

Hybrid Air, Solar, and Ground Source Heat Pump Designs

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Abstract

Air-Source Heat Pumps (ASHP) are often considered as an alternative to conventional air conditioners and gas-fired furnaces/boilers typically used in small and medium sized buildings to achieve more energy savings and reduce greenhouse gas emissions. Nevertheless, the variations and instabilities of outdoor weather conditions and instantaneous loads may decrease both Coefficient of Performance (COP) and the capacity of an ASHP unit. One of the sustainable solutions to overcome these shortcomings is to integrate a heat pump (HP) unit with an underground loop(s) to harvest and harness free energy from nature as heating and cooling sources, and is known as a Ground-Source Heat Pump. However, the integration of an HP unit with a single energy source is not able to maximize the potential for energy savings and to accomplish a thorough system performance optimization. Therefore, this paper will describe the design of a multi-source HP unit for more efficient and cost-effective space cooling and heating. The system consists of an HP unit(s), a dry cooler (air to liquid heat exchanger), and a horizontal underground loop that allows underground heat exchange as well as daily/seasonal thermal energy storage. This multi-source HP unit enables the alternate use of a dry cooler (air-source mode) and an underground loop (ground-source mode), which contributes to the optimization of system performance. Additionally, the underground loop may function as a thermal storage device that stores heat and cold produced by the heat pump and/or the dry cooler into the underground region for later use. Solar collectors may be used as well along with the dry cooler and underground loop to collect solar heat for the direct use for space heating or the later use by charging the underground region or a thermal storage tank with the heat. The primary objectives of the study are to maximize heating and cooling energy savings, optimize system integration, and minimize fossil fuel use in buildings.

Keywords: Multi-Source Heat Pump, Energy Efficiency, Solar Energy, Ground Loop, Dry Cooler

Introduction

According to the building energy data book [1] of the U.S. Department of Energy, the U.S. buildings (commercial and residential) account for 41% of primary energy consumption, where Heating, Ventilating, and Air Conditioning (HVAC), mainly including space cooling and heating, accounts for about half (37% for space heating and 10% for space cooling) of the U.S. building site energy consumption. The commonly used HVAC systems in small and medium sized buildings, especially residential buildings, e.g. single family houses, could be central/split air conditioners with natural gas furnaces/boilers. As an alternative, an Air-Source Heat Pump (ASHP) may be applied for energy savings and greenhouse gas emission reduction. When using an ASHP in a residential house, however, its operational COP and capacity will be decreased because of varied instantaneous loads and demands as well as unstable outdoor air temperatures [2-3]. One of the sustainable solutions to overcome these shortcomings and limitations is to integrate a heat pump unit with solar collector(s), thermal storage tank(s), and/or underground loop(s), etc. as supplemental heating and cooling sources in case of inadequate capacity of the ASHP. For example, Xu et al. [4] performed a simulation study on a new type of multi-source (solar + air) heat pump used for domestic water heating with the purpose of improving the overall energy efficiency. They concluded that hot water at 55 C may be constantly produced by using either solar or air or both as the heating source all year around. Nam [5] in 2012 integrated a heat pump system with a multi-source network to take advantage of solar and ground heat for space cooling and heating. He demonstrated the superior performance of the multi-source heat pump system compared

to a conventional heat pump with a single source and found that the heating COP was significantly enhanced by 146% compared to ASHP in cold climate regions and 119% in subtropical climate areas. Busato et al. [6] monitored the performance of a multi-source gas-fired absorption heat pump system for two years. The sources include solar and ground heat. They found that “the integration of different heat sources remarkably increases the efficiency of the system in terms of primary energy consumption.” Additionally, multi-source heat pumps contribute to the achievement of net/nearly zero energy buildings [7-8].

In this paper, the shortcomings of the current multi-source heat pump system designs will be identified and discussed. Improved heat pump systems that can be integrated with multiple heat sinks and/or sources for space heating and cooling in buildings will be described. The purposes of this study are to maximize heating and cooling energy savings, optimize system integration, and minimize fossil fuel use in buildings. Some of the concepts shown herein have been recently patented or are currently patent pending.

