GROUND LOOPS FOR HEAT PUMPS AND REFRIGERATION

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ABSTRACT

Ground loops are used for water source heat pumps. Refrigeration can be put on a ground loop. Water-cooled condensing units are more efficient than air-cooled, and they can be put indoors. Indoor location makes piping for desuperheater hot water easy. Since refrigeration equipment runs more than heat pumps, energy savings can be large for ground-coupled refrigeration. The paper presents a design procedure for ground loops for heat pumps, hot water, ice machines, and water-cooled refrigeration. It gives an overview of the commercial ground-coupled systems in Louisiana that have both refrigeration and heat pumps. Systems vary from small offices to a three-story office building with 187 tons. A chain of hamburger outlets uses total ground-coupling in all of its stores. A grocery store has ground-coupling for heat pumps and refrigeration. Desuperheaters provide 80 percent of the hot water for a coin laundry in the same building. A comparison of energy costs in a bank with a ground-coupled heat pump system to a similar bank with air-conditioning and gas for heat revealed a 31 percent reduction in utility costs for the ground-coupled building. Two buildings of the Mississippi Power and Light Co. have ground-coupled heat pumps in one, and high efficiency air source heat pumps in the other. Energy savings in nine months was 60,000 kWh (25 percent), and electric peak demand was reduced 42 kW (35 percent).

INTRODUCTION

Rising electric costs are affecting all segments of the nation's economy. In the home, space heating and cooling constitutes the largest energy use. Water heating is also a large energy user. In businesses, such as fast food outlets, restaurants, food storage and processing, refrigeration consumes large amounts of electric energy. Fortunately for the consumer, the heating and cooling equipment available today is more efficient than before. In cooling, and some heating processes, the natural environment (either air, water or earth) is the ultimate source or sink of the heat added to or removed from the material. The operating efficiency of refrigeration equipment and heat pumps is a direct function of the temperature of the environmental source or sink. Reduction in energy consumption can be achieved by using a thermally stable environmental source/sink and an energy recycling system that captures waste heat or cooling effect from one process and uses it in another. Both of these features are inherent in a ground-coupled system.

The majority of heat pumps and refrigeration equipment uses outdoor air as the thermal source or sink. Their energy efficiency is limited by the poor thermal capacity of air and the unfavorable temperature regime of the atmosphere. Due to the superior thermal capacity of water and more favorable temperatures of water in the environment, water source equipment is more energy efficient (Braud, 1981).

Closed-loop ground-coupled heat pumps have the energy-saving advantage of water source equipment and there are no water supply or disposal problems. Research led to the design of vertical-bore and horizontal-grid plastic pipe heat exchangers for use with water source heat pumps. Several plastic pipe configurations are used by contractors in Louisiana who install ground-coupled systems. Because of the large amount of pipe needed for the ground loop, ground-coupled heat pumps cost more than air source heat pumps. Cost for the ground-coupled heat pump is as much as $800 to $1,500 per ton more than air source systems (Braud et al., 1985). Despite the high cost, over 1000 homes in Louisiana have ground-coupled heat pumps. Significant energy savings have been documented in numerous residential installations with utility billing reduced as much as 20 to 50 percent compared to air-source equipment and/or gas heat (Braud et al., 1985).

A recent development in ground loop technology is to use a ground loop for refrigerators, freezers, display cases and ice machines. These machines can even be put on the same ground loop with a heat pump. Depending on the operating mode, season of the year and earth temperature, the effect of one unit or another can be either complementary or detrimental. Loop length must be adequate to provide safe loop water temperatures for all units in all seasons.

Commercial installations in the Baton Rouge area are increasing rapidly. Over twenty office buildings are on ground loops. The largest system known to the author is in a three-story office building that has 187 tons of water source heat pump capacity in multiple 3 to 5 ton units duplicated to share common ground loops. A chain of hamburger outlets, FAST TRACK, uses a ground loop for the heat pumps, hot water, ice machine, freezer and refrigeration loads. Two completely ground-coupled grocery stores are in operation and three more are in the planning or construction phase. Pool heating systems and water heating for a car wash can also be found.

A ground loop can take thermal energy rejected by one device and deliver it to another that requires heat. Energy transfer to or from the earth stabilizes loop water temperatures and

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satisfies energy balances. Loop design is basically a matter of providing enough heat transfer capacity between the circulating water and the earth to keep loop water temperatures within the limits dictated by the operating requirements of the equipment connected to the loop.

