

EARTH-COUPLED WATER-SOURCE HEAT PUMP RESEARCH,
DESIGN AND APPLICATIONS IN LOUISIANA

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ABSTRACT

An earth-coupled water-source heat pump uses the earth as the thermal source and sink for economical, energy efficient, space heating and cooling. Water exiting the heat pump passes through an earth heat exchanger, which is a closed loop of plastic pipe embedded in the earth, and gains or rejects heat before returning to the heat pump.

Three earth heat exchanger configurations have been field tested, and a design method for sizing these to water-source heat pumps for residential and commercial applications has been developed.

This paper summarizes the results of the field tests, explains the design method, overviews residential and commercial applications, and compares the economics of earth-coupled water-source heat pump systems to conventional space heating and cooling systems.

INTRODUCTION

In the decade of the 1960s low energy costs caused a decline in heat pump use for space heating and cooling. Since the energy crisis of the 1970s, however, the heat pump has grown in the marketplace. Most heat pumps use outdoor air as a thermal energy source and sink, but their performance is limited by the thermal capacity of air and the temperature regime of the atmosphere.

Due to the superior thermal capacity of water and more favorable temperatures, water-source heat pumps are more efficient. Ground water is an excellent source if available in good quality and quantity. Where ground water is not available or suitable, or if waste water disposal is a problem, an alternative is to circulate water in a closed loop of buried plastic pipe. Research in several climate zones in the United States has led to the design of several earth heat exchanger configurations for heat pumps. In Louisiana, several plastic pipe materials and earth heat exchanger configurations are used by contractors who install earth-coupled water-source heat pump systems. This paper summarizes the research done at Louisiana State University and gives the design method developed as a result of this research. Applications and the economics of utilizing this technology are also discussed.

HEAT EXCHANGER CONFIGURATIONS

The research at LSU has been on the design and evaluation of three plastic pipe configurations for earth heat exchangers used to supply and reject heat for the water-source heat pump.

VERTICAL CONCENTRIC PIPE

A concentric pipe heat exchanger has a closed pipe casing with an inner pipe for return flow, Fig. 1. It is inserted into a hole bored into the earth. Heat transfer between the water as it flows down the annular space and the surrounding earth is the useful heat transfer. As the water returns up the inner pipe it experiences heat exchange with the downward stream. This crossover heat flow is detrimental to the heat exchange process. It can be reduced to practical low values by proper selection of the inner pipe (8).

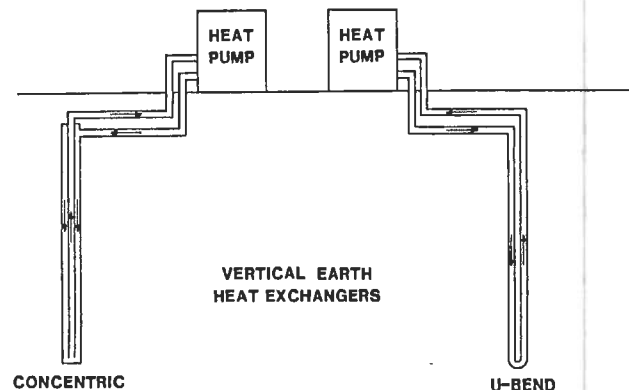


Figure 1.

VERTICAL U-BEND

The U-bend configuration consists of two pipes side-by-side and connected at the bottom with a 180 degree fitting, Fig. 1. Water flows down one pipe and returns up the other. The temperature difference between the water and the earth causes heat flow. Because of temperature differences in the two streams there is also some deleterious crossover heat flow. In this configuration two walls of pipe material impede the crossover heat flow, but the presence of each pipe interferes with the heat loss to earth of the other.

HORIZONTAL

A horizontal heat exchanger is a single or multiple length of plastic pipe laid in a trench and backfilled with the earth material. The length of horizontal heat exchanger required to match the load of the heat pump is expected to be greater for horizontal than vertical heat exchangers due to the temperature and soil moisture regime about the pipe.

Seasonal variations of the temperature profile give a smaller temperature difference between the pipe and earth to drive heat, and drier soil in summer has a lower thermal conductivity, which reduces the capacity of the heat exchanger.

