Contribution to a Life Cycle Exergy Analysis of Heat Pumps with Various Evaporator Sources

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Abstract

There is a growing need for the analysis of energy systems not only on the basis of their operational life, but also on the basis of considerations for the manufacturing and recycling phases. Environmental and to a lesser extent resource scarcity factors should also be taken into consideration. A general unified thermodynamic approach based on exergy was recently proposed [1,2,3] and is briefly summarized. The main idea of this approach is to minimize the cumulated exergetic losses of operation, manufacture and recycling, distributing the exergy of manufacture (the so-called gray exergy) and recycling over the life time of the system. Additional levels of analysis consist of introducing pollution and resource scarcity factors and using these to artificially penalize the above mentioned exergy terms. In this paper, the first level of analysis (exergy analysis with gray exergy) is applied to four domestic heat pumps operating with different evaporators (direct expansion horizontal ground coil, brine horizontal ground coil, brine geothermal U tubes and air-source).

1. INTRODUCTION

Heat pump systems are generally considered as among the most efficient space heating technologies. Their disadvantage is the relatively high cost associated with these systems when compared to boiler based heating systems. A comparison of heating systems on the basis of their capital costs and operational costs is not sufficient. In reality, costs other than the costs due to market prices intervene and should be taken into account. These costs are directly related to the manufacturing and recycling phases. Other costs are those associated with resource utilization and pollution. When these factors are considered, heat pump heating systems are not as heavily penalized as boiler based heating systems.

A general unified thermodynamic, economic and environmental approach based on exergy and taking into consideration factors related to resource utilization and pollution was recently proposed [1,2,3]. This Second Law approach simultaneously considers thermodynamic, economic and environmental aspects in the analysis and optimization of energy systems. The thermodynamic losses that occur during the system's life, from the manufacture to the recycling of its components are determined in order to take account of these in the total costs (whether on a monetary or a physical thermodynamic basis) associated with the system.

The main idea of this approach is to minimize the cumulated exergetic losses of operation, manufacture and recycling, distributing the exergy of manufacture and recycling (the so-called gray exergy) over the life time of the energy system. For the manufacture of some component n, the gray exergy is defined as

$$Eg_n = \frac{(E_{chem,n,out})}{h_{II}} = E_{chem,n,out} + Loss_n = E_{chem,n,in} + E_{res,n} \qquad (1)$$

where $E_{chem,n,in}$ is the chemical exergy content of the raw material used for the manufac-

	ture of component n
$E_{chem,n,out}$	is the chemical exergy content of component n (only chemical and not, for example, mechanical contributions are considered here)
$Loss_n$	is the exergetic loss which occurs during the manufacture of component n
$E_{res,n}$	is the exergy used by the manufacturing process of component n.

Now, neglecting recycling and using a purely physical thermodynamic basis for all costs, the objective for an energy conversion system such as a heat pump becomes

$$\text{Minimize} \qquad C = \sum_n Eg_n + \int_\tau \dot{\Gamma}_{res}\, dt - \int_t \dot{\Gamma}_{ben}\, dt + K \tag{2}$$

where	τ	is the period of analysis (e.g., the useful lifetime of the system)
	$\dot{\Gamma}_{res}$	is the exergy rate of the resources consumed by the system during its operation
	$\dot{\Gamma}_{ben}$	is the exergy rate of benefits (e.g., supplied heat exergy)
	K	are any additional costs other than the exergy spent for resources (e.g., such as costs related to pollution, the future scarcity of resources, the recycling of equipment, etc.).

A further step in the analysis is to introduce pollution costs in the form of factors directly into the objective for the system. The objective, thus, becomes:

$$\text{Minimize} \qquad C = \sum_n \frac{Eg_n}{f_A(P_i)} + \int_\tau \frac{\dot{\Gamma}_{res}}{f_B(P_i)}\, dt - \int_t \dot{\Gamma}_{ben}\, dt + K' \tag{3}$$

where	f_A	is the pollution penalty factor for the manufacturing process ($0 \leq f_A \leq 1$)
	f_B	is the pollution penalty factor for the operation of the system ($0 \leq f_B \leq 1$)
	P_i	is the pollution factor for pollutant i
	K'	is analogous to the K term of Eq. (2) except that now the pollution costs have been incorporated into the other terms of this equation.

An example of a pollution factor for some pollutant i (or pollutant stream i) appears in figure 1.

The present work involved the determination of the exergy spent for the manufacture of three ground coupled heat pump heating systems. A comparison with an air source heat pump is also presented. All the terms in Eq. (2) except the benefits were evaluated to determine a value for C for each system. The benefits (heat exergy supplied) were excluded since they are the same for the four heat pump systems considered. The term K was neglected. A consideration of pollution factors will be the objective of future work.

