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Evaluating a low exergy heating system from the power plant through the heat pump to the building envelope

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ABSTRACT

This study deals with an exergetic analysis and assessment of a low exergy heating system from the power plant through the ground-source heat pump to the building envelope. The methodology used is based on a pre-design analysis tool, which has been produced during ongoing work for the International Energy Agency (IEA) formed within the Energy Conservation in Buildings and Community Systems Programme (ECBCSP) Annex 37 to increase the understanding of exergy flows in buildings and to be able to find possibilities for further improvements in energy utilization in buildings. The analysis is applied to a room with a volume of 105 m^3 and a net floor area of 35 m^2 as an application place, while indoor and exterior air temperatures are 20 °C and −15 °C, respectively. The heat pump system used for heat production with a maximum supply temperature of 55 °C was designed, constructed and tested in Aksaray University, Aksaray, Turkey. In this context, energy and exergy flows were investigated, while exergy destructions in the overall system were quantified and illustrated. Total exergy input of the system was found to be 7.93 kW and the largest exergy destruction occurred in the primary energy transformation at 5.31 kW.

1. Introduction

Energy, which has a very limited convertibility potential, such as heat close to room air temperature, is low valued energy. Low exergy heating and cooling systems use low valued energy, which could also easily be obtained by sustainable energy sources (e.g. by using heat pumps, solar collectors, etc.), instead of high valued energy. Most of the energy carriers (i.e., fossil fuels), are defined as high valued energy. Most of the energy is used to maintain room temperatures at around 20 °C. Because of the low temperature level, the exergy demand for applications in room conditioning is naturally low. In most cases, however, this demand is satisfied with high quality sources, such as fossil fuels or using electricity [1,2].

In recent years, how to build sustainable buildings has been a discussion topic. To find and quantify further potentials in energy utilization, the thermodynamic concept of exergy can be effective. The low exergy approach is the main object to constitute a sustainable built environment. Future buildings should be planned to use sustainable energy sources for heating and cooling. One characteristic of these energy sources is that only a relatively moderate temperature level can be reached, if reasonably efficient systems are desired [3].

The climatic conditions of each region and the minimum energy consumption for air conditioning have to be considered in order to achieve a thermally efficient building design. A good thermal-environmental condition within built spaces in the winter season can be provided basically with the installation of thermally well-insulated building materials with appropriate heat capacity, which make it possible to utilize heat sources of lower temperature for heating [4].

Today, all estimations of the energy use in buildings, i.e., calculations of heating or cooling loads of rooms and buildings, as well as temperature calculations, are based on so-called energy balances. This is in reference to the first law of thermodynamics, which states that energy is conserved in every device and that it can neither be destroyed nor consumed. To enhance the understanding of the nature of energy flows in systems, we can use the concept of exergy, in addition to the energy conservation principle [5].

The exergy analysis is a methodology that allows locating if a system has energy losses due to irreversibilities. Exergy analysis is not a substitute for the first law analysis, rather a supplement. It

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Abbreviations: HP, heat pump; IEA, International Energy Agency; ECBCS, Energy Conservation in Buildings and Community Systems Programme; DHW, domestic hot water; EnEV, German energy conservation regulation; EN, European norm.

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Nomenclature

A	area (m^2)
c	specific heat (kJ/kg K)
COP	coefficient of performance
$\dot{E}$	energy rate (W)
$\dot{E}x$	exergy rate (W)
f	approximation factor
F	factor
g	total transmittance
I	radiation intensity (W/m^2)
l	length (m)
no	number
n_d	air exchange rate (1/h)
N	percentage of equipment resistance
p	specific power, pressure (W/m^2, N/m^2)
P	power (W)
$\dot{Q}$	heat transfer rate (kW)
R	pressure drop of the pipe (Pa/m)
T	temperature (K)
U	thermal transmittance (W/m^2K)
$\dot{v}$	volumetric flow rate (m^3/s)
V	volume (m^3)

