EXERGY ANALYSIS OF RESIDENTIAL HEATING SYSTEMS: PERFORMANCE OF WHOLE SYSTEM VS PERFORMANCE OF MAJOR EQUIPMENT

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ABSTRACT

This paper presents the evaluation of energy and exergy performance of several design alternatives of residential heating systems for a house. All component-based models, written and solved in the Engineering Equation Solver (EES) program, are assembled in several design alternatives for the heating, ventilation and domestic hot water (HEAT-DHW) systems. An energy-efficient house in Montreal is used as a case study. The following indices are used for assessing the overall performance of the selected systems at winter peak design conditions: energy efficiency, exergy efficiency, entropy generation, exergy destruction, energy demand, and exergy demand.

INTRODUCTION

The energy performance of HVAC systems is usually evaluated based on the first law of thermodynamics. The energy analysis alone is not adequate to gain a full understanding of all the important aspects of energy utilization processes, if the quality of available energy is not considered. Sometimes it misses the important aspects for improvement (Schmidt 2003).

Exergy, an important thermodynamic concept, is defined as the maximum possible useful work that a system can deliver when it undergoes a reversible process from the initial state to the state of its environment, the dead state. Exergy measures the quality and quantity of energy. In a process or system, the total amount of exergy is not conserved but is destroyed due to internal irreversibilities and heat transfer crossing the system boundaries. The exergy destruction is proportional to the entropy created due to irreversibilities associated with the process (Cegel and Boles 2002). Using exergy, different types of energy sources, such as solar energy, geothermal energy, fossil fuel energy and electricity, can be compared to each other (Dincer et al. 2004). Exergy is used as a single commodity to aggregate the power generated or lost by different components of a system. Contrary to the system operating energy cost, the exergy is not affected by geo-political or market conditions.

The exergy modeling techniques have been applied to various industrial sectors and thermal processes (Dincer et al. 2004). In relation to the energy analysis of buildings, Rosen et al. (2001) expressed the opinion that one major weakness in the building modeling and simulation is the lack of using the second law analysis and exergy modeling techniques.

Exergy analyses have been performed to evaluate the performance of heating systems and their components in the Annex 37 (IEA Annex 37 2002). The results have shown that: there is enormous waste of exergy, when electricity is used for space heating; low quality energy tasks such as space heating can be provided more efficiently and less expensively by other means, such as geothermal energy and solar energy; ground source heat pumps are an excellent way to make use of the low quality heat from the ground to provide for the low quality energy demand of space heating (Leskinen et al. 2000).

A few applications of the exergy analysis to the HVAC systems found in the literature are listed in this section: Shukuya and Komuro 1996, Asada and Takeda (2002), Badescu (2002), Ren et al. (2002), Kanoglu et al. (2004), Li et al. (2004), Zmeureanu and Zheng 2008, Zhentao and Zmeureanu 2009, Pua et al. 2010, Torio et al. 2009, Lohani et al. 2010, Sakulpipatsin et al. 2010.

This paper presents the evaluation of energy and exergy performance of several design alternatives of residential HEAT-DHW systems for a house. An energy-efficient house in Montreal, Canada is used as a case study. The following indices are used for assessing the overall performance of the selected systems at winter peak design conditions: energy efficiency, exergy efficiency, entropy generation, exergy destruction, energy demand, and exergy demand.

COMPONENT-BASED MODELS

The first step in the application of exergy analysis to the HEAT-DHW system is the representation of the system by a combination of blocks that can interact with other blocks and their surroundings. A block represents a component of the system. Once a block diagram is generated and the system boundaries defined, it is possible to assess the mass, energy, entropy and exergy balances based on first principle and correlation–based models from product data. The models for all the blocks are assembled together in order to represent the whole HEAT-DHW system. Then the system can be simulated to derive the entropy generation and exergy destruction in each component and in the whole system.

