems.

## 5. Simulation Results

Results from simulation studies of the underground storage are shown in Figure 7. The assumptions going in to this figure are that there is a heated hemisphere below a large area surface insulator with ground thermal characteristics as listed at the bottom right corner of the figure. To approximate a seasonal time frame, there is a heating (warm-up) time of 60 days followed by a 150 day cool down time. During this 150 day period, a certain fraction of the initial heat will be lost to the surrounding ground. For a 4 meter heated radius about 85 percent of the initial heat is lost. On the other hand, with a 15 meter heated radius, only 20 percent of the initial heat is lost. Since this design does not provide a perfect hemisphere for the isothermal surfaces, these numbers should be considered only as ballpark approximate. Another consideration is that some types of solar thermal collectors such as evacuated tubes can provide significant heat whenever the sun shines, so a span of 150 days with no heat added to the system may be overly pessimistic. More complete simulations and optimization studies are underway.

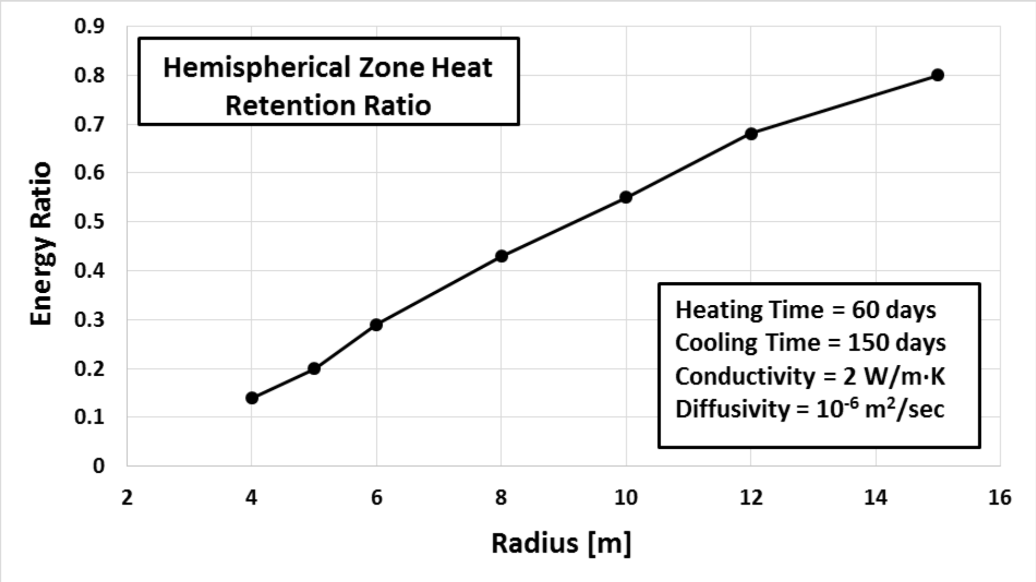


**Fig. 7: Simulation Results**

## 6. Summary and Conclusions

A variety of ideas have been described here that may be applied for specific building types and specific heating and cooling needs. These ideas may not have much advantage for an HVAC retrofit of a small house surrounded by trees. On the other hand, new construction of a one or two story office or apartment building with an adjacent parking lot would be a very good fit. A general concept would involve the ground under the parking lot, under the building, and space on the roof. Assuming that the building needs both heating and cooling, the ground beneath the parking lot could be for cold storage and the ground under the building for heat storage. A nearly ideal case would be a black asphalt parking lot surface with low visible light reflectivity (efficient collection of solar heat). With a horizontal pipe array just below the asphalt surface, the parking lot becomes both a solar thermal heat collector and also an effective winter or night time cold collector. The pipe array near the surface of the parking lot does not need to have a spiral shape. A few inches below the parking lot collection array there would be a layer of rigid insulation. Below the insulation there would be a spiral array for cold storage. Below the building there would be a similar layer of rigid insulation and below the insulation a second spiral array for heat storage. A reason for heat rather than cold under the building is to avoid frost heave damage to the foundation of the building. To obtain high temperature for heat storage there could be glazed or evacuated tube solar collectors on the roof. The connection between the parking lot collection and the collectors on the roof could be as shown in Figure 1(c) or 1(e) above. For a very cold climate region it could be better to use both underground regions for heat storage. For a very warm climate region or a building with large internal heat, both underground regions could be used for cold storage. A side benefit in having both hot and cold fluid available is the possibility to generate electricity using organic Rankine cycle generation (Organic Rankine cycle, 2016).

What is presented above is intended to be a very preliminary design concept. Many parameters remain to be studied and optimized. For example, the thickness of the insulation layer (or layers) will involve a tradeoff between cost and transfer of heat between the underground and the atmosphere or the underground and the building. Another interesting question is whether a heat pump is needed or not for a specific building design. For a building that adheres to many passive house principles with hydronic floor heating and radiative or chilled beam cooling it is possible that the HVAC design could avoid the heat pump and just use water pumps, valves and a control computer. This might be a significant savings in initial cost and also provide a building that would use essentially no fossil fuel for HVAC.

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