Greek letters

η	energy or first law efficiency
ρ	density (kg/m^3)
Δ	difference

Subscripts

aux	auxiliary energy requirement
circ	circulation
dis, D	distribution system
dt	design temperature
e	external surrounding, equipment
E, emis	emission system
elec	electricity
env	environment
f	window frame, parameter
G, Ge	generation
gp	generator position
h	heat
heat	heater
i	inside surrounding, counting variable
in	input, inlet
ins	insulation
j	counting variable
l	lighting
loss	thermal losses
max	maximum
N	netto
no	effect of non-orthogonal radiation
o	occupants
p	primary energy, constant pressure
plant	plant
prim	primary energy
q	quality
ref	reference
renew	from renewable source
ret	return
room	room
S	solar, supply
s	source, surface
sh	shading effects
T	transmission
td	temperature drop
tot	total
V, v	ventilation
w	window
x	part x
0	reference

Superscripts

over dot	rate

can thus indicate possibilities for improvement of a process but cannot indicate the practicality of any possibility [6].

Shukuya and Komuro [7] applied exergy analysis to thermal storage in buildings. They used concepts of entropy and exergy to investigate the relationship between a building, a passive solar heating system and the environment. However, they used a limited period of 10 days assuming that the typical winters day for Tokyo recurred cyclically. Saito and Shukuya [8] reported the results of how a pattern of human body exergy consumption related to the exergy balance of various heating and cooling systems and found out which were the low exergy systems.

Franconi and Brandemuehl [9] evaluated two HVAC systems using both the first and second laws of thermodynamics. They determined the useful work produced by these systems using exergy analysis method. However, when they calculated the exergy efficiency of the systems, they only considered the exergy produced by the sensible loads inside the conditioned space, apparently they did not consider the exergy related to the latent heat loads or to the ventilation needs.

In case of building applications, only a few papers, mainly from Japanese and German research teams, have appeared in the open literature [10–17]. In the last few years, also due to the increasing interest in low temperature heating and high temperature cooling systems, a research co-operation in a working group of the International Energy Agency (IEA) has been formed within the Energy Conservation in Buildings and Community Systems Programme (ECBCSP): "Low Exergy Systems for Heating and Cooling of Buildings" [18].

The main objective of the present study is to apply the exergy analysis to a low exergy heating system from the power plant through the ground-source heat pump to the building envelope and to find possibilities for further improvements in energy utilization in the overall building system.

2. System description

Fig. 1 illustrates a schematic of the room, where a geothermal heat pump (HP) system is used in the heating mode, while the HP system has been explained in more detail elsewhere [19,20]. The room, shown schematically in Fig. 2 has one window and a total floor area of 35 m^2. The construction materials locally manufactured consist of brick for the walls, reinforced concrete floors with a square cement floor tiles and sand/cement mixture plastering on the other interior surfaces. Nevertheless, for this study, insulation,

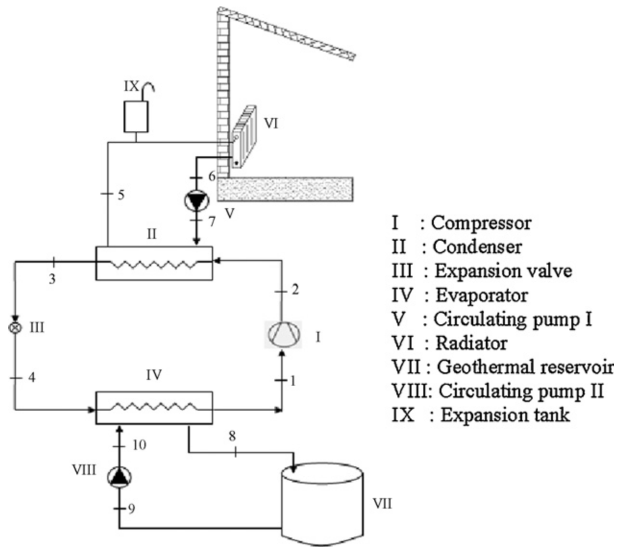

Fig. 1. A schematic of the heat pump system considered [19,20].