The terms Eg_n in Eq.(2) were calculated for the four evaporator subsystems on the basis of the exergy spent for the manufacture of the different components ($E_{res,n}$) and for the raw material exergy content ($E_{chem,n,in}$). The sum of the Eg_n as well as the integral of $\dot{\Gamma}_{res}$ were evaluated on the basis of a lifetime of 15 years.

2. DESCRIPTION OF THE SYSTEMS

The nominal heat demand (15 kWth at an outside temperature of -6°C) is identical for the

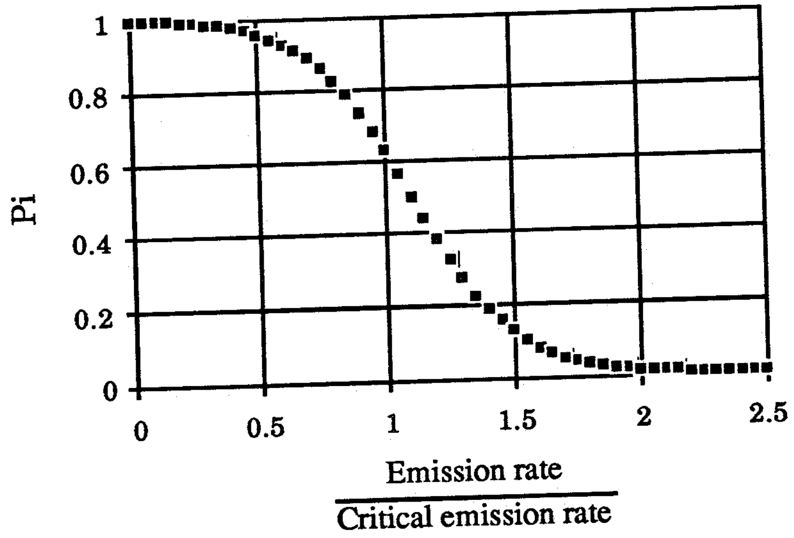

Figure 1. Pollution factor for pollutant i [1].

four systems and is used for dimensioning the equipment. The heat demand only includes space heating and is satisfied entirely by the heat pumps. Therefore, the differences which appear in this study between the four systems are essentially due to the different evaporator subsystems. The rest of the heat pump (condenser, compressor, etc.) has the same structure with slight adjustments in size as a function of the subsystems considered.

The electrical consumption of the heat pumps is based on manufacturer data sheets [4]. For the ground coupled systems, the seasonal ground temperature variation is assumed to result in the evaporator temperature patterns given in figure 2. In order to obtain the amount of consumption from the manufacturer data sheets, an estimated brine temperature is calculated from an evaporator temperature based on an 8°C cumulated temperature difference (5°C pinch + 3°C brine temperature difference). The consumption of the air-source heat pump is based on

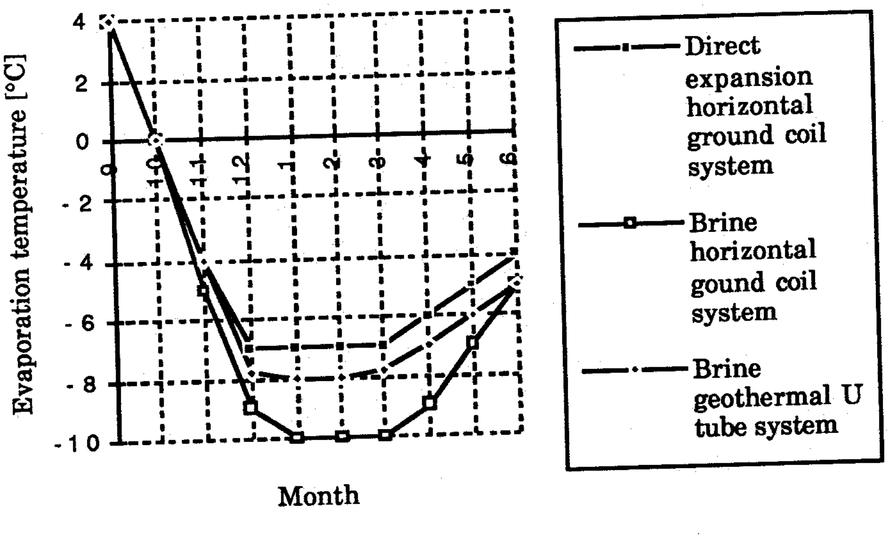

Figure 2. Evaporation temperatures for the horizontal direct expansion, the brine horizontal and the brine geothermal U-tube systems.

daily average air temperatures.