EQUATION FOR HEAT FLOW

The design method for sizing earth heat exchangers is based on the relationships among the thermal load of the heat pump, the thermal capacity of the heat exchanger, the water and earth temperatures, and the length of the heat exchanger, as given by:

$$Q = U \Delta T L \quad (1)$$

where

Q = the rate of heat transfer of the heat exchanger, Btu/hr.
 L = the length of the heat exchanger, ft.
 U = the average conductance rate for heat transfer from the circulating fluid to the earth, Btu/hr.°F.ft.,

$$\Delta T = (T_{EX} + T_{IN})/2 - T_E \quad (2)$$

where

T_{EX} = fluid exit temperature, °F.
 T_{IN} = fluid entry temperature, °F.
 T_E = the earth temperature, °F.

Each earth heat exchanger has a unique U-value. Variations are due to the operation of the heat pump, the pipe material used and the earth conditions.

EARTH HEAT EXCHANGER TESTS

Heat injection tests were made at Louisiana State University with:

- a vertical concentric pipe heat exchanger 504 ft deep that had 2½ in nominal diameter steel casing and 1½ in PVC inner pipe.
- a vertical polyethylene U-bend heat exchanger 265 ft deep made of 1½ in diameter pipe and
- a horizontal heat exchanger 1200 ft long made of 1½ in thin wall PVC pipe buried 6½ ft deep.

The concentric earth heat exchanger was evaluated for various operating conditions and the data were used to design a PVC pipe, vertical, concentric heat exchanger that has been in successful operation in a private residence for 4 years (6).

A horizontal, earth-coupled water-source heat pump system was installed as part of a demonstration project by the LSU Agricultural Center, the Ditch Witch Corp., and the Carrier Corp. The heat exchanger was installed in a wooded area adjacent to the residence. The objective was to monitor the heat exchange capacity of the buried single pipe during late winter and summer. It was assumed that seasonal soil moisture change would cause different heat transfer rates. Details of the test were given in (7).

RESULTS

STEEL CASING

The rate at which the earth would absorb heat was relatively high at the beginning of a run and declined as time went on. With on-off injection of heat, the instantaneous conductance values were always higher than with continuous run as shown in Fig. 2 where conductance values for 25%, 50% and 100% on-time are given. Asymptote values are the best estimates of the final conductance (U-value). They were derived from regression curve fits and are summarized in Table 1.

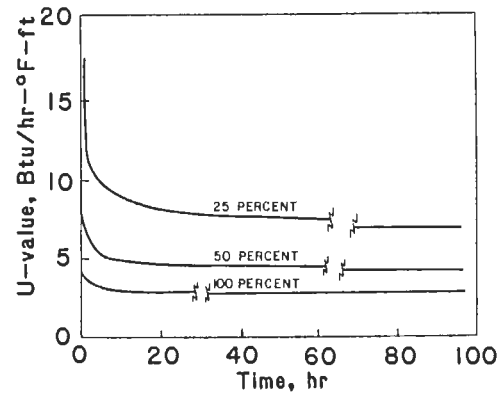


Figure 2. U-values vs. time for three duty cycles, 2½ in nominal steel casing with 1½ in PVC inner pipe, from (6).

Most of the runs were made with SCH 40 PVC inner return pipe. Runs with thin wall SDR 26 inner pipe exhibited less temperature change in the circulating water. This effect reduced effective conductance values by 13 per cent in 100% duty cycle. Schedule 80 (thick wall) inner pipe increased the heat transfer rate by only 5% over SCH 40.

PVC CASING

Using plastic pipe as the casing for a concentric heat exchanger is more economical than metal pipe. Earth heat transfer rates with PVC plastic pipe were calculated from the steel casing data using the thermal conductivity and wall thickness for PVC pipe. Thin wall PVC casing and SCH 40 PVC inner pipe is the most cost-effective combination. The U-values are given in Table 1.

A residential heat pump system using thin wall PVC casing pipe and SCH 40 inner pipe had U-values ranging from 1.0 to 1.7 depending on run-time for the particular test day. Heating mode operation during severe cold caused circulation water to drop to 58°F. This is a safe temperature, without need for antifreeze protection.