GROUND-COUPLED HEAT PUMP ENERGY FLOW

Energy transfer in a ground-coupled heat pump involves four media: indoor air, the refrigerant gas, water in the loop and the earth mass, Figure 1. Energy must pass through three heat exchangers: the indoor air-to-refrigerant coil, the refrigerant-to-water coil and the water-to-earth pipe wall.

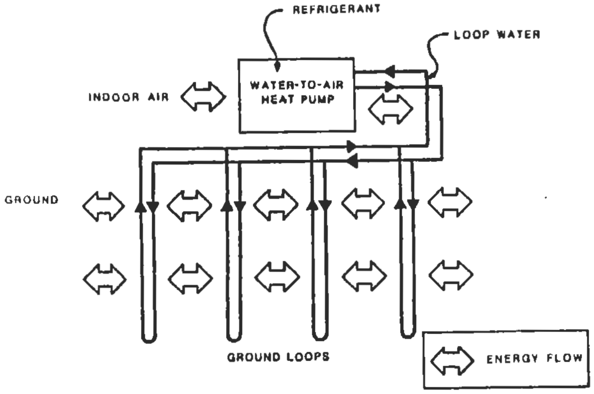

Figure 1. Ground-coupled heat pump.

COOLING MODE

In the cooling mode, thermal energy flows from the indoor air to the refrigerant, to the loop water, and to the earth. Electric energy that powers the compressor enters the refrigerant gas as heat of compression and sensible heat from the motor and passes on to the earth. The total heat rejected to the earth is the sum of the heat absorbed from the indoor space plus the electric energy needed to power the compressor, Figure 2. Thus

$$Q_r = Q_c + Q_e \qquad (1)$$

where

Q_r = total rate of heat rejection from the heat pump, Btu/hr.

Q_c = cooling capacity of the heat pump, Btu/hr.

Q_e = electric energy input to the heat pump, Btu/hr.

A cooling Coefficient of Performance (COPC) is

$$\mathrm{COPC} = Q_c/Q_e. \qquad (2)$$

Combining equations (1) and (2) one gets

$$Q_r = Q_c \times \frac{(\mathrm{COPC} + 1)}{\mathrm{COPC}} \qquad (3)$$

Cooling capacity (Q_c) and unit efficiency (COPC) should be taken at maximum loop operating temperature, not at standard rating conditions.

HEATING MODE

In the heating mode, the compressor heat energy goes to the indoor air along with heat absorbed from the earth, Figure 2. Thus

$$Q_h = Q_a + Q_e \qquad (4)$$

where

Q_h = heating capacity of heat pump, Btu/hr.

Q_a = heat absorption rate from the energy source, Btu/hr.

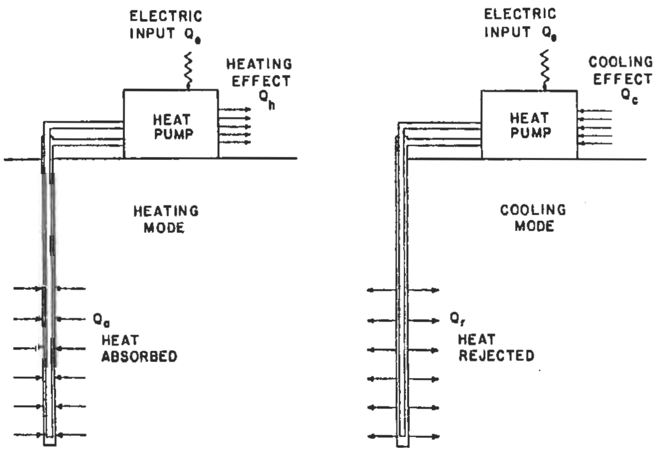

Figure 2. Energy flow of a ground-coupled heat pump for heating mode and cooling mode.

Heating mode energy efficiency is expressed with a Coefficient of Performance (COPH) that relates electric energy input to heating output

$$\mathrm{COPH} = Q_h/Q_e. \qquad (5)$$

Combining (4) and (5) one gets

$$Q_a = Q_h \times \frac{(\mathrm{COPH} - 1)}{\mathrm{COPH}} \qquad (6)$$

Usually the heat absorption (Q_a) is less than the heat rejection (Q_r). The ground loop must be able to accommodate the larger value.

