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Experimental exergy assessment of ground source heat pump system

Saif Nawaz Ahmad* and Om Prakash[a]

Department of Mechanical Engineering, National Institute of Technology, Patna, Ashok Raj Path, Patna, 800005, India

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Abstract. The principal intention of this experimental work is to confer upon the exergy study of GSHP associated with horizontal earth heat exchanger for space heating. The exergy analysis recognizes the assessment of the tendency of various energy flows and quantifies the extensive impression of inefficiencies in the system and its components. Consequently, this study intends to provide the enlightenment for well interpretation of exergy concept for GSHP. This GSHP system is composed of heat pump cycle, earth heat exchanger cycle and fan coil cycle. All the required data were measured and recorded when the experimental set up run at steady state and average of the measured data were used for exergy investigation purpose. In this study the rate at which exergy destructed at all the subsystems and system has been estimated using the analytical expression. The overall rational exergetic efficiency of the GSHP system was evaluated for estimating its effectiveness. Hence, we draw the exergy flow diagram by using the various calculated results. The result shows that in the whole system the maximum exergy destruction rate component was compressor and minimum exergy flow component was earth heat exchanger. Consequently, compressor and earth heat exchanger need to be pay more attention.

Keywords: exergy; earth heat exchanger; heat pump; exergetic efficiency

1. Introduction

Exergy is synonymous to the available work. The concepts of exergy may be uses for getting the effectiveness of any process to performing work. The main use of exergy analysis is to getting information about location, magnitude and type of exergy losses in a system, so that the system's efficiency should be increased by eliminating these losses. As we know that the non-ideal performance of system and equipment are the cause of entropy generation. Thus, this irreversible production of entropy imparts the exergy losses. Hence our main objective of this experimental study is to evaluate the exergy flow at various components of the system and recognizes the parts where more loses occurs. GSHP system utilizes earth stored energy for cooling or heating space. This earth stored energy also called geothermal energy which is a form of renewable energy. Since India is high energy consumption country related to heating or cooling a space, so it is necessary to

*Corresponding author, Ph.D. Student, E-mail: saif.nawaz.ahmad@gmail.com
[a]Professor, E-mail: om.prakash@nitp.ac.in