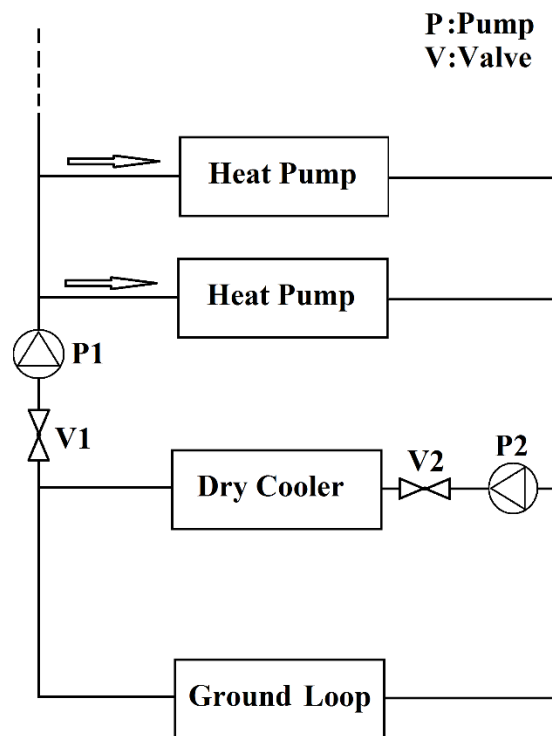


Figure 1: Double pump hybrid design

Multi-Source Heat Pump Designs

A recent paper [9] shows a very significant advantage for a combination of ground source and air source heat pumps operating together as a hybrid design with optimization of relative sizes of the two source elements. In this paper, the use of conventional air source and ground source (or more generally water source) heat pumps is involved, each with their own compressors, expansion valves, etc. On the other hand, it is possible that given one or more water source heat pumps in the system, an equivalent air source mode is possible by using one or more air-to-liquid heat exchangers (dry coolers) to allow an air source mode. This would be a significant simplification and would be less expensive, however attention needs to be given to the inefficiency caused by the extra heat exchange element. Figure 1 shows how two water pumps can be used to give a variety of operating modes for one or more heat pumps. Assuming that both water pumps are variable speed types, these four modes are possible:

1. Ground source mode - with all fluid flow through the ground loop and none through the dry cooler.
2. Air source mode - with all fluid flow through the dry cooler and none through the ground loop.
3. Parallel mode, with heat pump source fluid taken from both the ground loop and the dry cooler.
4. Preconditioning mode with little or no flow through P1 and higher flow through P2.

Following the lead of [9], since the range of air temperature fluctuations is much greater than for underground temperature, there will be a large percentage of time for which the output of the dry cooler gives a higher coefficient of performance (COP) for heat pump use than does the alternative from underground. Using multiple fluid temperature sensors and computer control, the best choice of fluid based on temperature will always be used. This allows a large reduction in the underground heat exchanger size (50 percent reduction [9]). In essence, a low cost dry cooler can replace expensive boreholes. Another benefit is obtained if the dry cooler is only used if the air temperature is above freezing. This avoids the use of a defrost cycle as needed by conventional ASHPs.

If the two water pumps, P1 and P2, shown in Figure 1 could block the flow adequately while in the off condition, the two valves, V1 and V2, would not be needed. They are included just to make sure that the liquid flow can go to zero when desired. The modes as shown here do not have a series connection. This may or may not be needed, however series connections and reverse flow direction modes are possible with the use of additional valves and/or pumps. A six-valve method for this can be found in [10].

Although the air source element in Figure 1 is called a dry cooler, it should be realized that this component can be either a cooler or a heater. Relatively hot liquid will be cooled and relatively cold liquid will be heated. Coolers that use water evaporation do not have this bidirectional feature, however if only cooling is needed, they could also be considered for use in this application. If only heating is needed, the dry cooler could instead be a solar thermal collector. Depending on the scale of the system, the air source or solar thermal element could be a single unit or an array of units connected together in parallel, series, or the combination of series and parallel. Dry coolers with a wide range of sizes are available from many suppliers [11-13].

