A VARIABLE-SPEED GROUND-SOURCE HEAT PUMP

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RESUMEN

Este artículo contiene una descripción detallada de una bomba de calor que es de velocidad variable y utiliza el suelo como fuente de calor, la cual fue diseñada, construida, y analizada por estudiantes y profesores en "The University of Alabama". Se demostró que las bombas de calor que usan el suelo como fuente de calor pueden trabajar más eficientemente que las bombas de calor que utilizan aire como fuente de calor.

SUMMARY

This article contains a detailed description of a variable-speed ground-source heat pump designed, constructed, and tested by students and professors at The University of Alabama. It was demonstrated that ground-source heat pumps can perform more efficiently than conventional air-to-air heat pumps.

INTRODUCTION

The objective of this paper is to provide information about the design and construction of a variable-speed ground-source heat pump (VSGSHP) at The University of Alabama. The VSGSHP is a new alternative to the conventional air-to-air heat pump which uses the outdoor air as a heat source or a heat sink. This new type of heat pump uses the ground as a heat source or a heat sink, and is expected to be more efficient than the air-to-air system.

HEAT PUMPS

A heat pump is a system of refrigeration components which operate to absorb heat from a heat source and reject it to a heat sink which is at a higher temperature than the source [8, 14]. The development of heat pump systems was temporarily accelerated for the first time in the early 1930's when many manufacturers became interested in this type of device. At approximately 1950, work was done in the United States and Britain on domestic heat pumps using ground coils to extract heat from the ground [14]. However, the primary development of heat pumps occurred after the first and second oil crises in 1973 and 1979 [13].

Modern control systems for heat pumps have been mainly developed in the last two decades. One of the factors that favored the growth of these control systems was the availability and "low" cost of electronic components and computers, which have become progressively more efficient and less expensive, and still continue on this course. Most of the heat pump control system advances have been directed to the air-to-air heat pump systems. This type of heat pump uses the outside air to absorb or sink the heat needed to heat or cool a conditioned space. The components of air-to-air heat pumps have been improved and the capacity of air conditioning units increased to outstanding values in recent years. Through search for better operation and efficiency of air-to-air heat pumps, compressors, thermostatic expansion valves, refrigerant-to-air heat exchangers, and fans, among other components, have become very sophisticated and continue to be developed. Even though this progress has occurred, there is still a principal limitation in the operation of the air-to-air heat pumps. The temperature of the outside air, from which heat is absorbed or rejected, is not always ideal. During the summer, when the outside temperatures are high, heat is supposed to be transferred (in the condenser) from the refrigerant to the outside air. As a consequence, the demand of energy (especially in the compressor) is extremely high, causing a decrease in the efficiency of the system. A similar situation occurs in the winter, but this time the temperature of the outside air is low and the heat is supposed to be transferred (in the evaporator) from the outside air to the refrigerant. Much of the time supplementary heat, in the form of electrical resistance, is necessary to supply the heating requirements. The operating condition of the compressor in these situations is

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critical. Electric energy is highly demanded, increasing the operating cost of the heat pump. When massive demand for energy takes place because the outdoor temperature conditions are extreme, the electrical generation facilities undergo a peak in power demand which sometimes reaches the maximum available supply. In terms of energy this situation is not only critical for the heat pump, but also for the power company. In terms of cost, it directly affects the consumer.

Due to the above mentioned drawbacks of air-to-air heat pumps, other types of heat pumps, which utilize other heat sources, have been developed. The heat sources most utilized are ground-water, rivers, lakes, city water, and the ground itself [3,9,16].

The advantage of using a ground-coupled heat pump, as it was done in this research, is that the temperature of the ground at certain depths is not extremely high or low during the different seasons. In addition, not much fluctuation occurs to the ground temperature throughout the year at certain depths. This is one of the reasons why the ground is potentially a better place to absorb or reject heat during extreme atmospheric conditions of temperature.

For the ground-coupled heat pump, a closed-loop heat exchanger, or ground coil, is installed underground. Water, usually mixed with an anti-freeze (methanol or ethylene glycol) is circulated through this heat exchanger and heat is absorbed from the ground when heating or rejected to the ground when cooling. For adequately designed systems, water can be supplied at 29.5 °C where outdoor air is at 35 °C [2]. Water-to-air heat pumps have high expectations in places with extreme weather conditions, where air-to-air heat pumps highly demand energy.