U-BEND

Twelve runs of heat injection were made with the 265 ft polyethylene pipe U-bend heat exchanger. U-values are given in Table 1. Because the earth resistance to heat flow is so much greater than the pipe wall resistance, the two designs - concentric

pipe vs. U-bend - provide about the same performance.

Table 1. Heat exchange rate of vertical concentric steel casing and PVC casing, U-bend vertical, and horizontal single pipe earth heat exchangers.

Percent run-time	100	50	25
--- U-value, Btu/hr·°F·ft ---			
Concentric			
Steel casing ²	1.41	2.17	3.44
PVC casing ²	1.04	1.40	1.84
U-bend ¹			
Polyethylene	1.00	1.36	2.54
Horizontal PVC			
Winter	1.61	1.80	2.10
Summer	1.03	1.28	1.85

1 - U-values based on total pipe length installed.

2 - Bore depth equals one-half total pipe length installed.

HORIZONTAL PIPE

U-values for both winter and summer are given in Table 1. Figure 3 gives plots of U-value vs. time for continuous heat pump operation for the summer and winter tests. The curves show that the minimum U-value obtained after a long period of operation should be used for design and that heat exchanger design should recognize the different seasonal values.

The earth is better able to move heat in winter than in summer because soils become saturated in the winter. In the wooded area at the test site, soil moisture extraction by tree roots lowered the soil moisture content in summer.

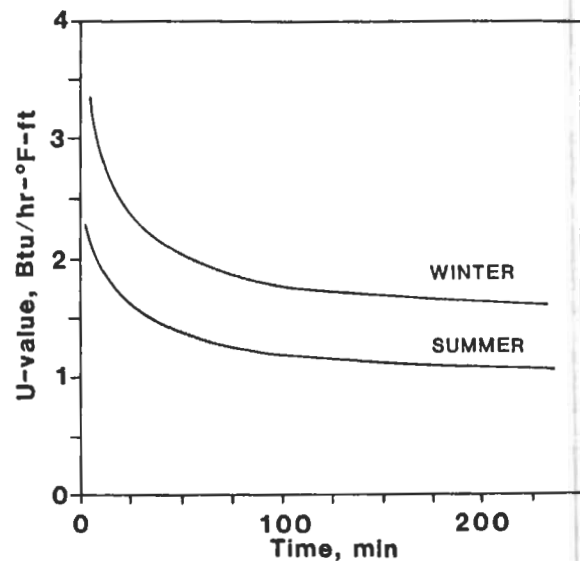


Figure 3. Heat exchange to earth with continuous operation of the heat pump -- winter and summer. $1\frac{1}{4}$ in PVC pipe installed horizontally $6\frac{1}{2}$ ft deep.

Continuous operation caused the water temperature to fall to 50°F in winter when the soil temperature was 58°F. In the summer the water temperature in the loop rose to 89°F when the earth temperature was 70°F. The summer earth temperature was cooler than expected, probably due to the shading of the ground in the wooded area.

Figure 4 gives a plot of U-value vs. time for operation under normal thermostatic control in the heating mode. The superimposed bar graphs and