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implement a system for heating/cooling a space that works on renewable energy. As solar heat pump is also a type of heating system which utilizes solar irradiation which available only in day time and energy should be stored in water using tanks while GSHP system does not require solar irradiation because it uses earth stored energy that available all time. So, selection of GSHP system is more preferable while using uniform time domain. Since India has more solar irradiation and some of this radiation is absorbed by earth and is in turn again uses in GSHP system for running it in day or night. GSHP system generally employs where there is low heating or cooling required. It requires large space for installation of its ground heat exchanger that buried in earth, but after installing ground heat exchanger we may use the space above the ground heat exchanger for any purposes. In case of solar heat pumps more free space required for installing its panel in order to absorbing more solar irradiation. It is also the environment friendly because it does not emit harmful gases. The cost of GSHP system is more than that of solar heat pump system but in GSHP system we may take multiple works at a time from the evaporator of the heat pump. Hence this property compensates the difference in cost between solar heat pump and GSHP system. (Esen *et al.* 2007) investigated the energetic as well as exergetic efficiencies of ground coupled heat pump system for heating mode of application at given varying depths of horizontal ground heat exchanger. They buried two parallel horizontal ground heat exchangers named HGHE1 and HGHE 2 at 1m and 2m respectively. Their result reveals that the energy efficiencies for both the heat exchangers were 2.5 and 2.8 respectively, while exergetic efficiencies for both type of heat exchanger were 53.1% and 56.35 respectively. Their result shows that both the efficiencies increase with increasing the ground temperature for heating application. They also concluded that the exergy efficiency for both trenches gets decreases while increasing the reference environment temperature. (Yildiz and Gungor 2009) carried out energy as well as exergy analysis for three types of space heating systems. They demonstrated the advantages of energy as well as exergy analysis using heating load only while cooling load were neglected. (Bi *et al.* 2009) give the capacious investigation of GSHP for heating and cooling purposes, they derived the various analytical formulae for exergy parameters. Their results show that the losses of exergy of GSHP for heating mode are more as compared with cooling mode. (Balbay and Esen 2010) carried out a practical study in order to check the feasibility of ground source heat pump system for melting snow/ice on pavements and bridge decks. (Self *et al.* 2013) reviewed the status and compared GSHP with heating choice in terms of CO2 emission, cost and other parameters. (Balbay and Esen 2013) determined the temperature distribution in pavements and bridge slabs that are heated using vertical ground source heat pump system by performing the experimental and computational fluid dynamics studies. (Esen and Tahsin 2013) experimentally investigates the heating of Greenhouses by biogas, solar and ground source heat pump with horizontal slinky ground heat exchanger. They also investigated the effect of climatic condition and various operating parameters on the system. (Ally et. al., 2015) identified the source of inefficiencies using exergy analysis and performance metrics were presented for vertical bore GSHP over 12-month study. (Ahmad *et al.* 2017) conducted an experiment for investigating the effectiveness of GSHP system in Indian climatic condition, and they calculated the coefficient of performance and rate of heat extraction from soil. (Esen et. Al., 2017) analyses the solar assisted ground source heat pump system with horizontal and vertical slinky ground heat exchanger by experimental and numerical modelling. They use Artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) for modelling of system. Their result reveals that the ANFIS is more successful than ANN in order to predicting the performance of the system. (Menberg *et al.* 2017) enumerate the thermal analysis of every subsystem of a hybrid GSHP system and segregate the different strategies that how the exergy efficiency should be increased. Ozturk (2014) focus on the energy and exergy efficiency of GSHP for space heating whose evaporator works as photo voltaic thermal collector (PV/T) furthermore investigated the location of inefficiencies and to give how these processes fit to actual operating conditions. (Younis*et al.* 2010) shows the current status and impact on environment of GSHP. (Mohanraj *et al.* 2010) discuss the exergy loss as well as exergy efficiency for entire elements of direct expansion solar coupled heat pump system using R22 and R407C/LPG Mixture as working fluid for different ambient conditions. They developed a new model named artificial neural network (ANN) model for investigating its performance and concluded that the whole exergy loss for RM 30 is less compared with R22 and is about 0.19kW. (Ahamed *et al.* 2012) presents the performance of domestic refrigerator using hydrocarbon refrigerant such as butane and isobutene on the basis of comparison of its energetic and exergetic efficiencies. The energy and exergy efficiency of isobutene were found 175% and 50% respectively more than that of R134. The exergy efficiency of butane is also higher as compared with isobutene and R134. (Padilla *et al.* 2010) performed the experimental test for exergy analysis of domestic VCRS using R413A as refrigerants, and he found that R 413A could be the ozone-friendly and safe alternative of R12. (Ozgener *et al.* 2007) point out the effect of energy as well as exergy efficiencies by varying reference state properties such as temperature. Their study reveals that the energy efficiency of the system varies between 0.53 and 0.73 while its exergy efficiency lies between 0.55 and 0.60. (Ahamed *et al.* 2011) reviewed the studies conducted in various countries or societies for evaluating and analyzing the exergy and its efficiency through thermodynamic relations. The comparative study of energetic and exergetic analysis of VCRS based on four different pure hydrocarbons have been presented by (Bayrakci *et al.* 2009). They concluded that when the working fluid R1270 used in the system it provides maximum energy as well as exergy efficiencies at all working conditions. (Suzuki *et al.* 2016) develop a special kind of heat exchanger named spiral heat exchanger and calculate the per unit initial cost of spiral and U-tube type heat exchanger. They use the numerical simulator "TOUGH2/EOS1." for investigating the performance of the system using various flow rates and soil conditions. (Kjellsson *et al.* 2010) optimize the GSHP combined with solar collector through the simulation tool TRANSYS. (Yumruta *et al.* 2002) investigate the effects of condensing and evaporating temperature on pressure losses, exergy losses, COP of VCRS through the computational model. (Dikici and Akbulut 2011) presented a new exergetic criterion that is exergetic performance coefficient for multiple source heat pump system. (Dincer and Cengel 2001) give the deliberated study of energy, entropy and exergy and they also explained their various roles in the thermal engineering with examples. (Bu *et al.* 2013) described the selection criteria of working fluid and thermal performance of vapour compression air conditioning powered by geothermal energy. (Akhmadullin and Tyagi 2017) presents the numerical analysis for extraction of geothermal energy through a down hole heat exchanger. (Major *et al.* 2018) accomplish the numerical investigation of a deep geothermal reservoir for both extraction and heat storage.

