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Sensitivity of Energy and Exergy Performances of Heating and Cooling Systems to Auxiliary Components

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ABSTRACT

Heating and cooling systems in buildings consist of three main subsystems: heating/cooling plant, distribution system, and indoor terminal unit. The choice of indoor terminal unit determines the characteristics of the distribution system and the heating and cooling plants that can be used.

Different forms of energy (electricity and heat) are used in heating and cooling systems, and therefore, a holistic approach to system design and analysis is needed. In particular, distribution systems use electricity as a direct input to pumps and fans, and to other components. Therefore, exergy concept should be used in design and analysis of the whole heating and cooling systems, in addition to the energy analysis.

In this study, water-based (floor heating and cooling, and radiator heating) and air-based (air heating and cooling) heating and cooling systems were compared in terms of their energy use and exergy consumption for auxiliary components (pumps and fans). The effects of the auxiliary components on whole system energy and exergy performance were identified.

Water-based heating systems required 68% lower auxiliary exergy input than the warm-air heating system with heat recovery, and floor cooling system required 53% lower auxiliary exergy input than the air cooling system, showing a clear benefit for the water-based systems over the air-based systems.

The auxiliary energy and exergy input to different systems is an important parameter for the whole system performance. Its effects become more pronounced and can be studied better in terms of exergy than energy. The required exergy input to the power plant for space heating and cooling purposes are comparable to the required exergy input for auxiliary components.

The exergy input to auxiliary components should be minimized to fully benefit from the water-based low temperature heating and high temperature cooling systems, and in general in heating and cooling systems, and to integrate effectively the renewable energy resources to building heating and cooling systems.

INTRODUCTION

Heating and cooling systems have direct effects on occupant comfort (thermal and acoustic), energy performance of buildings, and on the energy use and greenhouse gas emissions globally. In the most general form, building heating and cooling systems consist of three subsystems: generation (heating/cooling plant), distribution (using pumps and fans to move the heat transfer medium), and heat emission/removal (indoor terminal units).

Terminal units are mostly air-based (relying on convection) or water-based (relying primarily on radiation and secondarily on convection). Depending on the heat emission/removal characteristics of the terminal unit, different auxiliary components (pumps and fans) are needed to circulate the heat transfer medium between the heating/cooling plant and the indoor terminal unit. The choice of terminal unit will also influence the heating/cooling plant selection.

Different forms of energy (electricity and heat) are used in heating and cooling systems, which requires a

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holistic approach and additional tools other than energy analysis, since different studies have documented that energy analysis alone is not sufficient to completely understand energy use (Dovjak et al. 2010; Yildiz and Gungor 2009; Shukuya 1994). In addition to the energy analysis, exergy analysis is a useful tool that allows the comparison of the effects of working temperatures and qualities of different energy sources and flows.

Previous studies evaluated the thermal indoor environments created by air-based and water-based heating and cooling systems and their energy performance for office buildings (Sastry and Rumsey 2014; Fabrizio et al. 2012; Imanari et al. 1999). Kazanci et al. (2016a; 2016b; 2016c) have theoretically studied the exergy performance of different water-based and air-based heating and cooling systems for a single-family house.

Although there have been several studies focusing on heating and cooling plants and on terminal units, so far there has only been little focus on distribution systems. However, this is critical as distribution systems use electricity as a direct input (e.g., pumps, fans, valves, dampers, sensors, etc.), and this makes exergy analysis a suitable tool to be used.