2.1. Direct Expansion Horizontal Ground Coil System

Figure 3 shows the direct expansion system. A conventional brine-to-water heat pump where the brine coil and the evaporator have been substituted by a horizontal ground evaporator coil is considered here.

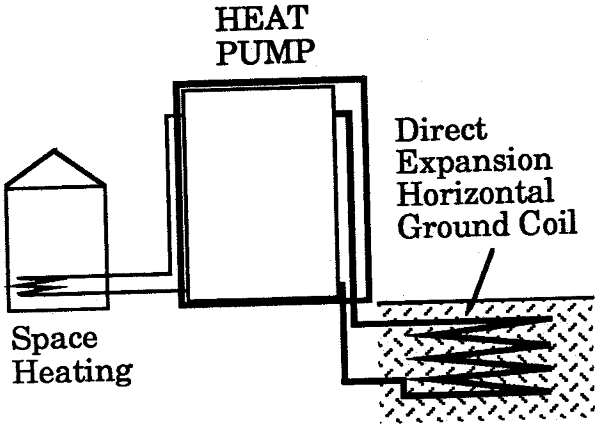

Figure 3. The Direct Expansion System.

The dimensioning of the direct expansion ground evaporator coil is based on data given by a single-fluid heat pump manufacturer [5]. The ground coil consists of several horizontal U-tubes connected in parallel. They are made of copper with a polyethylene external protection sheet. Their internal and external diameters are 11 and 12.5 mm, respectively while the polyethylene sheet is 1 mm thick. The manufacturer indications are that for a rated power of 15 kW, ten U-tubes are necessary, resulting in a total tube length of 600 m. The total excavation area is 300 m^2. based on figure 2, the minimal evaporation temperature is -7°C.

2.2. Brine Horizontal Ground Coil System

Figure 4 shows the brine horizontal ground coil system. The coil is made of several circuits connected in parallel while the coil tube is made of polyethylene. The internal and the external diameters are 16 and 20 mm, respectively, and the total tube length is 1000 m (heat rate per unit of length = 10 W/m). The evaporator subsystem is divided into 10 coils in parallel and the excavation area is 500 m^2.

2.3. Brine Geothermal U-Tube System

Figure 5 shows the brine geothermal U-tube system. The brine ground network consists of three vertical U-tubes made of polyethylene connected in parallel. The internal and the external diameters of the tube are 20 and 22 mm, respectively. Dimensioning is based on a calculated heat rate per unit length of 60 W/m resulting in a total drilling length of 165 m (3 drillings of 55 meters each).

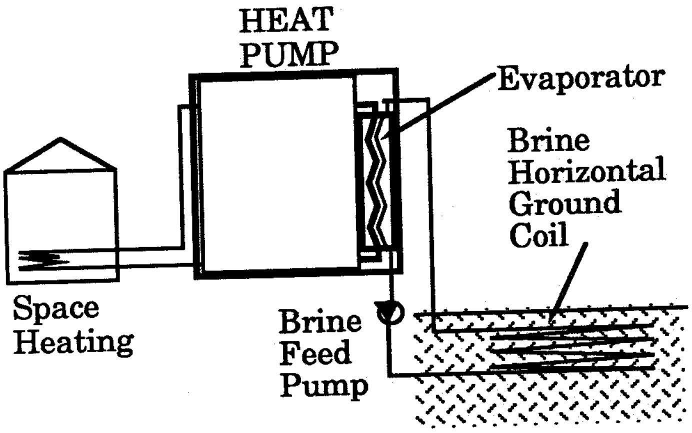

Figure 4. Brine Horizontal Ground Coil System.

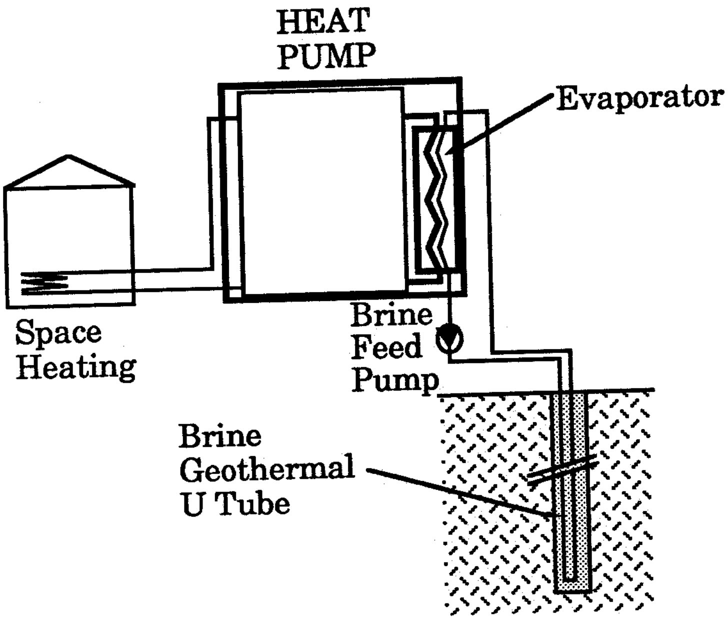

Figure 5. The Brine Geothermal U-Tube System.