DESUPERHEATERS

A desuperheater coil on a water source heat pump, Figure 3, is a cost-effective device. In summer, heat extracted from the hot compressor gas can provide most or all of the hot water in a residence. In commercial applications, heat pumps run long hours, and desuperheaters can provide very large quantities of hot water. When the heat pump is in space cool mode, heat removed from indoor space goes to the hot water tank and to the earth simultaneously until the hot water tank is satisfied; then the earth heat exchanger must provide the entire heat rejection. In winter, earth source heat provides both water heating and space heat. The reduction in space heating capacity due to hot water energy is not severe with a water source heat pump drawing on earth energy. Desuperheaters can be used on both air-cooled and water-cooled refrigeration condensing units. However, water-cooled condensing units are usually located indoors, which makes hot water piping easy.

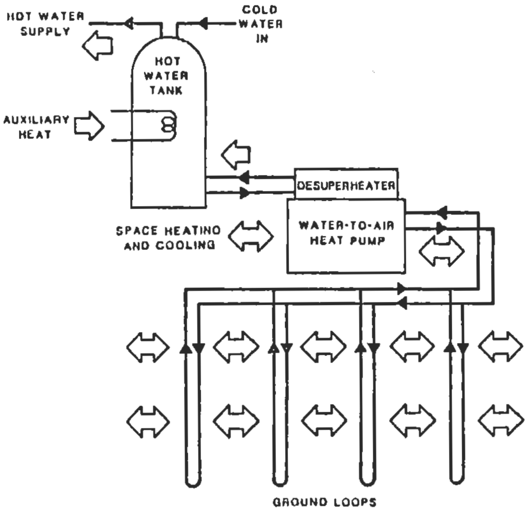

Figure 3. Ground-coupled heat pump with desuperheater.

Pierce (1983) found that a restaurant using 500 gallons of hot water per day was able to save $3,156 a year on hot water costs with desuperheaters on a total of 10 tons of refrigeration condensors. Pierce stated that desuperheaters have a fast payback, generally from 8 to 36 months in restaurants and fast food outlets. Other benefits are simple equipment with no moving parts, reduced electric demand, more efficient compressor operation and increased refrigeration capacity.

A grocery store in Gonzales, Louisiana has desuperheaters on the ground-coupled heat pumps and refrigeration condensers. Enough hot water is produced to provide 80 percent of the hot water for a coin laundry in the same building. A 4½ ton heat pump in a Baton Rouge office has generated enough hot water for restrooms and a small kitchen so that the electric elements have never been energized since installation in 1981. Desuperheaters on a 3½ ton heat pump in a fast food outlet produces the hot water needed for the kitchen.

WATER-TO-WATER HEAT PUMP

A water-to-water pump can generate hot water directly from a ground loop. Energy transfer, water-to-water, is very efficient; COP's of 3 to 5 are attainable in some situations. In Houma, Louisiana a dedicated 5 ton water-to-water heat pump serves as the sole water heating device for a car wash. The facility utilizes vertical bore heat exchangers and a 400 gallon storage tank. The owner reports that his utility bill is $300/month less than a similar car wash facility that uses gas for heat. Pool heating, hot tubs etc. are also good applications.

When very large quantities of hot water are needed, a water-to-water heat pump can be used in addition to the heat pump desuperheaters, Figure 4. A restaurant in Baton Rouge utilizes a 60,000 Btu/hr water-to-water heat pump to supplement desuperheaters on 37 tons of space heat/cool heat pumps on a ground loop. No auxiliary heat for hot water is needed in the restaurant which seats 300 people. Utility savings for the restaurant averages $1,900/month compared to a restaurant in Baton Rouge that has gas and electric service. A residential application of a water-to-water heat pump for hot water on a ground loop was described by Braud (1984). The seasonal COP of the unit was found to be 2.37.