2. Outline of GSHP

The illustrative scheme of proposed GSHP system coupled with horizontal earth heat exchanger is shown in Fig. 1. The proposed system can be disunited into three major subsystems (I) The ground heat exchanger subsystem built with G.I pipe that buried into the earth at about 3 m below the earth surface for harnessing the geothermal energy. The working fluid that flow

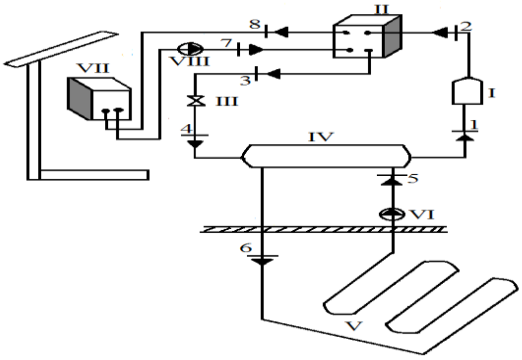


Fig. 1 Graphical layout of proposed system for heating mode. (I) Compressor (II) Condenser (III) Capillary tube (IV) Evaporator (V) Earth heat exchanger (VI) Water circulating pump

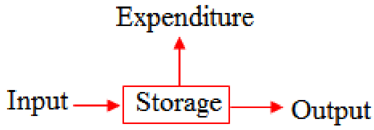
Table 1 Technical specification of different components of GSHP system

Main components	Sub components	Technical specifications
Heat pump unit (Refrigerating circuit)	Compressor	Mitsubishi, RH313CACT,4 kW, R22
	Condenser	LG, UAEBend80FPDM, Aluminum
	Capillary Tube	Copper, 3 meter,1.5 mm
	Evaporator	Shell tube type, Coil material: Copper, Coil nominal diameter: 35 mm, Pipe diameter: 3.4 mm, Shell material: Galvanized Iron, Shell diameter: 40 mm
Ground unit	Earth heat exchanger	Material: Galvanized Iron, Type of GHE: Horizontal Pipe length 20 m, Diameter: 12.7 mm, Piping depth: 3 m, Pipe distance: 152 mm
	Earth loop circulating pump	Kirloskar, 05BYXO31419, 50 W per kW heat pump capacity, RPM: 2700, 200-1800 l/h.
Fan coil unit	Water circulating pump	Kirloskar, 05BYXO31419, 50 W per kW heat pump capacity, RPM: 2700, 200-1800 l/h.
	Forced fan	Kwick,F.A.9", 230 V AC, 50 Hz,RPM: 2200,500 m^3/h.

throughout the earth heat exchanger is water and or mixture of water antifreeze (ethyl glycol). Water was mixed with antifreeze named ethyl glycol 10% by weight for preventing water to freeze under working condition mostly in winter season. (II) Heat pump subsystem that consist of four components namely evaporator, compressor, condenser expansion devices. All these components were interconnected by closed loop copper tubing. The working fluid for heat pump system is R22 and works on vapour compression cycle, the connection between heat pump and earth heat exchanger is evaporator where thermal energy of ground heat exchanger is taken by refrigerant R22. (iii) The third subsystem is the fan coil unit that provides the building heating in winter season. The fan takes air which is heated by hot water return from coil of condenser. All the components and their technical specifications are listed in Table 1.

3. Theoretical formulation of exergy for GSHP

The general balance equation in a system for given quantity is expressed as, Input +Formation= Output + Expenditure + Storage



As per steady condition

$$\frac{\partial(\,properties\,)}{\partial t} = 0 \tag{1}$$

Hence the storage term for balancing the ongoing equation must vanishes. So, for the steady condition the exergy equity equation in general form may be written as below that gives irreversibility.

$$\dot{X}\,destruction = \sum \dot{X}\,in - \sum \dot{X}\,out + \sum Q\left(1-\frac{T_O}{T}\right)_{in} - \sum Q\left(1-\frac{T_O}{T}\right)_{out} \pm W \tag{2}$$

$$\dot{X} = \dot{m}\,\dot{x} \tag{3}$$

As we know that the specific exergy at any state is given as,

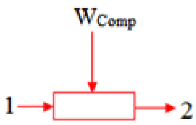
$$\dot{x} = h - h_o - T_O\left[s - s_o\right] \tag{4}$$

There are various ways through which we may estimate the exergetic efficiencies that has been taken from Corneilesion(1997). Among all those, the rational or overall rational efficiency is the ratio of aimed output exergy to the serviced exergy, and is given as,

$$\eta_{O.R} = \frac{\dot{X}_{aimed,output}}{\dot{X}_{serviced}} \tag{5}$$

For the proposed GSHP system shown in Fig.1 the exergy balance equation and efficiency for each component may be formulate as,

(1) For Compressor:



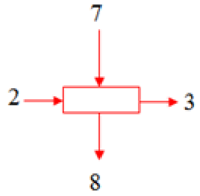
The rate at which exergy losses taken place in compression process is may be formulating as,

$$\dot{X}_{destruction} = \dot{X}_1 - \dot{X}_2 + W_{comp} \tag{6}$$

The exergetic efficiency for compression process may be formulate as,

$$\eta_{exergetic,comp} = \frac{\dot{X}_2 - \dot{X}_1}{W_c} \tag{7}$$

(2) For Condenser:



The rate at which exergy losses taken place in condensation process may be formulate as,

$$\dot{X}_{destruction} = \dot{X}_2 - \dot{X}_3 + \dot{X}_7 - \dot{X}_8 \quad (8)$$

The exergetic efficiency for condensation process may be formulate as,

$$\eta_{exergetic,cond} = \frac{\dot{X}_8 - \dot{X}_7}{\dot{X}_2 - \dot{X}_3} \quad (9)$$

(3) Capillary tube (Expansion process):

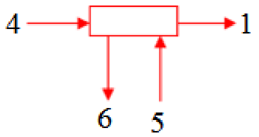
The rate at which exergy losses taken place in Expansion process may be formulate as,

$$\dot{X}_{destruction} = \dot{X}_3 - \dot{X}_4 \quad (10)$$

The Exergetic efficiency for expansion process may be formulate as,

$$\eta_{exergetic,Exap} = \frac{\dot{X}_4}{\dot{X}_3} \quad (11)$$

(4) For Evaporator:



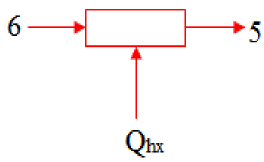
The rate at which exergy losses taken place in Evaporation process may be formulate as,

$$\dot{X}_{,destruction} = \dot{X}_4 - \dot{X}_1 + \dot{X}_5 - \dot{X}_6 \quad (12)$$

The Exergetic efficiency for Evaporation process may be formulate as,

$$\eta_{exergetic,Eva} = \frac{\dot{X}_1 - \dot{X}_4}{\dot{X}_5 - \dot{X}_6} \quad (13)$$

(5) Ground Heat Exchanger:



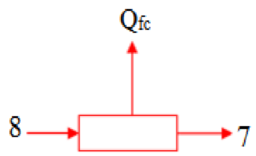
The rate at which exergy losses taken place in Ground Heat Exchanger may be formulate as,

$$\dot{X}_{destruction} = \dot{X}_6 - \dot{X}_5 + Q_{ghx}\left(1 - \frac{T_0}{T_{soil}}\right) \tag{14}$$

The Exergetic efficiency for Ground Heat Exchanger may be written as,

$$\eta_{exergetic,ghx} = \frac{\dot{X}_5 - \dot{X}_6}{Q_{ghx}\left(1 - \frac{T_0}{T_{soil}}\right)} \tag{15}$$

(6) Fan coil unit:



The rate of exergy destruction in Fan coil unit may be formulate as,

$$\dot{X}_{destruction} = \dot{X}_8 - \dot{X}_7 - Q_{fc}\left(1 - \frac{T_0}{T_{in,air}}\right) \tag{16}$$

The Exergetic efficiency for Fan coil unit may be formulate as,

$$\eta_{exergetic,fc} = \frac{Q_{fc}\left(1 - \frac{T_0}{T_{in,air}}\right)}{\dot{X}_8 - \dot{X}_7} \tag{17}$$

4. Result and discussion

A GSHP system was fabricated in the hydraulics lab of BIT Sindri, Dhanbad. In this experimental study the different measuring parameters were recorded with the help of appropriate instruments and, the average reading of different parameters is listed in Table 2. The experiment was brought under steady state conditions of GSHP system for heating mode in January 2015. From the Fig. 1 of the GSHP system, there are eight state points given which combine to form a cycle called GSHP cycle. The major property data at all the state points of GSHP cycle are compiled in Table 2. Some of the property data listed in Table. 2 are directly taken from refrigeration table and some are calculated using basic thermodynamic laws and balance equations.

The exergy destructions for each element of GSHP are calculated and listed in Table 3. The overall rational exergetic efficiency was found as 0.0278.

The Exergy destruction shows the reduction in available energy. The exergetic efficiency is used for estimating the effectiveness of different elements and whole GSHP system. The results listed in Table 3 reveals some important advantageous knowledge about exergy for different component of system. The exergy flow of compressor increases due to work input while the

Table 2 Measured and calculated properties data

Point	Temp(°C)	Enthalpy(kJ/kg)	Mass flux (kg/s)	Entropy(kJ/kgK)	Exergy(kJ/k)	Exergy rate(kW)
1	-4	250.30	0.017	0.9396	46.916	0.7975
2_{act}	74	295.55	0.017	0.970	92.166	1.566
2_{sat}	50	264.05	0.017	0.9396	64.1716	1.090
3	50	264.05	0.017	0.4003	62.097	1.0556
4	-4	112.86	0.017	0.422	55.956	0.9512
5	12	50.4	0.14	0.181	1.028	0.1439
6	8	33.6	0.14	0.121	2.108	0.29512
7	42	192.5	0.185	0.651	4.916	0.9094
8	46	175.8	0.185	0.599	6.9	1.2765