Selection of the EES program

Mathematical models of 25 components of residential heating, ventilation and domestic hot water (HEAT-DHW) systems were developed during this study based on thermodynamic formulation of quasi-steady-state processes (Cegel and Boles 2002), with some exceptions where the reference is indicated. The models were implemented in the Engineering Equation Solver (EES) environment (Klein 2003). There is no commercially available software to perform this kind of analysis on the selected systems. The EES is an ideal environment to develop mathematical models of HVAC components and systems based on the second law, since it was developed for thermodynamic applications. The thermodynamic properties of large number of working fluids are available by calling built-in functions. For instance, the entropy of water can be obtained in terms of two independent parameters, by using the following call function: s1=entropy(water,T=T1, P=P1). Since the EES is a programming environment and not an energy analysis program, there are not pre-defined heating components and systems available, and therefore the user must write every equation of mathematical models using an English-like language, in a similar way some researchers develop some computer programs using a Fortran or C++ language. The EES automatically identifies and groups equations that are solved simultaneously. Another feature offered by the EES is the diagram window that is used by the user to generate a graphical user interface; it may contain a schematic diagram of the system or it may be used for providing selected input data and displaying some results.

Models of HEAT-DHW systems and components

Six different design alternatives of HEAT-DHW systems are selected (Table 1) using some of the following components: earth tube heat exchanger (ETHEx); air-to-air heat exchanger (AAHEx); electric or hot water air heater; electric or hot water baseboard heater; radiant heating floor; domestic hot water tank; air source heat pump (ASHP); gas-fired boiler; fan; and pump.

The thermodynamic properties (e.g., temperature and entropy) of air, water and refrigerant streams are calculated every hour at important points of the systems, for instance for the water leaving the evaporator. The flowchart of design alternative no.3 is presented, as an example, in Figure 1. The electric demand of the electric compressor, pumps and fans is satisfied by the electricity mix, which is represented in Figure 1 by a power plant.

Power generation is included in this analysis to reflect the use of primary resources. For instance, in Quebec the contribution of energy sources to the off-site electricity generation is: hydro-electricity 96.7%; natural gas 1.1%; oil 1.1%; nuclear 1.1% (Baouendi 2003). The overall energy efficiency of the power plant is assumed to be as follows: coal-fired power plant: 37% (Rosen 2001); natural gas-fired power plant 43.1% (AIE 1998); oil-fired power plant 33% (Kannan 2004); nuclear power plant: 30% (Rosen 2001); hydro power plant: 80% (Ileri and Gurer 1998). The transmission and distribution loss is 14%, while the remaining 86% is supplied to the end users (Zhang 1995).

Table 2 presents sample formulas used in the performance evaluation. A few comments are made about the simulation of the Air Source Heat Pump.

The refrigerant R-134a enters the evaporator (state 6 in Figure 2) where it is heated at constant temperature and pressure (T_{evap} and P_{evap}, respectively), and leaves as saturated vapor (state 1). A vapor compressor is used to increase the refrigerant pressure before entering the condenser. If the compressing process is isentropic, the state before entering the condenser would be state 3. However, due to the irreversibilities in the compressor, there is entropy generation, and the actual process in the compressor is from state 1 to state 2. Inside the condenser, the refrigerant is cooled at constant pressure P_{cond}. The refrigerant is first cooled to saturated vapor (State 4), and then leaves the condenser as saturated liquid (state 5). Finally, an expansion valve is used to decrease the pressure of the refrigerant to P_{evap} before the evaporator inlet (state 6).

The refrigerant state parameters, specific entropy $s_{r,i}$ and specific enthalpy $h_{r,i}$ (i=1 to 6) are estimated in terms of temperature, pressure, or quality in the case of saturated state. In Table 2 the refrigerant parameters have the subscript "r", the water parameters have the subscript "w", and the air parameters have the subscript "air".

The following assumptions are used:

(1) The temperature difference between the water and refrigerant within evaporator and condenser is $\Delta T_{cond} = \Delta T_{evap} = 5^oC$;

(2) The temperature difference between the air entering and leaving the evaporator is $\Delta T = 6^oC$.

The electric power input, in kW, to the compressor is calculated based on (Henderson et al. 1999).