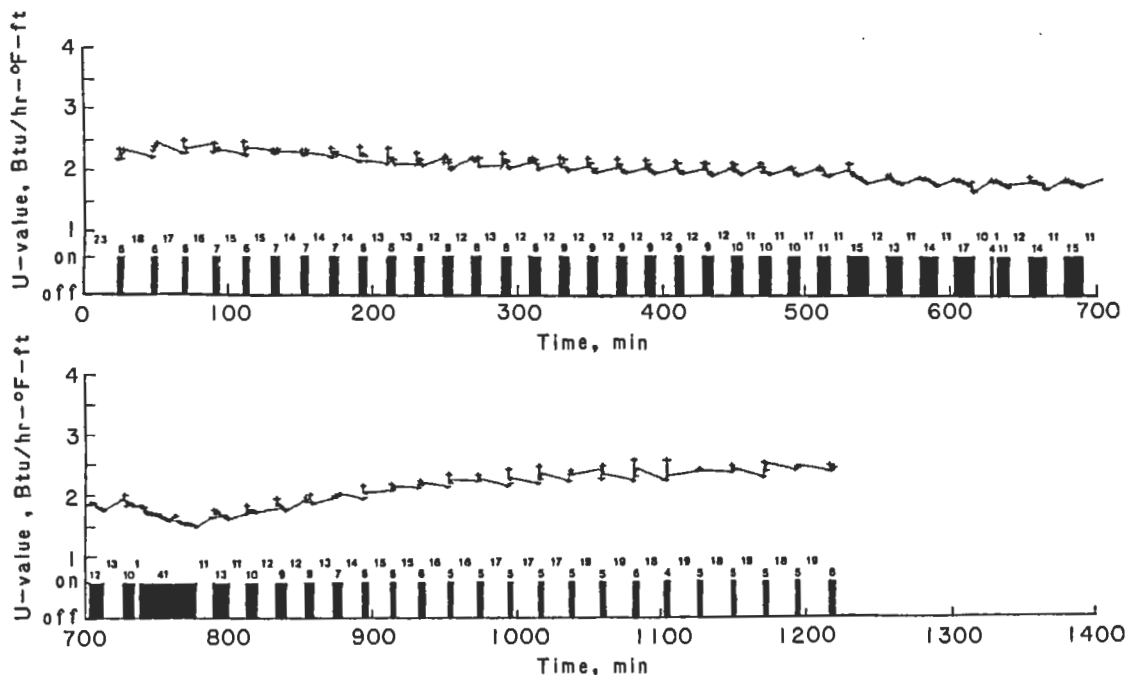


Figure 4. Heat exchange to earth with cyclic operation of the heat pump.

associated numbers give the length of time that the heat pump was on or off. This plot demonstrates the effect of cyclic operation of the heat pump. The U-value decreased with an increase of run-time in a cycle.

The length of the on-off cycles were also significant. U-values decreased from 2.23 to 1.85 Btu/hr·°F·ft as the length of the cycle decreased from 3 cycles per hour to 1 cycle per hour.

It is of interest to compare the results of the horizontal to the vertical design, Table 1. All U-values in Table 1 are based on conductance per unit of pipe length installed (pipe length = 2 x bore depth). Note the similarities of the U-values for the two configurations for winter soil conditions. Heat exchanger tests in Oklahoma were reported by Bose et al. (2,3) and Partin (9). Our results agree well with theirs.

DESIGN LENGTH OF HEAT EXCHANGER

If the U-value of a heat exchanger, the earth temperature and the heat pump operating characteristics are known, the required length of heat exchanger can be calculated. One must know the highest supply water temperature acceptable for cooling mode and the lowest temperature acceptable for heating mode.

EXAMPLE

Find the heat exchanger length for a heat pump rated at 24,000 Btu/hr cooling capacity in an area with earth temperature, $T_E = 75^\circ\text{F}$ late in summer. The heat pump duty cycle is estimated to be 50 percent run time during warmest summer days and 100 percent during coldest winter weather. Manufacturer specifications give a high temperature limit of 95°F for entering water. The heat pump discharge water will be 10°F warmer than entry. Total heat rejection of the heat pump is 32,400 Btu/hr. In the heating mode, the heat pump absorbs 25,000 Btu/hr at the low temperature water entry limit of 45°F . Earth temperature is 55°F in late winter. Discharge water will be 6°F cooler than entry. Design is for PVC pipe installed horizontally.

SOLUTION

Cooling Mode:

1. Find the design water to earth temperature difference, ΔT . In summer the earth temperature is 75°F . Use equation 2.

$$\Delta T = \frac{95 + (95 + 10)}{2} - 75 = 25^\circ\text{F} \quad (2a)$$

2. In Table 1, read the effective conductance rate for PVC pipe with 50 percent duty cycle, $U = 1.28 \text{ Btu/hr}\cdot^\circ\text{F}\cdot\text{ft}$.

3. Solve for L in equation 1.

$$L = \frac{32,400}{1.28 (25)} = 1,013 \text{ ft} \quad (3a)$$

Heating Mode:

1. Find the design water to earth temperature difference, ΔT . In winter, the earth temperature is 55°F

$$\Delta T = 55 - \frac{(45 - 6) + 45}{2} = 13^\circ\text{F} \quad (2b)$$

2. The 100 percent value for U for the heating mode applies. In Table 1 read $U = 1.61 \text{ Btu/hr}\cdot^\circ\text{F}\cdot\text{ft}$.