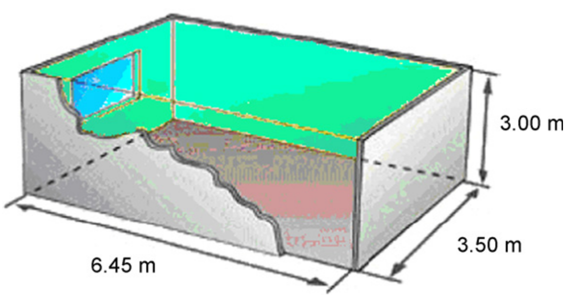

Fig. 2. A schematic of the room investigated.

in accordance with the current Turkish building standard [21], in walls and ceiling, as well as window shading was considered, which reduced the original cooling loads significantly.

3. Analysis

3.1. Estimation of energy and exergy demand in buildings

As stated above, an important step in the entire analysis is the estimation of the energy demand of the actual building. The calculation of the heating energy demand of the building itself is included, that is without any energy demand from the building services systems. The heat demand is a key figure in the analysis, as it corresponds to the building's exergy load. A low exergy load means a thermally well-constructed building envelope. The energy requirement for the service equipment is then estimated. The way, in which all energy demands are estimated throughout this paper, is based on the calculation method of the German Energy Conservation Regulation EnEV, which is in accordance with the European Standard EN ISO 13790. In contrast to the mentioned standards and regulations, the calculations presented here are done using steady state conditions. They provide an instantaneous view of the processes and are not meant for estimations of annual energy demand. In the following diagram, the basic ideas of the calculation principles, which have been taken and modified form the EnEV, are described [5].

The main focus in this paper is on the system "building", whose system border to be analyzed here encompass the building envelope. All energy and exergy flows outside of the border are indicated in Fig. 3.

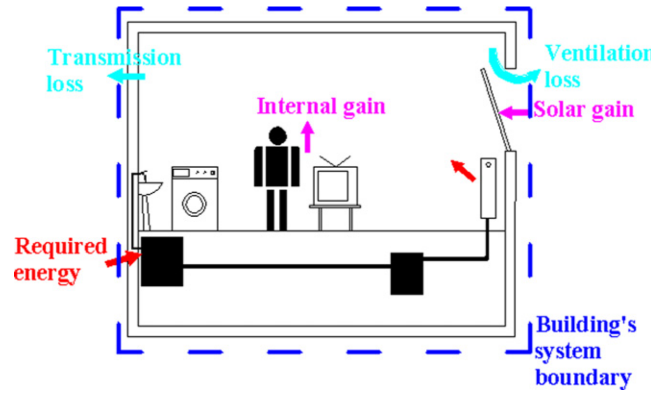

Fig. 3. Energy/exergy flows over the system boundaries of a building.

3.2. Modeling

In this study, the methodology and relations used are based on a pre-design analysis tool, which has been produced during ongoing work for the IEA ECBCS Annex 37 to increase the understanding of exergy flows in buildings and to be able to find possibilities for further improvements in energy utilization in buildings [5,18,22]. The aim of this tool is to produce a "transparent" tool, easy to understand for the target group of architects and building designers, as a whole. Other requirements were that the exergy analysis approach is to be made clear and the required inputs need to be limited [18].

In the first section, the general project data and boundary conditions are questioned. V and A_N are the internal volume of the building and the net floor area, while T_i and T_e are the indoor and outdoor temperatures under the design conditions, respectively. The outdoor temperature is also the reference temperature T_{ref} for this analysis.

The heat loss through the building envelope can be divided in these two major classes. In this study, thermal bridges are neglected. The total transmission heat loss is the sum of the losses from all surfaces i can be calculated as

$$\dot{Q}_T = \sum (U_i A_i F_{x,i})(T_i - T_e) \quad (1)$$

where $\dot{Q}_T$ is the transmission heat loss and U_i is the thermal transmittance in i surface. $F_{x,i}$ is their specific temperature correction factor.