RESULTS AND DISCUSSION

A house with the total floor area of 310 m^2, located in Montreal, is used as a case study. The house was designed and built with the goal of being energy-efficient, and exceeds the minimum values prescribed by Quebec regulations (Kassab et al. 2003). The hourly heating loads were obtained from the simulation of the existing house with the BLAST program, and input to the EES environment. The peak thermal loads used in this study are as follows: the peak space heating load is 11.1 kW, calculated at (-23˚C) outdoor air temperature, the DHW load is 2.3 kW, and the heating of ventilation air is 3.9 kW. The outdoor air temperature was considered as the reference (dead) state for the exergy calculation. The flame temperature of natural gas-fired hot water boiler is selected as 2200 K (Bennett 2002).

A series of simulation programs were developed on the EES platform to perform the second law analysis for the six models presented in Table 1.

Overall performance of the HVAC-DHW systems

Table 3 presents the overall results for design alternatives No.1 to No.6 at winter peak design conditions. Design alternative No.4 has the highest energy efficiency of 81.2%, the design alternative No.5 has the highest exergy efficiency of 14.8%.

Design alternative No.1

Design alternative No.1 has electric baseboard heaters for space heating and electric domestic water heater. There is no mechanical ventilation system. The energy efficiency is 65.9% while the exergy efficiency is only 10.3%.

The electric baseboard heater and electric DHW tank account for 9.44 kW (52.1%) and 1.87 kW (10.3%) of exergy destruction, respectively. The power generation and transmission accounts for 6.81 kW of exergy destruction (37.6%). If electricity is replaced by low temperature hot water, the exergy destruction in the electric baseboard heater and electric DHW tank would be reduced.

Design alternative No.2

Compared to design alternative No. 1, this design alternative has a mechanical ventilation system. The heating of ventilation outdoor air to the indoor air temperature adds 5.32 kW of exergy destruction to the case no.1, plus 2.70 kW at the power generation and transmission. Consequently, both energy energy efficiency and exergy efficiency are smaller than in the first case.

Design alternative No.3

The adoption of an earth tube heat exchanger and an air-to-air heat exchanger, used to recover heat from the earth and exhaust air to preheat outdoor ventilation air (Figure 1), reduces the exergy destruction in the ventilation system by 70% from 5.32 kW to 1.57 kW, and by 21% from 9.51 kW to 7.56 kW at power generation and transmission. The electric baseboard heaters have the largest contribution (46.3%) to the overall exergy destruction (Figure 3), followed by the power generation and transmission (37%) and the electric DHW tank (9.1%).

Design alternative No.4

In this design alternative, hot water baseboard heaters with gas-fired boiler heat the space, and the DHW tank is heated by hot water from boiler. The gas-fired boiler and baseboard heaters account for 14.37 kW or 90.5% of total exergy destruction, while the DHW accounts for only 0.24 kW (1.5%) of exergy destruction. The power generation and transmission account for 0.30 kW or 1.9% of total exergy destruction. The use of natural gas as energy source for heating and DHW increases both energy efficiency and exergy efficiency of this design alternative compared to those using electricity for the same purposes.

Design alternative No.5

This design alternative integrates an air source heat pump, a forced air system for space heating and a gas-fired hot water boiler. The gas-fired boiler, air-source heat pump and fans account for 71.7% of total exergy destruction (Figure 4), while the power generation and transmission account for 18.5%. This result indicates that the overall exergy performance is improved to 14.8% from 12.4% if natural gas is replaced by low quality energy sources such as geothermal energy.

Design alternative No.6

This design alternative integrates radiant heating floor and gas-fired boiler with water-to-water heat exchanger for space heating; earth tube heat exchanger, air-to-air heat exchanger, and electric air heater for ventilation; and hot water DHW tank for DHW heating. The gas-fired boiler accounts for 79.8% of the total exergy destruction and water-to-water heat exchanger accounts for 7.9%. As for the case of design alternative no.5, the overall exergy performance would be improved if natural gas is replaced by low quality energy sources such as geothermal energy.