3. Solve for L in equation 1.

$$L = \frac{25,000}{1.61 (13)} = 1,194 \text{ ft} \quad (3b)$$

The heat exchanger length needed is the larger value which is 1,194 ft of PVC pipe for the heat pump in heating mode.

APPLICATIONS

Although no formal survey was made, it is estimated that there are over 500 residential earth-coupled water-source heat pump systems in Louisiana. Commercial systems from 6 to 180 tons capacity can be found in the Baton Rouge area. One restaurant has 37 tons of capacity with desuperheaters for hot water on all units. The utility bill averages \$1900/month less than a comparable restaurant that has gas and electric service. Earth heat exchangers are being installed with PVC, polyethylene and polybutylene pipe. Five years ago the concentric PVC pipe design was the most used; today U-bend designs in polybutylene and polyethylene pipe are more popular. The reliability of heat-fused joints and the flexibility and long lengths of polyethylene and polybutylene are advantages. Total installed costs for vertical U-bend heat exchangers range from \$2.00 to \$3.00 per foot of bore. The U-bend heat exchanger with continuous pipe lengths can be pressure-tested before insertion into the bore hole. State sanitary regulations require that the bore be backfilled and that the upper length be grouted like a water well. Licensing of installers of heat exchangers is being considered by the state regulatory agency.

Horizontal pipe installations cost less than vertical bores. They are used where land area is available. Costs range from \$1.00 to \$1.50 per foot of trench, including the cost of pipe.

ECONOMICS

Earth-coupled water-source heat pump systems are more expensive to install than conventional systems because of the large amount of pipe needed for the heat exchanger. Nevertheless, long life and low maintenance and operating costs make them a good investment.

The space conditioning system is a "big ticket" item in the typical family budget. Smilie et al. (10) compared five 3-ton space conditioning systems in the Baton Rouge, La. trade area, Table 2. The analysis included installation costs with specifications as obtained from Baton Rouge HVAC dealers, and the operating costs were derived from

Table 2. Summary of costs of five heating and cooling systems. Three ton capacity. Baton Rouge, LA (10).

System	Installation ¹ Cost	Operating Cost ²	10 Year Total Cost
1. Air Conditioner 8.65 EER, electric heat	\$2500	\$1740	\$19,903
2. Air Conditioner 9.15 EER, Gas furnace @ 55% efficiency	2900	1294	15,836
3. Air-to-Air Heat Pump, 9.02 EER, 3.05 COP	3300	1308	16,378
4. Air Conditioner 11.00 EER, Gas furnace @ 95% efficiency	3500	1058	14,082
5. Earth-coupled water-source heat pump, 11.1 EER, 4.01 COP	4730	969	12,840

1. Costs shown are for a new home. Based on average quotations of local HVAC contractors in Baton Rouge trade area. Electricity @ 8¢/Kwh and gas @ \$7.00/mcf.

2. Average annual operating cost based on 10 year life expectancy for air-source and 15 for water-source, 5% annual rate of inflation and energy costs, maintenance cost included.

the Baton Rouge weather data and utility costs for gas and electricity. Maintenance cost was assumed to be \$50/year for all systems except for air-to-air heat pumps for which it was assumed to be \$70/year. Inflation of energy and maintenance cost was estimated at 5%/year. All costs were on a cash basis.

Low initial cost for equipment usually means high operating costs, especially with energy cost escalation. The earth-coupled water-source heat pump system had the lowest 10 year total cost, even in comparison to a high efficiency air-conditioner (EER = 11) and high efficiency gas furnace (eff. = 95%).

Residential energy savings were documented in two residences which had conventional heating and cooling systems that were replaced with earth-coupled heat pumps. In one, electric energy saving was 21 percent, and natural gas for central heat was discontinued. Average gas consumption had been 16.6 mcf/year previously (4). The system used water-to-air heat pumps for space heating and cooling and a water-to-water heat pump for hot water. In the second, the earth-coupled water-source heat pump reduced electric consumption for heating by 68 percent from electric resistance heat and reduced the overall residential use by 28 percent (1).

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