The ventilation heat loss $\dot{Q}_V$ is calculated by

$$\dot{Q}_V = [c_p \rho V n_d (1 - \eta_V)](T_i - T_e), \quad (2)$$

where n_d and η_V are the air exchange rate and the heat exchanger efficiency if a mechanical balanced ventilation system with heat recovery has been installed.

The solar gain is calculated from

$$\dot{Q}_S = \sum [I_{s,j}(1 - F_f) A_{w,j} g_j F_{sh} F_{no}], \quad (3)$$

where $\dot{Q}_S$ is the solar gain, $I_{s,j}$ is the solar radiation, F_f is the window frame fraction, $A_{w,j}$ is all window areas, g_j is the total energy transmittance of the glazing, and F_{sh} is the possible shading effects of other surrounding buildings and the correction for non-orthogonal radiation on the windowpanes F_{no}. Both are estimated to be 0.9 for most cases.

The internal gain can be estimated as

$$\dot{Q}_{i,o} = \dot{Q}''_{i,o}\, \mathrm{no}_o \quad (4)$$

and

$$\dot{Q}_{i,e} = \dot{Q}''_{i,e} A_N. \tag{5}$$

Other uses of electricity, such as for artificial lighting and ventilation, can be defined as follows:

$$P_l = P''_l A_N = \dot{Q}_{i,l}, \tag{6}$$

where P_l, P''_l and $\dot{Q}_{i,l}$ are lighting power, specific power and lighting gains, respectively.

$$P_v = p_v V \tag{7}$$

where P_v and p_v are the ventilation power and specific ventilation power, respectively.

Energy balance for the whole system can be written as follows:

$$\begin{gathered}\text{heat demand} = \text{sum of heat losses-sum of heat gains}\\ \dot{Q}_h = (\dot{Q}_T + \dot{Q}_V) - (\dot{Q}_S + \dot{Q}_{i,o} + \dot{Q}_{i,e} + \dot{Q}_{i,l})\end{gathered} \tag{8}$$

This demand is usually expressed in a specific number, in order to be able to compare different buildings with each other:

$$\dot{Q}''_h = \frac{\dot{Q}_h}{A_N}. \tag{9}$$

The thermal efficiency of the distribution system is calculated by

$$\eta_D = 0.98 f_{gp} f_{ins} f_{dt} f_{td}, \tag{10}$$

whose values can be found in Ref. [5].

Auxiliary energy factor $p_{aux,D}$ can be obtained from

$$p_{aux,D} = \frac{\Delta p \dot{v}}{\eta_{circ}} \tag{11}$$

where η_{circ} is the electrical efficiency of the circulator. The following calculation results in the pressure difference in the distribution Δp as

$$\Delta p = (1 + N) R l_{max} A_N + p_{ex}. \tag{12}$$

where N is the percentage of equipment resistances with a typical value of 0.3. R is the pressure drop of the pipe. The maximal pipe length of the distribution is given as an area specific value l_{max} and length per net floor area A_N.

For the average volumetric flow under design conditions ($\dot{v}$), the following must be applied:

$$\dot{v} = \frac{1}{1.163 \Delta T_{dis} 0.0036 (\mathrm{s/m^3K})} \tag{13}$$

In the heat emission system, radiator is used with a thermal efficiency of 0.95, while the quality factor of the room air $F_{q,room}$ is estimated by

$$F_{q,room} = 1 - \frac{T_o}{T_i}. \tag{14}$$

The exergy load can be given by

$$\dot{E}x_{room} = F_{q,room} \dot{Q}_h. \tag{15}$$

The surface temperature of the heater, T_{heat} in K is calculated by [23]

$$T_{heat} = \frac{T_{in} - T_{ret}}{2 \ln(T_{in} - T_i / T_{ret} - T_i)} + T_i \tag{16}$$

where T_{in} and T_{ret} are the inlet and return temperatures of the emission system in K, respectively. Another quality factor at the heater surface can be calculated from