CONCLUSION

This paper presents the method used for assessment of exergy performance of six heating, ventilating and domestic hot water systems for a case study of an energy-efficient house in Montreal. The results suggest that in the design process a higher priority should be given to the increase of exergy performance by using (1) the natural gas-fired boiler for heating and DHW purposes instead of electricity from power generating plants, (2) the heat recovery devices and heat pumps, and (3) the use of renewable energy sources such as geothermal. The exergy destruction in power generation and transmission is unavoidable when electricity is generated far from the residential areas and transmitted to the end users. However, it can be reduced by using the on-site generation of electricity using renewable sources such as solar energy (e.g., by using photovoltaic panels) or wind.

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NOMENCLATURE

COP	Coefficient of Performance
$E_{gas,house}$	Power input from natural gas, kW
EX_{de}	Exergy destruction, kW
m_{air}	Mass flow rate of air of ASHP, kg/s
m_{vent}	Outdoor air mass flow rate through AAHEx, kg/s
m_w	Mass flow rate of domestic hot water, kg/s
$T_{air,out,HE}$	Temperature of outdoor air leaving AAHEx, ºC
T_{city}	Temperature of water from the city main, ºC
T_{DHW}	Setpoint temperature of domestic hot water, ºC
$T_{exh,in,HE}$	Temperature of exhaust air entering AAHEx, ºC
T_i	Indoor air temperature, ºC
TK_i	Indoor air temperature, K
TK_{flame}	Flame temperature in the natural gas-fired boiler, K
TK_o	Outdoor air temperature, K; reference temperature for entropy and exergy calculations
T_o	Outdoor air temperature, ºC
η_{trans}	Energy efficiency of transmission and distribution of electricity
η_i	Energy efficiency of power plant
α_i	Contribution of energy sources to the off-site generation of electricity
Δs	Specific entropy difference, kJ/(kg K)
$s_{w,out,floor}$	Specific entropy of water leaving the radiant heating floor, kJ/(kg K)
$s_{w,in,floor}$	Specific entropy of water entering the radiant heating floor, kJ/(kg·K).

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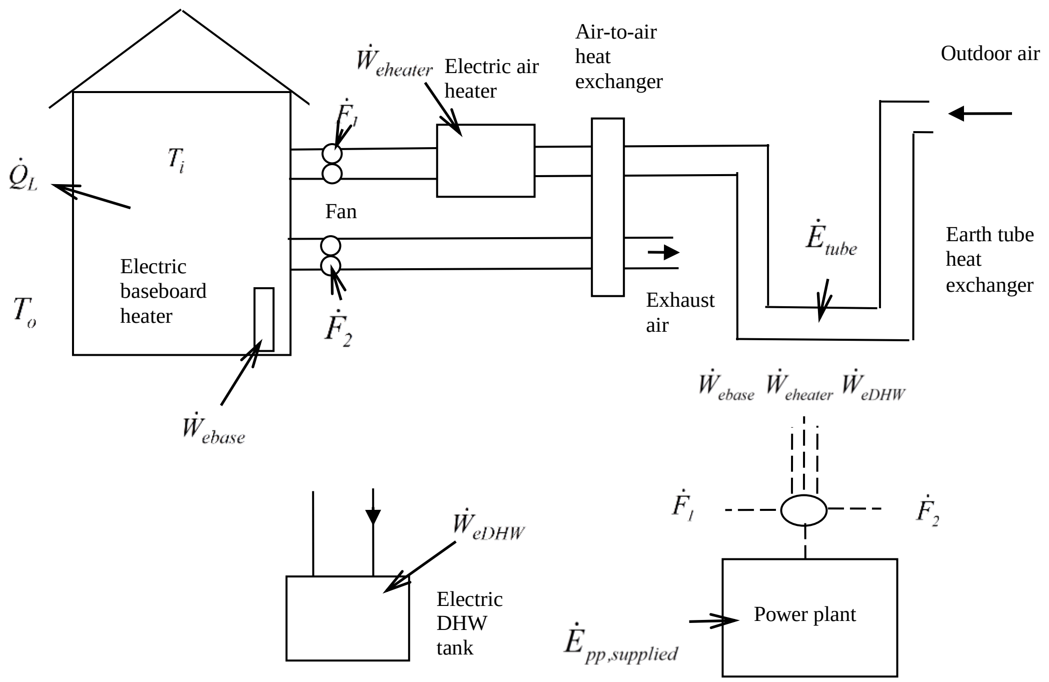