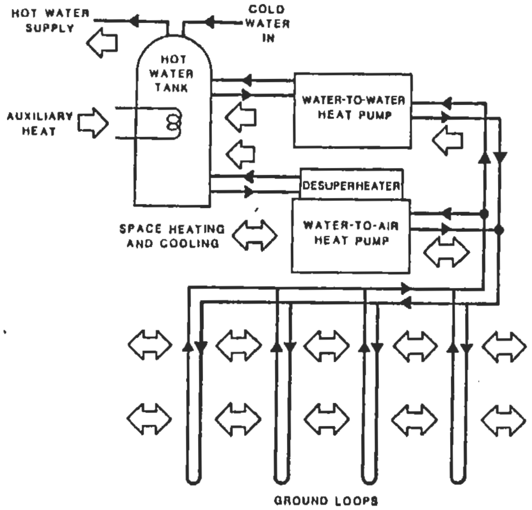

Figure 4. Ground-coupled heat pump and water-to-water heat pump for hot water.

HEAT PUMPS AND REFRIGERATION ON A GROUND LOOP

Ground loops offer several advantages for businesses that have refrigeration as well as heat pumps. Restaurants, fast food outlets and grocery stores are examples. All heating and cooling units can be put on the ground loop. Water-cooled condensing units for refrigerators and ice machines operate much more efficiently on water, and all mechanical equipment can be put indoors. Besides inherent energy recovery and transfer, a total ground loop system has very little maintenance and obvious asthetic advantage. Elimination of outdoor units reduces land requirement. Air-cooled roof top units operate in a harsh environment and create roof leaks and noise problems.

Two grocery stores in Louisiana use the total ground-loop concept as shown in Figure 5. A 3,300 sq ft store with 9½ tons of heat pumps and a 3 3/4 hp refrigeration load has a 200 amp, 115/230 volt, single phase electric service to serve the whole building that also contains an auto repair shop and a small seafood market.

Refrigeration heat rejection to a ground loop is always beneficial to heating devices sharing the loop. In zones of cool earth temperature, the capture of refrigeration waste heat would improve seasonal heating performance efficiency of heat pumps. Cool earth and loop water temperatures would allow water-cooled refrigeration units to operate very efficiently year-round. It is interesting to note that combined heat pump/refrigeration loops are being installed in south Louisiana where earth temperature (70°F) is relatively warm and space-cooling mode dominates. It would seem that in any climatic zone where annual heating energy exceeds cooling energy, refrigeration heat rejection would be highly beneficial. Loop energy transfer from cooling devices to heating devices would occur in many hours of the year. Loop length and cost could possibly be reduced for combined loads.

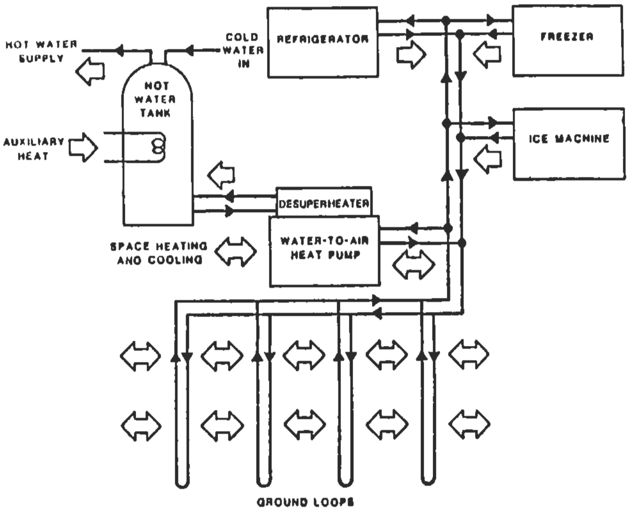

Figure 5. Ground-coupled heat pump and refrigeration.

Note: Desuperheaters for hot water can be put on refrigeration compressors.

REFRIGERATION HEAT REJECTION

In refrigeration, heat absorbed from the material being cooled must be rejected by the ground loop. Work performed by the compressor converted to heat must also be expelled via the ground loop to earth. Compressor heat is usually 20 to 40 percent of the evaporator heat. The net refrigeration effect (NRE) multiplied by the heat rejection factor (HRF) gives condenser heat rejection (HR) to the ground loop.

$$HR = NRE \times HRF \qquad (7)$$

Heat rejection factors are a function of refrigerant condensing temperatures, evaporating temperatures and mechanical design of the compressor and the refrigerant circuit. The range of values is about 1.2 to 1.6. Equipment manufacturers publish heat rejection factors for their equipment. Water-cooled condenser ratings may be given in Btu/hr of heat rejection, which is the value needed in ground loop design.