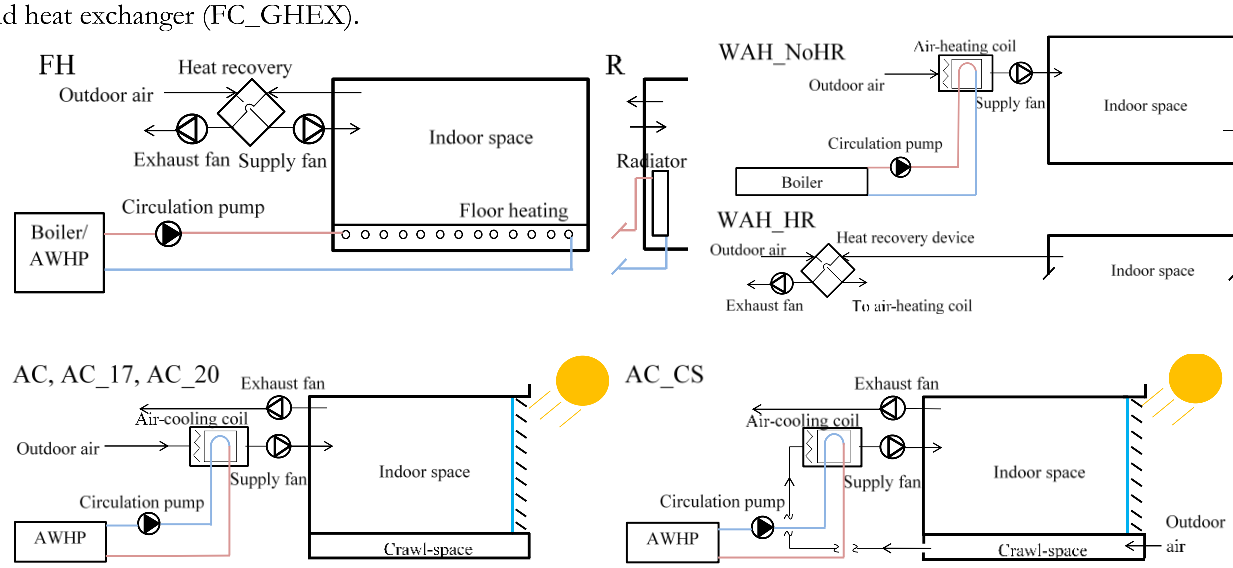
This study compares the performances of water-based (floor heating and cooling, and radiator heating) and air-based (air heating and cooling) heating and cooling systems in terms of their energy use and exergy consumption for auxiliary components (pumps and fans). The importance of the auxiliary components for the whole system energy and exergy performance was also identified.

DETAILS OF THE STUDIED SYSTEMS

The studied systems were assumed to be installed in a detached, single-family house, which was assumed to be in Copenhagen, Denmark. Construction details, description and details of the heating, cooling and ventilation systems of the actual house are given in Kazanci et al. (2016a) and Kazanci and Olesen (2014).

Description of the Studied Systems and Determination of the Operation Parameters

Six different heating and six different cooling systems were studied. Figure 1 shows the schematic drawings of these systems: floor heating (FH), radiators with different operating temperatures (R_55: 55°C [131.0°F] supply and 45°C [113.0°F] return, R_70: 70°C [158°F] supply and 55°C [131.0°F] return, and R_90: 90°C [194°F] supply and 70°C [158°F] return), warm-air heating with or without heat recovery on the exhaust air (WAH_HR and WAH_NoHR), air cooling using outdoor air as the intake with different supply air temperatures of 14°C (57.2°F), 17°C (62.6°F), and 20°C (68.0°F) (AC, AC_17, and AC_20), air cooling using cooler air from the crawl-space as intake air with a supply air temperature of 14°C (57.2°F) (AC_CS), floor cooling (FC), and floor cooling connected to a ground heat exchanger (FC_GHEX).



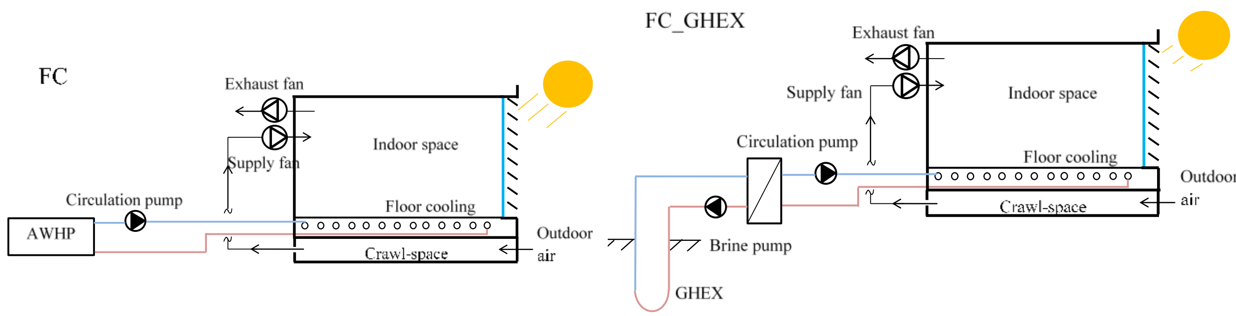


Figure 1 Schematic drawings of the studied systems (Kazanci et al. 2016a; 2016b)

The heat source for radiator heating and warm-air heating cases was a boiler. For all other cases, a reversible air-to-water heat pump was used as the heating or cooling source. The air-to-water heat pump was replaced with a ground heat exchanger in FC_GHEX.