Figure 1 Configuration of design alternative No.3

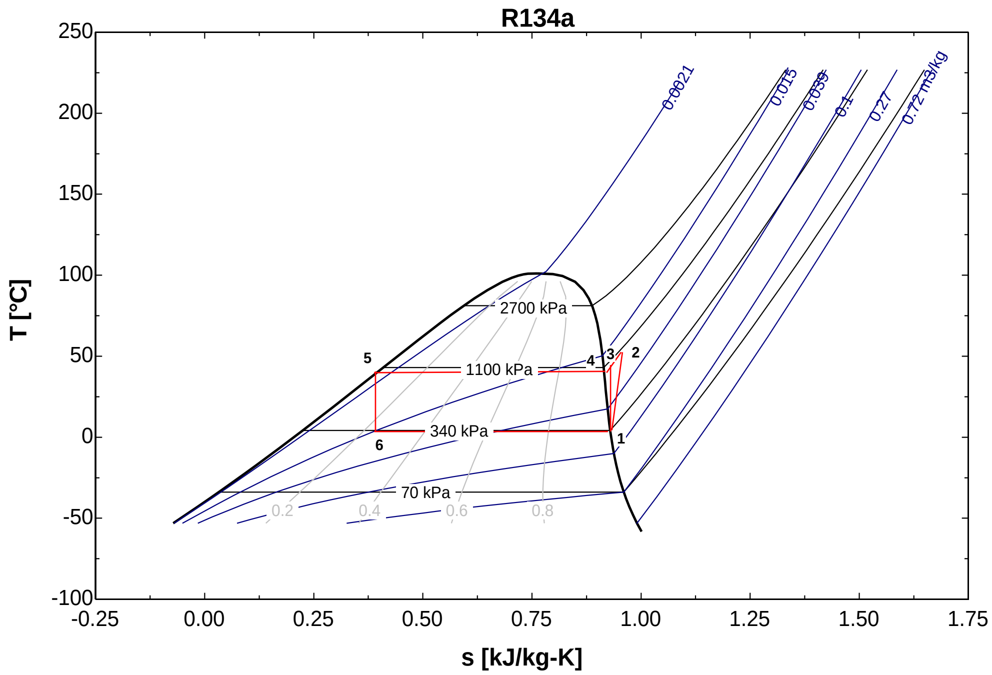

Figure 2 Representation of the thermodynamic cycle of ASHP in temperature-specific entropy diagram