Table 3 Exergy destruction rate of various elements of GSHP system

Various elements	Exergy Losses (kW)
Compressor	0.3615
Condenser	0.1433
Throttle	0.1044
Evaporator	0.0025
Ground heat exchanger	0.0783
Fan coil unit	0.3986

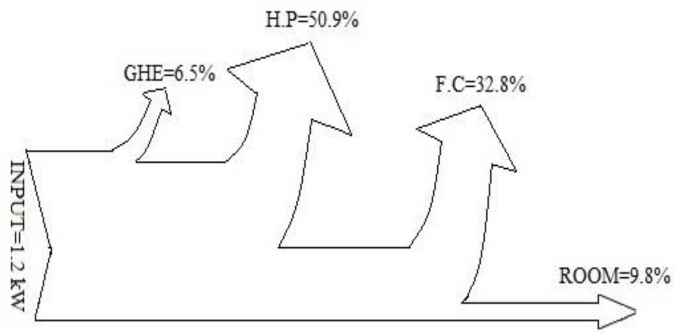


Fig. 2 Exergy flow diagram of GSHP System

exergy flows of other components decrease. For getting quantitative idea of exergy input to GSHP system and their destruction in the various components, we draw an exergy flow diagram for GSHP system as shown in Fig. 2.

Fig. 2 shows that the highest exergy debt is taken place at heat pump subsystem (viz combination of compressor, condenser, expansion and evaporator) and is given as 0.61170 Kw or 50.9% of total available exergy. The exergy destruction at ground heat exchanger subsystem is given as 0.0783 Kw or 6.5% of the total exergy available which is minimum amongst the all subsystem. By analyzing the exergy destruction for different components of heat pump subsystem the sequence of exergy in decreasing order is given as compressor, condenser, evaporator and expansion. In heat pump subsystem the highest exergy loss at compressor is due electrical, mechanical and isentropic efficiencies. Owing to higher degree of superheat at closing stages of compression the second largest destruction occurs at condenser. Because of pressure drop while the working fluid refrigerant passing through the expansion device there is third largest destruction exist. Instead of these the lowest destruction occurs at evaporator amongst the heat pump system. As per similar studies performed by (Chen and Hao 2015) the exergy losses at heat pump unit was 55.3 %, at ground heat exchanger unit it was 7.19% and at terminal losses it was 22.06% while exergy transferred to room was 14.88%. Hence by comparing the results of this paper with (Chen and Hao 2015) we found that our results are in the acceptable range.

5. Conclusions

After study the exergy testing of horizontal ground source heat pump system for heating mode of operation, we conclude the following points such as.

- As we know that exergy is the maximum obtainable energy, thus for this analysis we may search the any energy saving elements in the given system.
- In the GSHP system the maximum exergy destruction occurs at compressor that shows there is need of improvement in compressor.
- The exergy out is minimum at earth heat exchanger so it should also be enhanced.
- For the future studies the exergy and economic analysis that are combine to called exergonomic analysis are recommended.

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CC

Nomenclature

$\dot{X}$	Exergy rate (kW)
W	Work done (kW)
Q	Heat transfer rate (kW)
$\dot{m}$	Mass flow rate(kg/s)
$\dot{x}$	Specific exergy rate (Kw/kg)
T	Temperature(ºC)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kgK)

Greek letters

η	Efficiency

Subscripts

In	Inlet
Out	Outlet
0	Dead state
O.R	Overall Rational
Comp	Compressor
Cond	Condenser
Exap	Expansion

Evap	Evaporator
ghx	Ground heat exchanger
fc	Fan coil
1	Outlet and Inlet point of Evaporator and compressor respectively for refrigerant.
2	Outlet and Inlet point of compressor and Condenser respectively for refrigerant.
3	Outlet and Inlet point of Condenser and Capillary tube respectively for refrigerant.
4	Outlet and Inlet point of Capillary tube and Evaporator respectively for refrigerant.
5	Outlet and Inlet point of Ground heat exchanger and Evaporator respectively for water.
6	Outlet and Inlet point of Evaporator and Ground heat exchanger respectively for water.
7	Outlet and Inlet point of Fan coil unit and Condenser respectively for water.
8	Outlet and Inlet point of Condenser and Fan coil unit respectively for water.