THE VARIABLE-SPEED GROUND-SOURCE HEAT PUMP AT THE UNIVERSITY OF ALABAMA

The first two stages of the development of a VSGSHP had been completed at The University of Alabama in 1991. First, a 10.6 KW (three tons of refrigeration) variable-speed air-to-air heat pump was modified and converted to a ground-source heat pump. The compressor, indoor fan, air coil and controls were the same as in the original system. However, the outdoor coil was exchanged for a water-to-refrigerant heat coil, and a vented water-heating coil was added [4,6]. The performance of the modified heat pump varied within a range of 3.75 to 8.09 W/W (12.8 to 27.6 Btu/h-W) energy efficiency ratio (EER) during cooling, and within a range of 3.1 to 6.0 coeficient of performance (COP) during heating. The original air-to-air heat pump was rated by ARI at 4.45 W/W (15.2 Btu/h-W) EER and at 2.6 COP [4]. The modified heat pump was capable of operating at the rated values, and at a wide range of values most of them higher than the rated values. It was demonstrated that the VSGSHP performs better than the air-to-air heat pump. In addition, the ground-source heat pump was capable of heating water in a dedicated fashion, and COPs ranging from 1.3 to 3.3 were obtained [4].

Two other reasons that make the VSGSHP more propitious than an air-to-air heat pump are:

1- The air-to-air heat pump does not possess the capability of heating water.
2- When heating water, the VSGSHP performs better than an electrical resistance, which has COP of 1.

Since good results were obtained with the ground-source heat pump, the first control logic program was designed and tested. This control system was designed to vary the speeds of the compressor, the fan, and the two pumps, with the purpose of optimizing the performance of the heat pump. An eight-bit 8031 microcontroller was used to control the heat pump [4,6]. Though the control system performed an excellent job controlling the room temperature, it has some limitations controlling the relative humidity and the consumption of energy. The reason for these limitations was that the speeds of the motors of the compressor, fan, and the pumps, were varied based only on the difference between the actual room temperature and the set point room temperature. The set of rules used to vary the speed of the motors is represented in fig. 1, where "minimum" refers to the lower speed at which the motor should operate, and ΔT is the diference between the actual temperature and the set point tempera-

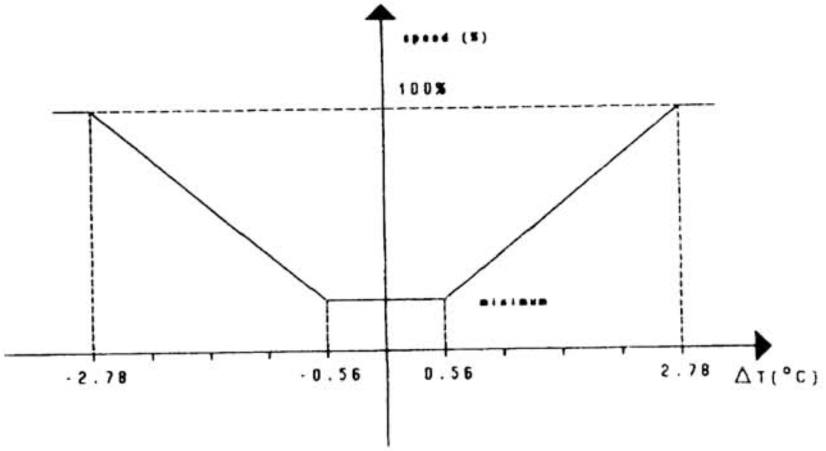

Fig. 1. Speed of the Motors versus Δ T

ture in the room. For instance, when the temperature difference (ΔT) was lower or equal to 0.56 °C (1°F), the compressor operated at its "minimum" speed which was set to 25% of its full speed to avoid lubrication problems [4,6].

To facilitate the description of the VSGSHP installed at The University of Alabama, the system has been divided in four subsystems:

1. Heat source subsystem
2. Refrigerant cycle subsystem
3. Air distribution subsystem
4. Hot water subsystem

A detailed description of subsystem 1 is presented in the next section, the other subsystems are described in subsequent sections.

SUBSYSTEM 1: HEAT SOURCE

The heat source or heat sink for the heat pump is the ground. A heat exchanger to circulate the water (mixed with 15% methanol) and extract or reject heat to the ground was installed. Also, a 245 Watt (1/6 HP) pump to circulate the water was installed in the main water loop. This pump is driven by an AC motor which is controlled with a phase control system and 60 different motor speeds are attainable. Consequently, it is possible to change the water flow rate in the main loop according to the speed of the pump's motor. A water-to-refrigerant coil is also part of this subsystem. The coil selected is a Koax model K-36 A-SC which has a nominal 10.6 KW (three tons of refrigeration) capacity, and is used in counterflow during heating [4]. Fig. 2 presents the components and parameters of subsystem 1. The arrows in the coils indicate the direction of the heat transfer when the unit is in the heating mode. In the cooling mode, the direction of the arrows would be the opposite to the one shown in the figure.