2.4. Air-source heat pump

Figure 6 shows the air-source heat pump system. Its evaporator consists of 6 rows of 26 copper tubes with aluminum fins.

3. THERMODYNAMIC COSTS

3.1. Operational costs

The heat demand and the temperature at which it is supplied are assumed to vary linearly as a

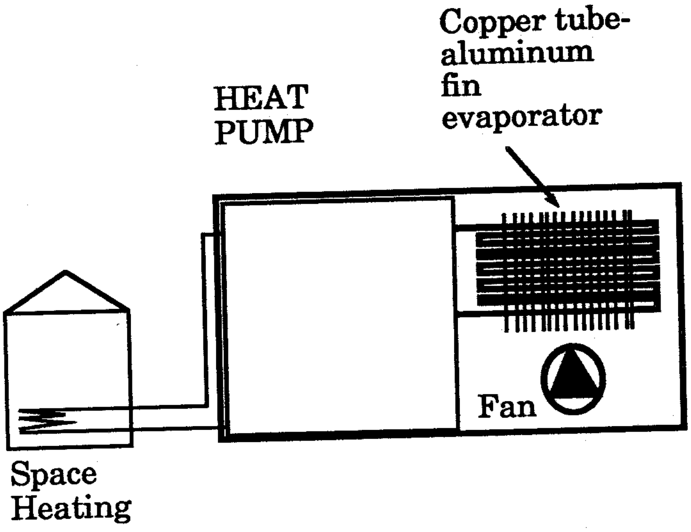

Figure 6. The Air-Source Heat Pump System.

function of the outside air temperature. For example, the water supply temperature of the heating demand is 50°C at an outside air temperature of -6°C .A yearly heating energy of 105610 MJ is delivered by each of the four systems which corresponds to a yearly heating exergy of 11855 MJ.

A summary of all the operational parameters for the four systems appears in Tables 1 to 3. The operational costs (the integral of the $\dot{\Gamma}_{res}$) for each system per year and per lifetime (15 years) are given in Table 1.

Table 1
Exergy (electricity) consumed by the systems during the heating season and their lifetime (MJ).

Direct Expansion	Brine Horizontal Ground Coil	Brine Geothermal U-tube	Air-Source Heat Pump
33,062	35,345	36,634	36,007
495,930	530,175	549,510	540,105

Table 2
Average seasonal coefficient of performance (COP) - operational only since the gray energy (energy counterpart of the gray exergy) is not included.

Direct Expansion	Brine Horizontal Ground Coil	Brine Geothermal U-tube	Air-Source Heat Pump
3.19	2.99	2.88	2.93

Table 3
Average seasonal exergetic efficiency (without accounting for gray exergy).

Direct Expansion	Brine Horizontal Ground Coil	Brine Geothermal U-tube	Air-Source Heat Pump
0.358	0.335	0.324	0.329

3.2. Gray Exergy

The calculation of the gray exergy is often a difficult and approximate process requiring a decomposition of the equipment considered into individual subcomponents, materials and related functions. Exergy losses which occur during the preparation and distribution of the final energies used for the manufacture of the equipment must be evaluated. In this study, the exergy value of the fuels used was approximated by their higher heating values. For the electricity, an exergy efficiency of production of 0.24 [6] was assumed. Process exergies were determined primarily from Boustead, et al. [6] and the chemical exergies of the raw materials from Szargut, et al. [7].

Calculated values for the gray exergy of the subcomponents, materials and related functions considered in this paper are shown in Table 4. Tables 5-8 show the results of the gray exergy calculations.

Table 4
Gray exergy of the basic subcomponents, materials and related functions.