LOOP TEMPERATURES

Although earth temperatures below 30 ft deep remain constant year-round, the temperature of water in ground loops varies over the course of a day depending on heat rejection and absorption loads and run hours of the equipment operating on the loop. Temperature difference between the water in the pipes and the earth mass is the necessary driving force to move heat. The length of a ground loop necessary to keep loop water temperatures very near earth temperature would be excessive and not cost-effective. In loop design, it is important to choose proper temperature limits.

In Louisiana with 70°F earth temperature and heaving cooling loads, bottom line economics shows that loop temperatures rising to 100°F is an acceptable design value because water source heat pumps have a relatively flat capacity vs. entering water temperature curve and peak hot summer conditions occur only for a very few hours a year, on the average. The majority of run hours occur with loop temperatures between earth temperature and the upper design limit. In spring and fall loop temperatures remain near earth temperature.

In winter, a loop temperature of 55°F as the worst condition is an acceptable design value for the heating mode. Again, most of the operating hours occur with loop water temperature warmer than this. The record cold temperature for the century that occurred in January 1985 gives credence to this value for Louisiana conditions.

Improvements in water source heat pump manufacturing allow equipment operation over a wide range of entering water temperatures. Some manufacturers offer models especially designed for ground loops. A wide range of acceptable water temperatures is desirable for ground-coupling because narrow water temperature limits increase the length and cost for the ground loop.

GROUND LOOP DESIGN

A significant contribution to the knowledge of ground-coupled heat pump design is the new ASHRAE design/data manual by Bose, Parker and McQuistion, (1985). The manual encompasses seven years of research, analysis and design work at Oklahoma State University. Braud, et al. (1983), suggested a design method based on earth heat conductance values for vertical ground bores tested in Louisiana. Partin (1981) used the same method in Oklahoma. Several heat pump manufacturers and private parties now offer computer software for ground loop design.

This report presents a design method for ground loops with heat pump and refrigeration loads. In any design method, several energy and thermal parameters for the system must be known or estimated beforehand. Experience has shown that weather extremes cause maximum loads to be put on a ground loop, so that the loop design should consider energy flux requirements in both the warmest summer and coldest winter conditions. Although the loop acts as a closed energy transfer medium to collect heat from one unit and deliver it to another, loop length must be adequate to maintain safe loop temperatures for the maximum total heat rejection and absorption to the earth under all possible modes of equipment operation.

Definitive data on equipment run times are lacking; judgement and experience must prevail.

DESIGN PROCEDURE

Loop design involves the following parameters.

1. Loop Temperature Limits: The designer must choose maximum (summer) and minimum (winter) loop water temperatures to use in the design process. Manufacturer water temperature specifications for the equipment to operate on the loop is the source of information.
2. Total Heat Rejection: Heat pump and refrigeration heat rejection loads at maximum loop temperature must be added to get the total heat rejection load on the loop.
3. Total Heat Absorption: Heat pump plus another heating device heat absorption at minimum loop temperature must be added to get a total value to be provided by the ground loop.
4. Earth Conductance Values for the Ground Loop to be Used: Because the conductance rate for a ground loop is time dependent due to the increase in effective thermal resistance of the earth to energy flux near the pipes, design values for earth conductance must recognize equipment duty cycles and run time history. This effect is well covered by Bose et al. (1985). In commercial applications, mechanical equipment runs many hours more than in residential. Conductance values for long term operation have been reported by Partin (1981), Bose et al. (1985), Braud et al. (1983), and Klimkowski (1986). Values are summarized in Table 1. To meet maximum loads of heat rejection and absorption it is recommended that the loop length be based on earth conductance values for 100 percent run time for the connected equipment; or, knowledge of the equipment cycling might allow duty cycles of less than 100 percent.
5. Earth Temperature: Local data or published values for U.S. in Armitage et al. (1980).
6. Equation For Ground Loop Heat Flow: The equation for rate of heat transfer from the water in the ground-loop to the earth mass is

$$Q = U \times \Delta T \times L \qquad (8)$$

where

Q is rate of heat transfer, Btu/hr for the ground heat exchanger, either total heat rejection or absorption.

L is the loop length of the heat exchanger, ft, either total bore length for vertical bore(s) or pipe length for a horizontal loop.