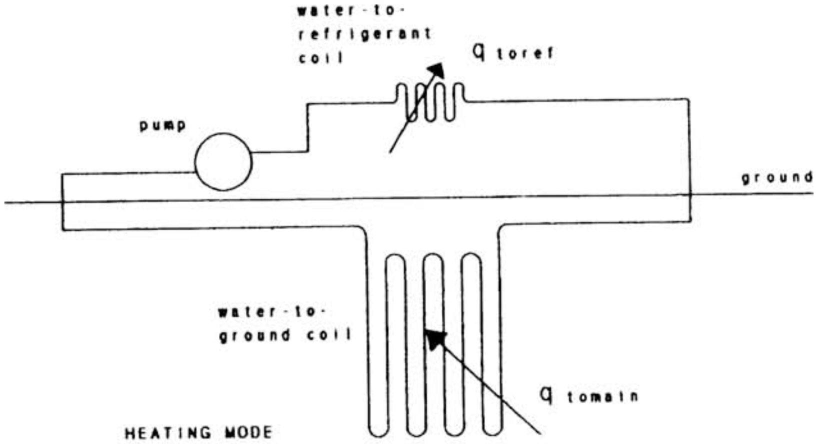

Fig. 2. Heat Source Subsystem

SUBSYSTEM 2: REFRIGERANT CYCLE

The refrigerant cycle subsystem is comprised of a compressor, water-to-refrigerant coil (as described for subsystem 1), refrigerant-to-air coil, refrigerant-to-hot water coil, thermostatic expansion valve, reversing valve, and suction accumulator, as shown in fig. 3.

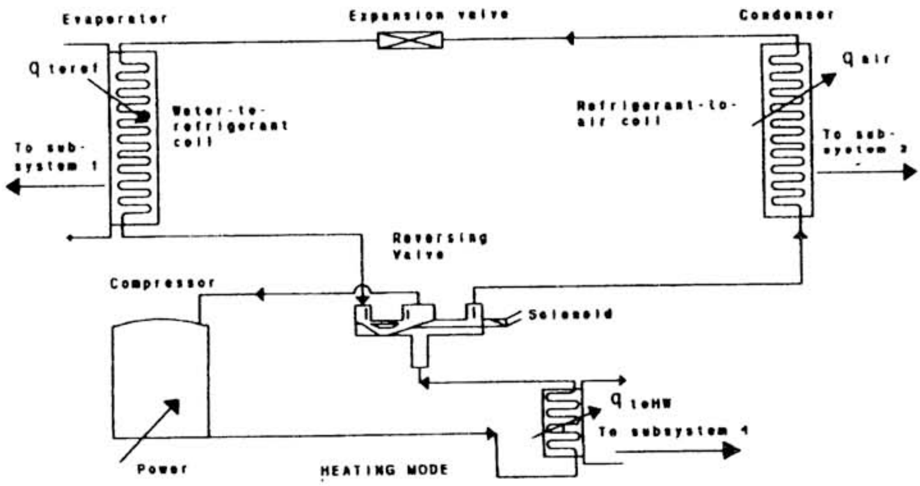

Fig. 3. Refrigerant Cycle Subsystem

A variable frequency pulse width modulation (PWM) inverter was used to control the brushless permanent magnet DC motor (PMDC) which drives the compressor. PWM is a method of controlling the voltage supplied to the motor, and consequently of varying the speed of the motor [4]. The flow rate of the refrigerant can be changed according to 51 different motor speeds available for the compressor. Finally as part of this subsystem there is a refrigerant-to-hot water coil, which is a Koax 24 A-SC helical tube-in-tube, with a nominal capacity of 7.03 KW (24 Mbtuh) [4].

SUBSYSTEM 3: AIR DISTRIBUTION

The heat pump unit is connected to a distribution air duct which discharges the air uniformly in the conditioned space. A model TWV739E150B fan, from the Trane Company, moves the air over the heat exchanger and in the duct. The speed of the fan is controlled using the same method used for the compressor, a PWM controller system. The fan speed determines the flow rate of air passing over the refrigerant-to-air coil, and 84 different fan speeds are obtainable. Fig. 4 shows the components of subsystem 3.