The ground loop in Figure 1 could be any type of liquid pipe array buried in the ground such as one or more boreholes, one or more trenches, energy piles, etc. The ground interface shown in [9] happens to be something similar to a vertical slinky design, but this geometry is not relevant to the main point of the system. The use of a preconditioning mode implies the capability for the system to have at least some degree of underground thermal storage. This can be either a feature or a bug. For undersized and unbalanced conventional borehole systems, too much long term thermal storage can lead to eventual failure. The ground around the pipes becomes either too hot or too cold to be useful. On the other hand, with useful storage over a time of at least several months, the preconditioning mode as mentioned above might be used to make the ground very cold at the beginning of the summer, or very warm at the beginning of the winter. This will improve the annual average COP. Thermal storage capability would be especially useful for office buildings that may be mostly unoccupied at night and during weekends. The ground preconditioning mode would be used during unoccupied times. A more general HVAC system is usually just turned off when not needed, whereas the dry cooler shown here can be used to make the ground warmer or cooler whenever desired and do this without using fossil fuel or power for a heat pump compressor.

If seasonal storage is desired, the shape of the isothermal surface (or surfaces) underground becomes important. A single borehole has an isothermal surface which is a very long, narrow cylinder. This is not conducive to long term efficient storage. Borehole arrays can be used for long term thermal storage,

however the spacing between boreholes needs to be relatively small and the array diameter needs to be similar to the borehole depth. This leads to an isothermal surface which is still a cylinder, but a better ratio between length and width brings higher storage efficiency. Size of the underground storage region is also important for long term storage. In general terms, a larger storage volume gives a longer thermal time constant. An ideal shape for underground thermal storage is a hemisphere with the center point near the surface of the earth, and an insulation layer at the top. A sphere or insulated hemisphere has the absolute maximum ratio between volume and surface area. The rate of heat loss is dependent on the isothermal surface area, and thermal energy stored is dependent on total volume within the hemisphere. Although it may not be cost-effective to develop a true hemisphere for the isothermal surface shape, it is possible to get an approximation to this with a spiral horizontal pipe underground heat exchanger. A quasi-spiral rectangular version of this is shown in Figure 2. The important point is to have a connection point at the center of the storage volume, so the most extreme temperature (either hot or cold) will always be at this point. A single flat spiral is just one of many ways to do this. As a side note, the rectangular quasi-spiral shape could be matched to the dimensions of a new building, so the insulated pipe array would be placed in the earth before the foundation slab is poured. A combination ground heat exchanger with thermal storage enhancement would be ready for use when the building is completed. Examples of this type of system have been done [14-16], but they do not have a connection at the center, so they are fine for heat exchange, but they are not optimum for heat storage. In [16], a variation on the theme is demonstrated by embedding the heat exchange pipe array in a concrete layer before putting the insulation on top.

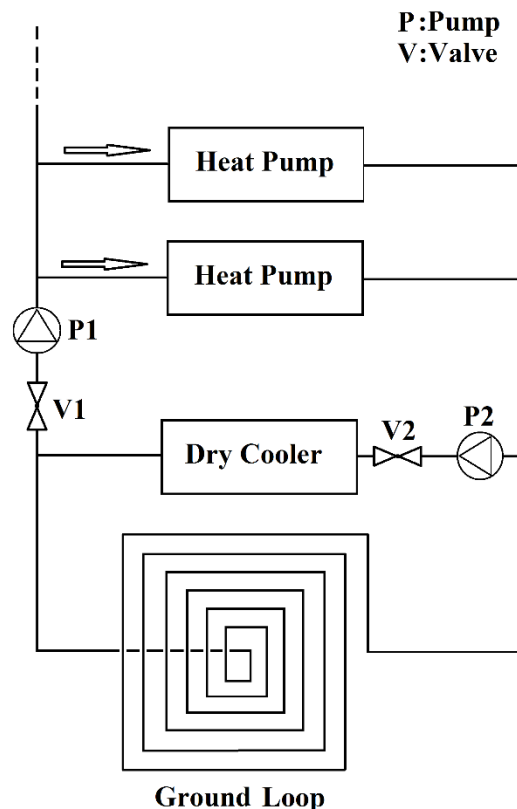


Figure 2: Double pump design with spiral heat exchanger

With respect to the hydraulic flow directions in Figure 2, notice that for the preconditioning mode, the flow will be in a counter-clockwise direction, so the preconditioning fluid will be going into the center of the spiral, which is desired for best results. Also notice that when the heat pumps are in use, the flow direction is clockwise, which means that the extreme temperature will be taken from the center of the