U is the conductance rate for heat transfer from the circulating water to the earth, Btu per hour per degree Fahrenheit temperature difference per foot of length, for the particular ground loop configuration and the operating conditions.

ΔT is the difference in average water temperature in the loop and the earth temperature T_o.

$$\Delta T = \frac{T_2 + T_1}{2} - T_o \qquad (9)$$

T_2 is loop water exit temperature, °F.

T_1 is loop water entry temperature, °F.

T_o is the earth temperature, °F.

Table 1. Conductance to earth for vertical and horizontal heat exchangers.

Earth Heat Exchanger Configuration	U, Overall Thermal Conductance Btu/hr-°F-ft		
Run Time, Percent	100	50	25
Vertical, concentric nominal 2½ in, SCH 40 steel outer pipe nominal 3/4 in, SCH 40 PVC inner pipe	2.81	4.34	6.87
	(Braud et al., 1983)		
Vertical, concentric nominal 2½ in, 160 psi rated PVC inner pipe	2.07	2.80	3.68
	(Braud et al., 1983)		
nominal 3/4 in, SCH 40 PVC inner pipe	1.71	2.76	3.85
	(Klimkowski, 1986)		
Vertical, concentric nominal 5 in, PVC outer pipe nominal 1¼ in, PVC inner pipe	1.70	--	--
	(Bose et al., 1984)		
Vertical, U-bend nominal 1¼ in, 160 psi rated polybutylene	2.00	2.72	5.07
	(Braud et al., 1983)		
Vertical, U-bend nominal 1 in, 160 psi rated polybutylene	1.89[a]	--	--
Horizontal, single pipe nominal 1¼ in, 160 psi rated PVC, 6½ ft deep			
Summer (dry soil)	1.78	2.21	3.21
Winter (wet soil)	2.78	3.10	3.60
	(Klimkowski et al., 1985)		

a-Calculated with local earth resistance value, $R_{soil} = 0.389$. $R_{pipe} = 0.140$. $U = 1/(R_{soil} + R_{pipe})$. From Bose et al. (1985).

EXAMPLE

Find the length of ground loop(s) needed for a restaurant with two heat pumps, a walk-in refrigerator, freezer and ice machine. Location is south Louisiana with earth temperature = 70°F. Previous experience with ground-coupled systems in that area and equipment specifications indicate that minimum loop exit water temperature can be 55°F and maximum 100°F. Equipment energy characteristics are given in Table 2. Heat rejection and absorption values were taken from equipment literature. Duty cycles were based on experience and observation of operation of the different units during open hours for the type of business. Local contractors use one-inch polybutylene U-bend 2 pipe parallel in vertical bores to 300 ft deep.

SOLUTION

Cooling Mode:

1. Find the design water-to-earth temperature difference, ΔT. Earth temperature is 70°F. Temperature rise through the equipment is 10°F. Use Equation 9.

$$\Delta T = \frac{100 + (100 + 10)}{2} - 70 = 35°F$$

2. In Table 1, find the earth conductance rate for a vertical, U-bend loop with two one-inch polybutylene pipes in wet earth. For continuous equipment operation, its value is 1.89 Btu/hr-°F-ft.

3. Solve for L in equation 8. Heat rejection value from Table 2 is 127,720 Btu/hr.

$$L = \frac{127{,}720}{(1.89)(35)} = 1{,}931 \text{ ft}$$

Heating Mode:

1. Find the design water-to-earth temperature difference, ΔT. In winter, the minimum loop temperature is 55°F. Temperature drop through heat pumps is 6°F in the heating mode.

$$\Delta T = 70 - \frac{(55 - 6) + 55}{2} = 18°F$$

2. Solve for L in equation 8 using overall conductance value. U = 1.89 and heat absorption from Table 2 is 26,650 Btu/hr

$$L = \frac{26{,}650}{(1.89)(18)} = 783 \text{ ft}$$

The heat exchanger needed is the larger value which is 1,931 ft of ground loop length. For 300 ft bore depth, 1,931 ÷ 300 = 7 bores needed.

ENERGY SAVINGS IN COMMERCIAL APPLICATIONS

Energy use reduction with ground-coupled heat pumps has been documented in two commercial installations, one in Baton Rouge, Louisiana and one in Jackson, Mississippi.