$$F_{q,heat} = 1 - T_0 / T_{heat}. \tag{17}$$

The exergy load at the heater is

$$\dot{E}x_{heat} = F_{q,heat} \dot{Q}_h \tag{18}$$

Because the energy efficiency of the emission system, η_E is not 100%, the heat losses are found using

$$\dot{Q}_{loss,E} = \dot{Q}_h \left(\frac{1}{\eta_E} - 1 \right). \tag{19}$$

The demand on auxiliary energy or electricity of the emission system is

$$P_{aux,E} = p_{aux,E} \dot{Q}_h. \tag{20}$$

Keeping the derivation of the exergy demand of the emission system is calculated from

$$\Delta \dot{E}x_{emis} = \frac{(\dot{Q}_h + \dot{Q}_{loss,E})}{(T_{in} - T_{ret})} \left\{ (T_{in} - T_{ret}) - T_o \ln\left(\frac{T_{in}}{T_{ret}} \right) \right\}, \tag{21}$$

and the exergy load of the emission system is:

$$\dot{E}x_{emis} = \dot{E}x_{heat} + \Delta \dot{E}x_{emis}. \tag{22}$$

The heat loss of the distribution system is

$$\dot{Q}_{loss,D} = (\dot{Q}_h + \dot{Q}_{loss,E}) \left(\frac{1}{\eta_D} - 1 \right), \tag{23}$$

where η_D is the energy efficiency of the distribution system.

The demand on auxiliary energy or electricity of the distribution system is given by

$$P_{aux,D} = p_{aux,D} (\dot{Q}_h + \dot{Q}_{loss,E}) \tag{24}$$

Exergy demand of the emission system is

$$\Delta \dot{E}x_{dis} = \frac{\dot{Q}_{loss,D}}{\Delta T_{dis}} \left\{ T_{dis} - T_o \ln\left(\frac{T_{dis}}{T_{dis} - \Delta T_{dis}} \right) \right\}, \tag{25}$$

where the above temperatures should be evaluated in K.

The exergy load of the distribution system is

$$\dot{E}x_{dis} = \dot{E}x_{emis} + \Delta \dot{E}x_{dis} \tag{26}$$

If a seasonal storage is integrated into the system design, some of the required heat is covered by thermal solar power with a certain solar fraction F_S. The required energy to be covered by the generator is

$$\dot{Q}_{Ge} = (\dot{Q}_h + \dot{Q}_{loss,E} + \dot{Q}_{loss,D} + \dot{Q}_{loss,S})(1 - F_S) \frac{1}{\eta_G}. \tag{27}$$

The demand on auxiliary energy of the generation system to drive pumps and fans is

$$P_{aux,G} = p_{aux,G} (\dot{Q}_h + \dot{Q}_{loss,E} + \dot{Q}_{loss,D} + \dot{Q}_{loss,S}). \tag{28}$$

For the energy source in the primary energy transformation given parameters, F_p and $F_{q,s}$ are the figures of the primary energy factor and the quality factor of the energy source, respectively. F_{renew} is a fraction factor for the environmental. In this study, F_p and $F_{q,s}$ are estimated to be 3 and 1, respectively. Because ground heat pump is used for heat generation and its COP is 2.32 so F_{renew} is taken as 1.32. In this study, the heat storage system is not considered.

Exergy load of the generation is calculated directly

$$\dot{E}x_{Ge} = \dot{Q}_{Ge} F_{q,s}. \tag{29}$$

The DHW energy demand is ignored in this study.

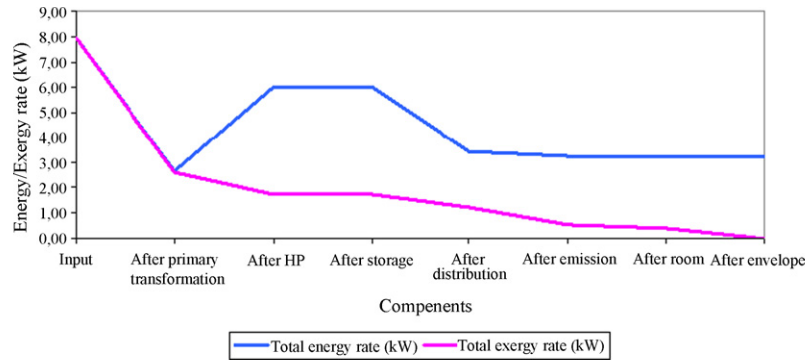

Fig. 4. Exergy and energy flows through components.