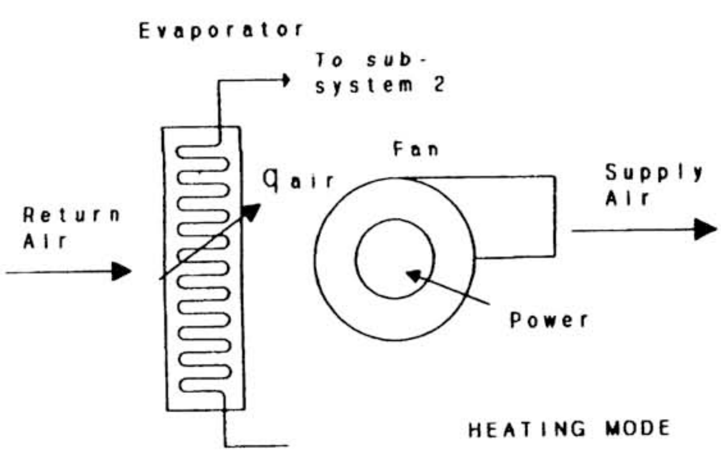

Fig 4. Air Distribution Subsystem

SUBSYSTEM 4: HOT WATER

Another capability of the heat pump is to supply hot water to the residential building. A 40 gallon hot water tank is installed near the heat pump. The hot water is circulated over the refrigerant-to-hot water coil using a 86 Watt (1/25 HP) pump, whose speed is controlled using the phase control method, in the same way as it is done for the pump in the water main loop. The refrigerant-to-hot water coil acts always as a condenser with the water and the refrigerant in counterflow. Fig. 5 presents the main elements of subsystem 4.

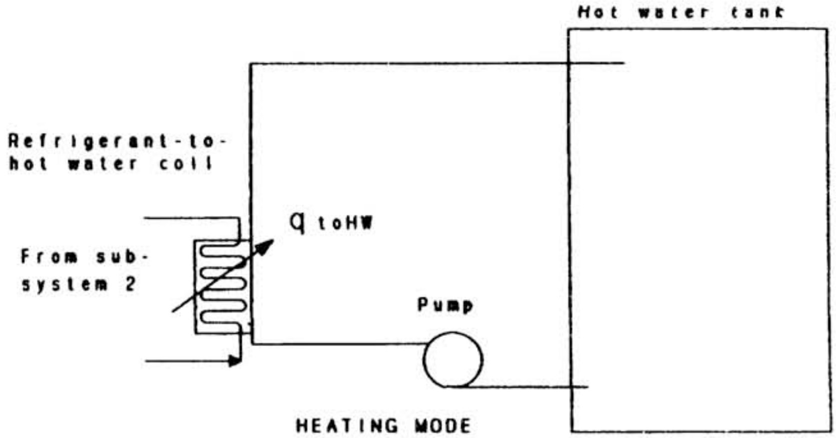

Fig. 5. Hot Water Subsystem

TEST RESULTS

This section contains a description of the tests performed to the heat pump and the results obtained in the heating mode. The results from such tests were first analyzed, linearized, and written into equations, and then used to design the control system and to simulate the heat pump performance. Information is available about the VSGSHP operating in the following four modes:

1. Mode 0: the heat pump is not operating.
2. Mode 1: the heat pump operates in a dedicated air heating mode.
3. Mode 2: the heat pump heats air and water simultaneously, with flow rate of hot water of 0.5 GPM.
4. Mode 3: the heat pump operates in a dedicated water heating mode, with flow rate of hot water of 3 GPM.

The desired conditions for operation of the heat pump in each of the modes are presented in table 1.

Table 1. Conditions for the Different Operating Modes of the Heat Pump during Heating

Operating Mode	ELT (°C)	T_{airr} (°C)	Q_{main} GPM	Q_{HW} GPM
Mode 1	7.2	21.1	6	0
Mode 2	7.2	21.1	6	0.5
Mode 3	7.2	21.1	6	3

Tests were performed at 25, 50, 75, and 100% compressor speed, with fan speed following compressor speed. The entering liquid temperature (ELT) in the water main loop was set at 1.6, 7.2, and 12.8 °C for all the compressor speeds. In total, 12 test cases were performed in both the dedicated air heating mode and the air-and-water heating mode. For the dedicated water heating mode, tests were performed at 25, 50, and 75% compressor speed, with ELT set at 4.4 and 12.8 °C; a total of 6 test cases were performed in this mode [4,6]. The results obtained when the heat pump was operated in modes 1, 2, and 3 are in tables 2, 3, and 4.

Table 2. Tests Results during Operation Mode 1

Compressor Speed (% of full)	q_{air} (KW)	Input Power (KW)	COP
25	3.56	0.65	5.47
50	5.74	1.27	4.53
75	8.89	2.50	3.56
100	10.12	3.10	3.27

Source: S.P. Kavanaugh, R.S. Falls, J.K. Parker, A Variable-Speed Ground-Source Heat Pump.