storage region. This is also the optimum direction. This combination of flow directions is accomplished without using a four-port reversing valve in the system, although such a valve could be used if it is desired to select either the perimeter or the center of the storage region as the source for the heat pumps. The perimeter of the storage region may be preferred if the pipe array is to be used as a heat exchanger rather than as a thermal storage element.

Another consideration for any type of shallow pipe array with insulation on top is the lack of moisture in the ground because of diversion of rainfall away from the insulated region. It is possible to introduce moisture into the region of earth used for thermal storage and exchange by use of a perforated pipe array along with the heat exchange pipe array. Water is introduced through the perforated pipe. This has been done by several different designers and installers of ground source heat pump systems in both trenches and horizontal pipe arrays. Damp soil has a much higher thermal conductivity than dry soil, so an optimum for this parameter may be desired. This is another opportunity for computer control and optimization. This type of controlled conductivity would not be possible with the randomness in the timing of natural rainfall. This type of moisture introduction might use some of the methods already being used for subsurface drip irrigation [17].

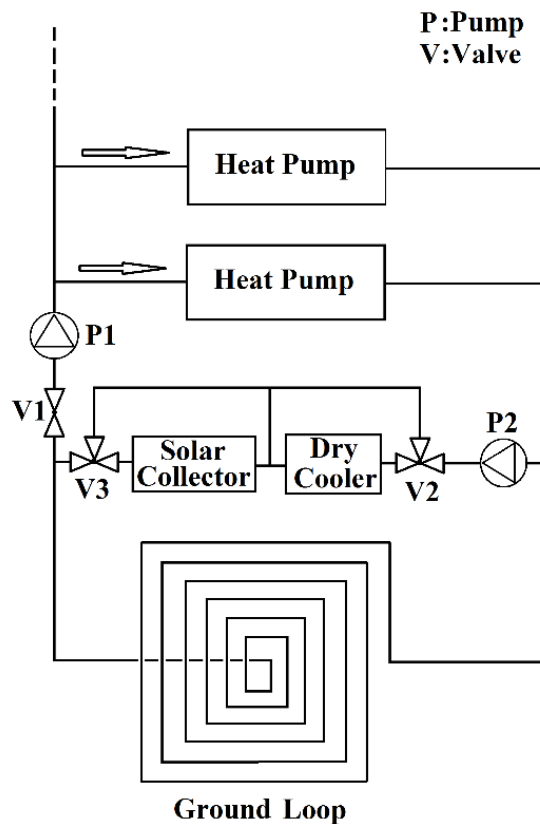


Figure 3: Double pump design with spiral heat exchanger, solar collector and dry cooler

Another possible enhancement to what is described above is the use of both a dry cooler and a solar thermal collector in the same system as shown in Figure 3. In this case, one more valve (V3) is also added. The general concept for Figure 3 is such that V2 has three settings, one of which blocks the flow from P2, another setting passes water to the dry cooler, and a third setting bypasses around the dry cooler. V3 has two settings, one of which takes water from the solar collector and a second setting which takes water from the bypass line. In this way the flow path can be any of these:

1. Series flow through both the dry cooler and the solar collector. Preheating water with the dry cooler can provide a higher thermal collection rate for some situations.
2. Bypassing around the dry cooler but still using the solar collector for heating. This mode is used if the dry cooler is cooling the liquid rather than heating it.
3. Flow through the dry cooler but bypassing around the solar collector. This mode would be used when collection of cold rather than heat is desired.

Although Figure 3 adds some complexity to the system, it has the potential for the greatest reduction of ground loop size and cost. With sufficient collection of heat and/or cold, it may be possible to either bypass around the heat pumps for building conditioning during some parts of the year, or as shown in [18] to avoid the need for heat pumps altogether.