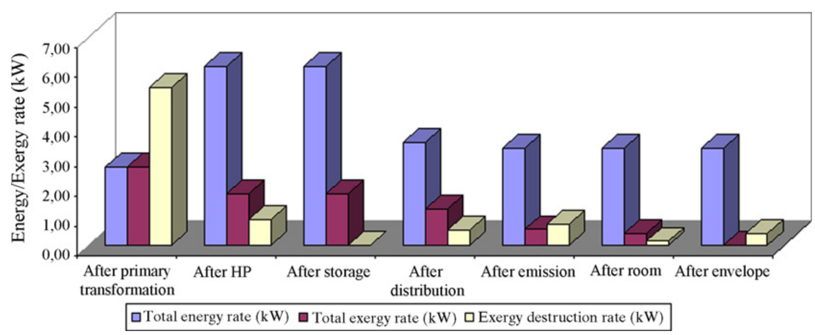

Fig. 5. Variation of exergy destruction/consumption values by components.

As a second step the exergy load of other building service appliances, such as lighting, ventilation are taken into consideration and, in this case, named "plant".

$$\dot{E}x_{\text{plant}} = (P_{\text{l}} + P_{\text{V}})F_{\text{q,elec}} \tag{30}$$

The overall energy and exergy loads of the building are expressed in the required primary energy and exergy inputs. For the fossil or non-renewable part of the primary energy, the result is

$$\dot{E}_{\text{prim,tot}} = \dot{Q}_{\text{Ge}}F_{\text{P}} + (P_{\text{l}} + P_{\text{V}} + P_{\text{aux,G}} + P_{\text{aux,S}} + P_{\text{aux,D}} + P_{\text{aux,E}})F_{\text{p,elec}} \tag{31}$$

If the generation utilizes a renewable energy source or extracts heat from the environment, as heat pumps do, the additional renewable energy load is

$$\dot{E}_{\text{renew}} = \dot{Q}_{\text{Ge}}F_{\text{renew}} + \dot{E}_{\text{env}} \tag{32}$$

The total exergy load of the building is

$$\dot{E}x_{\text{tot}} = \dot{Q}_{\text{Ge}}F_{\text{p}}F_{\text{q,s}} + (P_{\text{l}} + P_{\text{V}} + P_{\text{aux,G}} + P_{\text{aux,S}} + P_{\text{aux,D}} + P_{\text{aux,E}})F_{\text{p,elec}} + \dot{E}_{\text{renew}}F_{\text{q,renew}} \tag{33}$$

This last figure is a key figure and can be used for a ranking in a specific value, for comparing buildings and their efficiency and quality of exergy utilization, and for evaluating the success of the exergy optimization

$$\dot{E}x''_{\text{tot}} = \frac{\dot{E}x_{\text{tot}}}{A_{\text{N}}}. \tag{34}$$

4. Results and discussion

The process begins with the power plant, through the generation of heat (GHP), via a distribution system, to the heat emission system and from there, via the room air, across the building envelope to the outside environment. For this room, project data and boundary conditions: volume is 105 m^3, net floor area is 35 m^2, while indoor and exterior air temperatures are 20 °C and, −15 °C, respectively.

Using these data and Eqs. (1) and (2), the transmission losses and ventilation heat loses are calculated to be 1.58 and 1.84 kW, respectively.

Heat gains from solar, internal and other uses are obtained to be 0.033, 0.08 and 0.036 kW using Eqs. (3)–(7), respectively. According to these data, heat demand and specific heat demand from Eqs. (8) and (9) are calculated to be 3.28 kW and 0.094 kW/m^2, respectively.