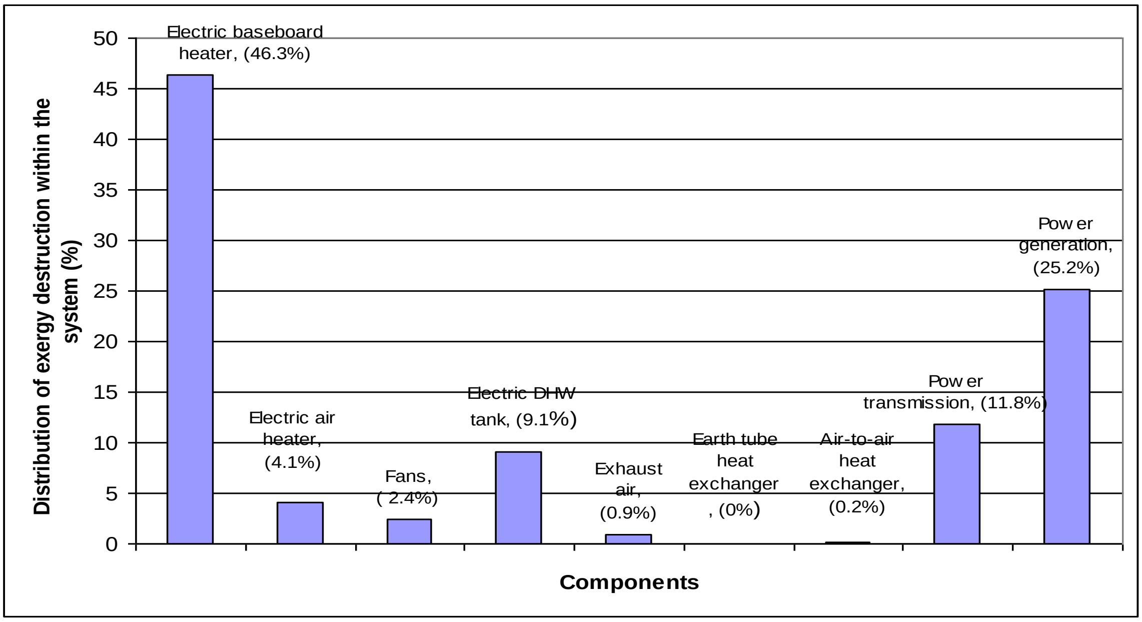

Figure 3 Exergy destruction in the components of design alternative No.3 at winter peak design conditions (Total exergy destruction is 20.43 kW)

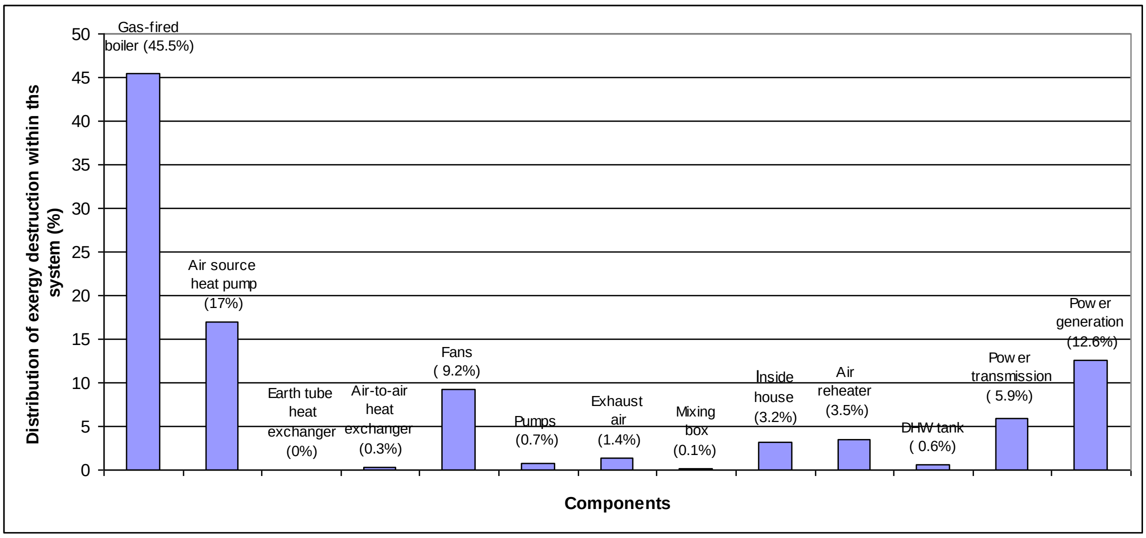

Figure 4 Exergy destruction in the components of design alternative No.5 at winter peak design conditions (Total exergy destruction is 13.42 kW)

Table 1
Description of the selected HEAT-DHW design alternatives

Alt. No.	HEATING	VENTILATION	DHW
1	Electric baseboard heaters	None	Electric water heater
2	Electric baseboard heaters	Electric air heater	Electric water heater
3	Electric baseboard heaters	Electric air heater, air-to-air heat exchanger and earth tube heat exchanger	Electric water heater
4	Hot water baseboard heaters with gas-fired boiler	Hot water air heater, air-to-air heat exchanger, and earth tube heat exchanger	Heat exchanger with gas-fired boiler
5	Forced air system with hot water heating coil, gas-fired boiler and ASHP	Air-to-air heat exchanger and earth tube heat exchanger	ASHP and gas-fired boiler
6	Radiant floor with gas-fired boiler	Hot water air heater, air-to-air heat exchanger and earth tube heat exchanger	Heat exchanger with gas-fired boiler

Table 2
Sample formulas used in the evaluation of energy and exergy performance of systems