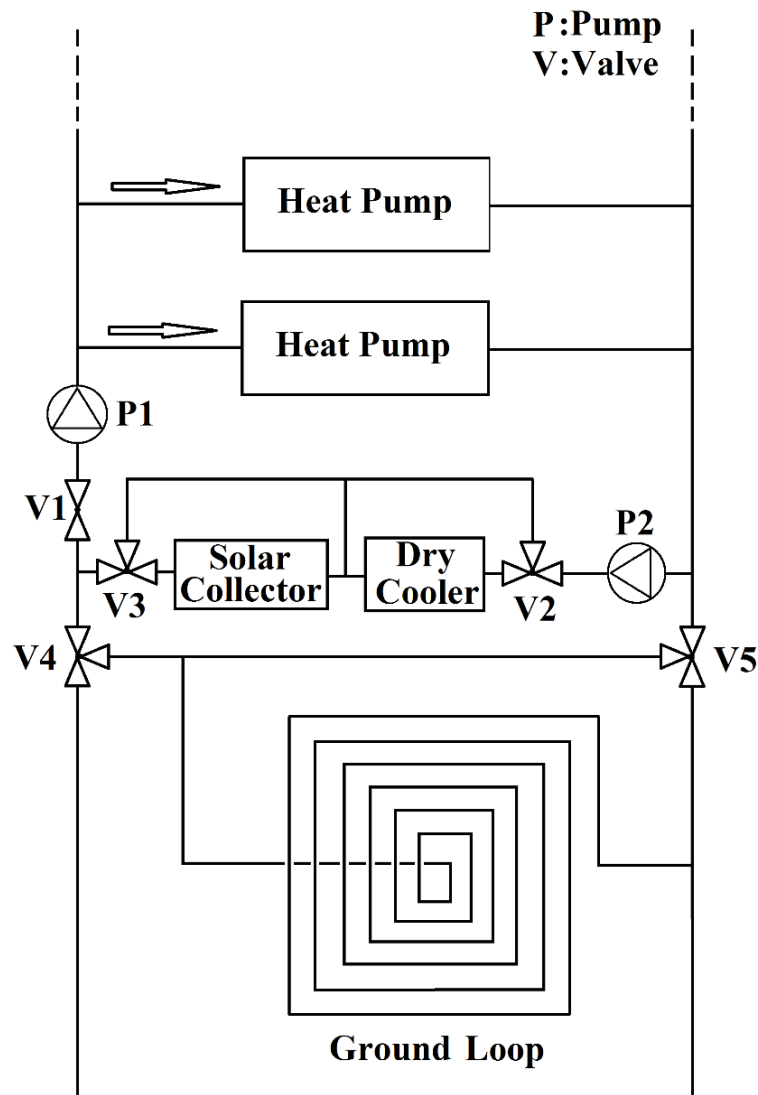


Figure 4: Double pump design with reversible flow in spiral heat exchanger

A limitation of the designs in Figure 2 and Figure 3 is the inability to provide and maintain the desired temperature at the center of the storage region at the end of the heating season and the end of the cooling season. For example, in the second half of the heating season, the heat pump output water may be significantly colder than the yearly average earth temperature. The best place for this cold water is the center of the storage region, so as to be more prepared for the upcoming cooling season. Similarly, in

the second half of the cooling season, the heat pumps will have output temperatures significantly warmer than the yearly average earth temperature. Again, the best place for this warm water is the center of the storage region, so as to be more prepared for the upcoming heating season. The designs in Figure 2 and Figure 3 do not allow for this. The heat pump output water always flows into the perimeter of the storage region. One way to correct for this limitation is shown in Figure 4. Figure 4 shows two more valves which provide for a reversing of the flow direction in the spiral heat exchanger. Instead of two three-port valves (as shown in Figure 4) it is possible to do the same function with a single 4-port valve or four two-port valves. The valves and their control would be based on temperature sensing and knowledge of climate and weather prediction related to the expected needs for the building for heating and cooling in the forthcoming days, weeks, and months. The optimum situation is such that the flow direction in the spiral heat exchanger is changed four times per year. It should be understood that although Figure 4 is specifically a modification of Figure 3, the same modification could be applied to Figure 2.