Product	Gray Exergy
Steel Sheet from ore in the ground [6]	55.46 MJ/kg
Steel Heavy Plate from ore in the ground [6]	43.5 MJ/kg
Aluminum Sheet from ore in the ground [6]	283.5 MJ/kg
Copper Tube[1] from ore in the ground [6]	122 MJ/kg
HDPE (high density polyethylene) pipes from crude oil [6]	180 MJ/kg
Ethylene Glycol from crude oil [6]	142.5 MJ/kg
Gravel from raw materials in the ground [6]	0.11 MJ/kg
Excavation [8]	11.5 MJ/m^3
Drilling[2]	24.71 MJ/m
Heat Pump[3] [9]	77.5 MJ/kg
Brine Feed Pump [8]	142.4 MJ/kg

[1] "Copper General Product from Ore in the Ground" in reference [6].

[2] The drilling gray exergy value was estimated by measuring the real fuel consumption for 3 drillings at a 55 m depth (mainly in sandstone) .

[3] Gray exergy of a heat pump was estimated on the basis of the gray energy of a domestic refrigerator given by Spreng [9] and extrapolated for various sizes of the four heat pump concepts considered. In the particular case of the direct expansion system, the gray exergy of a standard evaporator was subtracted.

Table 5
Gray exergy required for the direct expansion system.

Component	Quantity	Specific Gray Exergy	Gray Exergy
Heat Pump	184 kg	77.5 MJ/kg	14260 MJ
Evaporator Plates: 50 thin plates	5 kg	55.46 MJ/kg	277 MJ [1]
Evaporator Plates: 2 thick plates	2 kg	43.5 MJ/kg	87 MJ [1]
Copper Tube (600 m)	149 kg	122 MJ/kg	18178 MJ
PE (polyethylene) layer	24 kg	180 MJ/kg	4320 MJ
Excavation	300 m^3	11.5 MJ/m^3	3450 MJ
TOTAL			**39844 MJ**

[1] These values are subtracted from the heat pump value of 14260 MJ.

Table 6
Gray exergy required for the brine horizontal ground coil system.

Component	Quantity	Specific Gray Exergy	Gray Exergy
Heat Pump	184 kg	77.5 MJ/kg	14260 MJ
Brine Feed Pump	4.7 kg	142.4 MJ/kg	669 MJ
HDPE Pipe (1000 m)	105 kg	180 MJ/kg	18900 MJ
Excavation	500 m^3	11.5 MJ/m^3	5750 MJ
Ethylene Glycol	63.15 kg	142.5 MJ/kg	8999 MJ
TOTAL			**48578 MJ**

Table 7
Gray exergy required for the brine geothermal U-tube system.

Component	Quantity	Specific Gray Exergy	Gray Exergy
Heat Pump	184 kg	77.5 MJ/kg	14260 MJ
Brine Feed Pump	36 kg	142.4 MJ/kg	5126 MJ
HDPE Pipe (354 m)	45.5 kg	180 MJ/kg	8190 MJ
Drilling	180 m	24.71 MJ/m	4448 MJ
Gravel	4072 kg	0.11 MJ/m^3	448 MJ
Ethylene Glycol	35 kg	142.5 MJ/kg	4987 MJ
TOTAL			**37459 MJ**

Table 8
Gray exergy required for the air-source system.

Component	Quantity	Specific Gray Exergy	Gray Exergy
Air-Source Heat Pump	420 kg	77.5 MJ/kg	32550 MJ
Air Conduits (Steel sheets)	43 kg	55.46 MJ/kg	2385 MJ
TOTAL			**34935 MJ**

The gray exergy of the air-source heat pump includes the gray exergy of the evaporator which is shown in Table 9 below.

Table 9
Gray exergy required for the evaporator of the air-source heat pump.

Component	Quantity	Specific Gray Exergy	Gray Exergy
Evaporator Copper Tubes	22.6 kg	122 MJ/kg	2757 MJ
Evaporator Aluminum Fins	37 kg	283.5 MJ/kg	10489 MJ
TOTAL			**13246 MJ**

4. CONCLUSIONS

For all four evaporator schemes, the gray exergy of the manufacturing and installation of the evaporator subsystems only represents a small proportion of the global exergy use over the useful life of the heat pumps. In terms of the exergy balance, this indicates the existence of a substantial margin for improvement (larger heat exchanger areas, etc.) with rather low exergy payback times. Based on the exergy life cycle analysis presented here, differences between evaporator schemes are relatively small.

Future work will include the extension of this study to competitive boiler technologies and the introduction of the additional aspects of the general methodology discussed, i.e., pollution factors, scarcity factors and recycling. This extension of the method should contribute to being able to more clearly emphasize and quantify the environmental and resource conservation advantages of heat pumps over conventional boiler technologies

Finally, for two of the horizontal evaporator subsystem schemes (direct evaporation and brine coil), performance comparisons with field tests in parallel and on the same tract of land are currently underway.

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