In Baton Rouge two identical bank buildings were equipped with ground source heat pumps in one and conventional air-conditioning and gas heat in the other. The ground-coupled building was slightly larger (3,300 sq ft vs 3,000 sq ft) than the other building with the air-conditioning and gas. Architectural design of the two structures was similar as was operating schedules. The ground-coupled (Perkins) bank required 15 tons of capacity vs 11.5 tons in the other (Jones Creek). Energy use in the ground-coupled building was 27,146 kWh less in the seven month period Aug. 1985 to Feb. 1986 than in the other building with air-conditioning and gas. Gas consumption in the Jones Creek branch was 323 ccf for the mild 85-86 winter. Total utility billing for the Perkins bank was $3,900.48 vs $5,675.75 for the Jones Creek bank, a 31 percent difference.

The Mississippi Power and Light Co. compared ground-coupled heat pumps to standard air source

Table 2. Equipment specifications, heat rejection and absorption for example problem.

Load	Heat Rejection Rate @ 100°F Water, Btu/hr	Heat Absorption Rate @ 55°F Water, Btu/hr	Duty Cycle, Percent	Duty Rejection x Duty Cycle, Btu/hr	Heat Absorption Rate x Duty Cycle, Btu/hr
Heat Pump No. 1 41,000 Btu/hr cooling capacity	52,000	-	100	52,000	-
44,000 Btu/hr heating capacity	-	30,600	50	-	15,300
Heat Pump No. 2 38,000 Btu/hr cooling capacity	46,800	-	100	46,800	-
32,000 Btu/hr heating capacity	-	22,700	50	-	11,350
Walk In Refrigerator 7,000 Btu/hr	11,600	-	85	9,860	-
Freezer 8,000 Btu/hr	13,200	-	80	10,560	-
Ice Machine	8,500	-	100	8,500	-
Total	132,100	53,300		127,720	26,650

heat pumps in two of its office buildings. The two offices are the same in architectural design with identical 11,500 square feet of floor space. Both buildings have similar operating schedules and the insulation levels of the envelope are identical. However, glass on the ground-coupled (Rankin) office faces east and west and that on the air source (Madison) office faces north and south. Additional cost for ground-coupled system over air source was $835 per installed ton. Peak kilowatt demand was 120 in the air source building and 78 in the ground-coupled building. Energy use was 243,840 kWh in the air source and 183,840 kWh in the ground-coupled, a 25 percent difference in a 9 month period, July 1985 through March 1986 (Steen, 1986).

ADVANTAGES OF A GROUND-COUPLED HEAT PUMP/REFRIGERATION SYSTEM

1. Energy savings of 20 to 50 percent over air source equipment. Electric demand is also reduced with water-cooled condensing units for refrigeration and heat pumps.
2. Elimination of all outdoor air-conditioning and/or refrigeration units, also cooling towers and boilers. Corrosion, dirt, vandalism, theft, high maintenance, and freeze problems are eliminated. Elimination of roof top units reduces roof damage, noise, leaks, etc.
3. No additional outdoor space required. Earth bores can be put under lawns, landscape zones, driveways and parking lots. A three-story building in Baton Rouge, Louisiana has all bores underneath the building.
4. "Free" hot water from desuperheaters during the summer months. Year round with refrigeration waste heat. Hot water produced with COP advantage from an earth source in the winter.
5. No depletion of ground water. Presence or quality of ground water is of no concern because heat transfer is to the earth mass.
6. No wastewater expense or disposal problem. Closed loop uses ordinary tap water for heating and cooling energy transfer to earth.
7. Elimination or reduction in electric heat strips that are required with air source heat pumps.
8. Elimination of gas service to premises. No flue or ancillary costs for gas heat that are often hidden in the plumbing contract.
9. Long life, low maintenance system. Recent trade figures indicate that water-cooled condensers have 20+ year life expectancy. Compressor life is long because of low head pressure when operating with water.
10. No equipment to hide in the landscape. An important point to architects.

DISADVANTAGES

1. High cost, $600 per ton for earth bores in Louisiana. Manifold piping, pumps, etc. will increase total cost to $800 to $1500 per ton over other types of air-conditioning systems.
2. Not all air-conditioning contractors are familiar with this technology.
3. Earth drilling and trenching is difficult in rock or other problem areas.
4. Antifreeze solution needed in loop in Northern U.S.

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