From an energy point of view, the solution of using direct electricity does not lead to the best possible choice with the highest demand on primary energy. As for the possibility of implementing renewable sources into building systems is concerned, the major prerequisite is that of flexible storage, distribution and emission systems in buildings. Renewable sources are highly efficient within moderate temperature ranges, thermal solar. Heat could easily and efficiently be produced at temperatures of about 40 °C. At this temperature level, with this low level of exergy, only building service equipment with a low exergy demand could be fed, like the low temperature floor heating system discussing the issue of the integration of renewable energy sources on a larger scale and in buildings opens new possibilities by utilizing the potential of exergy optimized service designs [5].

In this case, ground heat pump water/water is used for heat production. Its COP is calculated to be 2.32 and maximum supply temperature is 55 °C [20]. For the emission system, HT radiators have the flow and return temperatures of 55 and 45 °C with a heat loss/efficiency of 0.95, respectively.

The calculated results of the analysis are illustrated in Figs. 4 and 5, where losses occurred are indicated. In Fig. 4, the useable flow of energy and exergy through the heating process from source to sink is given. The components consumption is quantified in

Table 1
Total energy/exergy flow and exergy destruction rate of the system components

Component	Total energy rate (kW)	Total exergy rate (kW)	Exergy destruction rate (kW)
Input	7.93	7.93	0.00
After primary transformation	2.64	2.62	5.31
After HP	6.01	1.74	0.88
After storage	6.01	1.74	0.00
After distribution	3.45	1.23	0.51
After emission	3.28	0.53	0.70
After room	3.28	0.39	0.14
After envelope	3.28	0.00	0.39

Fig. 5, where the primary energy/exergy is shown on the left side of the diagram. As a result of the energy analysis, "energy production" of the heat pump is remarkable. Energy production is impossible, according to the first law of thermodynamics. The explanation here is the amount of renewable environmental heat included in the process.

In the generation section, an increase in the energy flow is due to the geothermal heat pump, which produces 6.01 kW. Exergy is consumed in each component at the same time. While the flow of energy leaves the building envelope, there is still a remarkable amount of energy left seems, but it is not true for exergy. At the ambient environment, energy has no potential of doing work; so all exergy has been consumed. The exergy flow on the right side of the diagram is required to be zero. Total exergy input of the system is 7.93 kW and the largest exergy destruction is 5.31 kW, which occurs in the primary energy transformation, as shown in Figs. 4 and 5. Total energy/exergy flow and exergy destruction of the system components are listed in Table 1. The total exergy efficiency of the system (exergy demand room/total exergy input) is calculated to be 4.9%.

5. Conclusions

As indicated in this study, the energy conservation concept alone is not enough to gain a full understanding of all the important aspects of energy utilization processes [24]. From this aspect, the method of exergy analyses facilitates a clearer understanding and improved design in energy flows in buildings.

In this study, exergy analysis method is applied to a room heated by a geothermal heat pump. Energy and exergy flows are investigated from the primary energy source to the building envelope. Exergy destructions in the overall system are quantified and illustrated.

Some concluding remarks from this study can be extracted as follows:

(a) Total exergy input is found to be about 7.93 kW and the largest exergy destruction of the system occurs in the primary energy transformation at 5.31 kW.
(b) Although the amount of energy leaves from the building envelope, energy has no potential of doing work at the ambient environment. So all the exergy is consumed.
(c) In the generation-sub-system, although input energy is 2.64 kW, output energy is 6.01 kW. The amount of renewable environmental heat included in the process is 3.37 kW.
(d) It is already possible to build a "low exergy house" with today's technology, as studied here. A careful planning process and a good design of all systems are mandatory in achieving this goal, since some of the methods implemented are not today's everyday building practice.
(e) For a future work, an exergoeconomic analysis, which is a combination of exergy and economics, is recommended.
(f) The results are expected to be beneficial to the researchers, government administration, and engineers working in the area of low exergy systems.

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