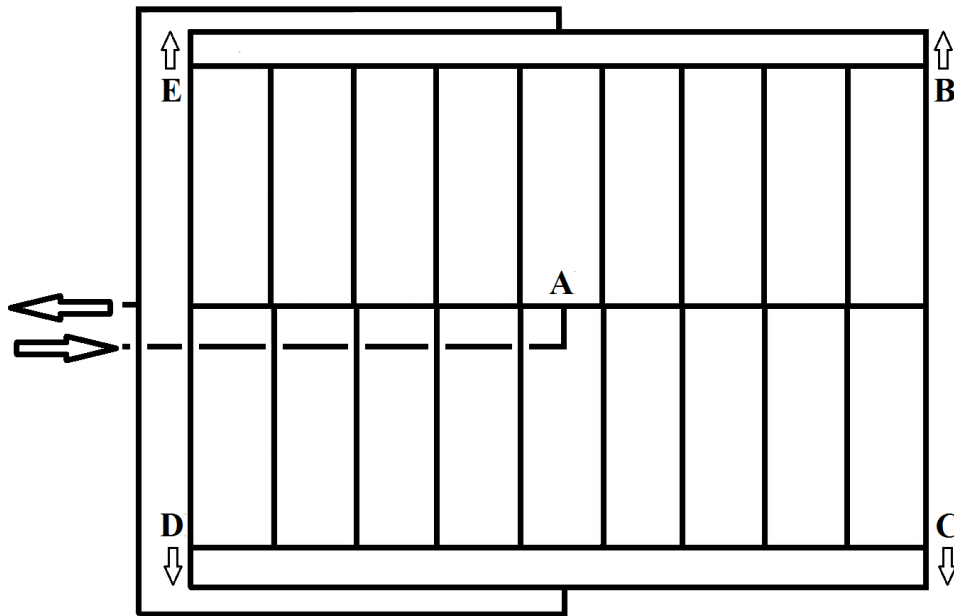


Figure 5: Quad reverse return pipe array

For efficient seasonal thermal storage underground, the volume of earth used for storage needs to be sufficiently large. The general assumption here is that the storage region will be insulated on the top, but not along the sides or the bottom. Heat or cold can flow away from the storage region both in the horizontal directions and also in a downward direction. The horizontal size (diameter) required for efficient full seasonal storage is in the range of 80 to 120 feet [10]. The assumption for the designs here is that storage might need to be for a few months, but not as long as 6 or 7 months. In either case, the storage region may be so large that a single spiral pipe array may not be appropriate. The flow resistance for a single, very long pipe may be too high. A way to avoid this limitation is shown in Figure 5. Figure 5 shows a way to have a pipe array with many parallel pipes but still have a single connection point for the center and also for the four corner locations. Of course the four corner locations can be connected together as the figure shows. The design in Figure 5 can be considered as a replacement of the spiral array in the previous figures.

In all the above-mentioned designs, a thermal storage tank(s) could be used along with the dry cooler(s), underground loop(s), and/or solar collector(s) to either store heat/cold for later use or be regarded as a buffer between different modes [18]. Additionally, the integration of domestic hot water heating into the design along with space heating and cooling is another reason for the use of a thermal storage tank(s).

Conclusions and Future Work

A multi-source heat pump system is known to have superior performance compared to a single-source heat pump system. The combined and alternate use of various heating and cooling sources along with a heat pump system may contribute to maximizing the utilization of renewable energy on site and maintaining a constant heating/cooling output all year around in buildings. This paper introduces and demonstrates the possible improvements in the current multi-source heat pump system design, including the mixed use of dry cooler(s), underground loop(s), solar thermal collector(s), and thermal storage tank(s). These innovative designs mentioned in this paper are useful for designers and engineers to think out of the box and explore the most optimized design parameters under various scenarios through advanced system control strategies. This paper also shows researchers the way to develop a new type of multi-source system. The validation and optimization of the above-mentioned system designs are currently ongoing, whose results will be demonstrated in the future.

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