Table 3. Tests Results during Operation in Mode 2

Compressor Speed (% of full)	q_{air} (KW)	q_{air} (KW)	Input Power (KW)	COP
25	2.24	1.67	0.61	6.38
50	3.84	2.49	1.19	5.32
75	5.92	3.78	2.38	4.08
100	6.57	4.38	3.71	3.71

Source: S.P. Kavanaugh, R.S. Falls, J.K. Parker, A Variable-Speed Ground-Source Heat Pump.

Table 4. Tests Results during Operation Mode 3

Compressor Speed (% of full)	q_{HW} (KW)	Input Power (KW)	COP
25	1.00	0.61	1.57
50	2.40	1.18	1.93
75	4.51	2.44	1.80

Source: S.P. Kavanaugh, R.S. Falls, J.K. Parker, A Variable-Speed Ground-Source Heat Pump.

For operation in mode 3, the ELT was assumed to be 7.2 °C, therefore, the results in table 4 were obtained by interpolating the original results, which were obtained with ELT of 4.4 and 12.8° C. The entering hot water temperature was assumed to be about 37.8 °C.

The performance of the heat pump in mode 3 noticeably improves when the entering liquid temperature (ELT) is greater than 7.2 °C, or when the entering hot water temperature (EHWT) is less than 37.8 °C. On the contrary, if ELT is less than 7.2 °C or EHWT is greater than 37.8 °C the performance of the heat pump decreases [4,6].

From the test results in tables 2 through 4, it was not possible to determine the performance of the heat pump when the flow rates of water in the main and hot water loops were varied. Therefore, both pumps must operate to supply a desired constant flow rate according to the operating mode utilized by the heat pump.

During heating, the relative humidity of the room was not controlled. However, this was not a major problem when operating in the heating mode. As can be obtained from the psychometric chart, the comfort zone during the winter allows the relative humidity to be in the 30-70% range which is almost always the case in a residential building [11].

CONCLUSION

The most important conclusion obtained from this article is that the VSGSHP performed better than an air-to-air heat pump, without the inconvenience of defrost cycles. Besides that, the VSGSHP was capable of heating water in a dedicated manner with COP values greater than 1 and even as high as 3.3. This last result is important because heating water with electrical resistance implies a COP of 1, which was noticeably improved by the heat pump. In this research, heating water was a secondary task for the heat pump; heating the air in the house was the most important task. The heat pump was allowed to heat water only when the conditions permitted it. A principal goal of this project was also to operate the heat pump at the most efficient point: minimize energy consumption while meeting the heating or cooling demand. Since the test results demonstrated that the heat pump operates at impressive efficiencies, specially at low compressor speeds, a control system was designed to guide the VSGSHP to operate at the most desirable conditions whenever it was possible. The heat pump was commanded to operate, according to the circumstances, in any of the four operating modes during heating. When heat was needed for the indoor air, the heat pump operated in mode 1 or mode 2; and when heat was needed for the hot water, the heat pump operated in mode 2 or mode 3; otherwise, the heat pump was turned off.

The results obtained when testing the heat pump were very satisfactory, specially when the compressor operated within the range of 25% to 50% of full speed. The most desirable operating conditions for the heat pump were determined to be:

1. Low speed of the compressor and fan
2. Flow rate of 6 GPM in the water main loop
3. Flow rate of the hot water of 0.5 GPM in mode 2 and 3 GPM in mode 3
4. Return air temperature of about 21.1 C
5. ELT of about 7.2 C
6. EHWT of about 37.8 C

As a result, when these operation conditions are accomplished, the heat pump would operate with a COP of about 5.5 in mode 1, 6.4 in mode 2, and 2.0 in mode 3. The COP values decreased when the compressor and fan speeds were increased.

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NOMENCLATURE

ARI	American Refrigeration Institute
Btu	British Thermal Units
Btuh	British Thermal Units per Hour
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
ELT	Entering Liquid (water in main loop) Temperature
EHWT	Entering Hot Water Temperature
GPM	Gallons per Minute
KW	Kilowatt
Power	Input Power to the Heat Pump
q	Heat Transfer Rate
q_{load}	Cooling Load or Heating Load
T	Temperature

SUBSCRIPTS

air	Indoor Air
HW	Hot Water
main	Referring to the Water in the Main Loop
op	At the most Desired Operating Conditions
r	Return
ref	Refrigerant
s	Supply Air
to	Indicates the Direction