DESCRIPTION	FORMULAS
Energy efficiency of the HEAT-DHW system	$\eta_1 = E_{useful}/ E_{pp,supply}\cdot 100$
Useful electric input	$E_{useful}=W_{eheating}+E_{eheater}+W_{eDHW}$
Useful electric input for space heating	$W_{eheating}=Q_L$
Useful electric input for heating the ventilation air	$E_{eheater}=m_{vent}\cdot c_a\cdot(T_i-T_o)$
Useful electric input for DHW	$W_{eDHW}=m_w\cdot c_w\cdot(T_{DHW}-T_{city})$
Total primary power input	$E_{pp,supply}=W_{primary,plant}+E_{gas,house}$
Primary power input to the power generation plant	$W_{primary,plant}=W_{elec,house}/\eta_{trans}\cdot\Sigma\alpha_i/\eta_i$
Electric power input to house	$W_{elec,house}=E_{compressor}+E_{pumps}+E_{fans}$
Electric power input to compressor (ASHP)	$W_{compressor}=CAP_{design}\cdot EIR\cdot FRAC$
Heating capacity at design conditions (ASHP)	$CAP_{design}= 20.152\cdot m_{air} + 0.3572\cdot T_o -3.8946$
Electric power input ratio (ASHP)	$EIR=(1.17517\cdot PLR - 0.201513\cdot PLR^2 + 0.0263344\cdot PLR^3 - 0.0000626)/COP_{design}$
Part-load ratio (ASHP)	$PLR=Q_L/CAP_{design}$
COP at design conditions (ASHP)	$COP_{design}= 4.087 + 0.0748\cdot T_o - 0.5957\cdot m_{air}$
Fraction of the hour ASHP is running	FRAC = PLR/RMIN
Minimum part-load ratio	RMIN=0.1
Sensible heat recovery efficiency of AAHEx	$\eta_{HE}=(T_{air,out,HE}- T_o)/(T_{exh,in,HE}- T_o)$
Electric power input for heating the ventilation air	$W_{eheater} = m_{vent}\cdot c_a\cdot(T_i - T_{air,out,HE})$
Exergy efficiency of the HEAT-DHW system	$\eta_2 = (1-EX_{de}/EX_{supply})\cdot 100$
Total exergy destruction	$EX_{de}=TK_o\cdot S_{gen,total}$
Total entropy generation	$S_{gen,total}= S_{AAHEx} + S_{eheater} + S_{eheating} + S_{eDHW} + S_{exhaust} + S_{fans} + S_{trans} + S_{gen,plant}$
Entropy generation in heating system	$S_{heating}=S_{floor}+S_{ASHP}+S_{pumps}$
Entropy generation in ASHP	$S_{ASHP}=S_{compressor}+S_{evaporator}+S_{condenser}+S_{valve}$
Entropy generation in evaporator	$S_{evaporator}= m_r\cdot\Delta s_r+ m_w\cdot\Delta s_w$
Entropy generation in radiant floor	$S_{floor}=Q_L/TK_i+m_{w,floor}\cdot(s_{w,out,floor}-s_{w,in,floor})$
Exergy destruction in AAHEx	$EX_{de,AAHEx}=TK_o\cdot S_{AAHEx}$
Exergy supply	$EX_{supply}=\Sigma Q_{plant,i}\cdot(1-TK_o/TK_{flame})+E_{hydro}+E_{nuclear}+ E_{gas,house}\cdot(1-TK_o/TK_{flame})$

Table 3
Overall results of the second law analysis at winter peak design conditions

Alt. No.	η_1 %	η_2 %	$S_{gen,total}$ kW/K	E_{useful} kW	$E_{pp,supply}$ kW	EX_{supply} kW	EX_{de} kW
1	65.9	10.3	0.0724	13.38	20.30	20.19	18.11
2	64.2	7.4	0.1045	18.22	28.37	28.22	26.14
3	73.1	9.9	0.0817	18.22	24.91	22.68	20.43
4	81.2	12.4	0.0635	18.22	22.43	18.13	15.88
5	79.6	14.8	0.0537	18.22	22.88	15.76	13.42
6	80.5	12.2	0.0643	18.22	22.63	18.33	16.09