The details of the operation parameters (floor surface temperatures, flow rates, supply and return water temperatures to and from different components, heat pump COP values, etc.) have been described thoroughly in Kazanci et al. (2016a; 201b; 2016c). For the determination of the pump and fan powers, actual components installed in the house were used (Kazanci and Olesen 2014). Table 1 summarizes the pump and fan powers.

Table 1. Summary of Pump, Fan, and Total Power for the Studied Cases

Case	E_{pump}, W (Btu/h)	E_{fans}, W (Btu/h)	E_{total}, W (Btu/h)
FH	27.5 (93.8)	67.9 (231.7)	95.4 (325.5)
R_55	24.5 (83.6)	67.9 (231.7)	92.4 (315.3)
R_70	23.0 (78.5)	67.9 (231.7)	90.9 (310.2)
R_90	22.0 (75.1)	67.9 (231.7)	89.9 (306.8)
WAH_NoHR	27.0 (92.1)	136.5 (465.8)	163.5 (557.9)
WAH_HR	25.0 (85.3)	273.0 (931.5)	298.0 (1016.8)
FC & FC_GHEX*	25.2 (86.0)	67.9 (231.7)	93.1 (317.7)
AC	25.0 (85.3)	173.6 (592.3)	198.6 (677.7)
AC_17	25.3 (86.3)	231.5 (789.9)	256.8 (876.2)
AC_20	26.0 (88.7)	347.3 (1185)	373.3 (1273.8)
AC_CS	23.0 (78.5)	173.6 (592.3)	196.6 (670.8)

*: The electricity input to the brine pump is not shown in this table, it is not considered as an auxiliary component but rather as a component similar to a heat pump, which is used to deliver the "coolness" from the ground to the floor loops.

Determination of the Design Heating and Cooling Loads

The heating and cooling loads were calculated from an energy balance under steady state conditions. The outdoor temperatures were assumed to be -5°C (23°F) and 30°C (86°F) in winter and summer, respectively. The indoor temperatures (air and mean radiant temperatures) were 20°C (68°F) and 26°C (78.8°F) in winter and summer, respectively.

The internal heat gain was assumed to be 4.5 W/m² (1.4 Btu/hft²), which represents two persons at 1.2 met and other household equipment. No solar heat gains were considered in heating season. In cooling season, the solar heat gains were determined as described in (Kazanci et al. 2016b) by using the direct and diffuse solar radiation values for Copenhagen, Denmark on a representative day in July at noon.

For floor heating and cooling, and radiator cases, the ventilation rate was 0.5 ach. For all cases, the infiltration rate was 0.2 ach. For floor heating and radiator cases, supply air temperature was 16.3°C (61.3°F) after the heat recovery and in warm-air heating cases the supply air temperature was 35°C (95°F), limited by the building code in Denmark. In cooling cases, the intake air was 21.3°C (70.3°F) when taken from the crawl-space and this was the supply air temperature in floor cooling cases. Supply air temperature was 14°C (57.2°F) for air cooling cases, except for AC_17 and AC_20 cases, in which the supply air temperature was 17°C (62.6°F) and 20°C (68.0°F), respectively. Resulting space heating loads were 2180 W (32.9 W/m² [10.4 Btu/hft²]) for floor heating and radiator cases, and 2048 W (30.9 W/m² [9.8 Btu/hft²]) for warm-air heating cases. Space cooling loads were 876 W (13.2 W/m² [4.2 Btu/hft²]) for floor cooling cases, and 1042 W (15.7 W/m² [5.0 Btu/hft²]) for air cooling cases.

EXERGY CALCULATION METHODOLOGY

Exergy performance of the systems was analyzed following the methodology described by Shukuya (2013). Only heating approach is described in the following. Details of the cooling calculation methodology are given in Kazanci et al. (2016b).

In the most general form under steady-state conditions, exergy balance can be written as follows.

$$[Exergy\ input] - [Exergy\ consumed] = [Exergy\ output] \tag{1}$$

where [Exergy consumed] = [Entropy generated] · To. Heating exergy load, $X_{heating}$ [W], (Shukuya 1994) is defined as

$$X_{heating} = Q_{heating}\ (1 - \frac{T_o}{T_i}) \tag{2}$$

where $Q_{heating}$ is space heating load [W], T_o is outdoor (environmental) temperature [K] and T_i is indoor temperature [K]. Once the heating exergy load is known, the exergy supplied to the indoor space from floor heating, $X_{FH,out}$ [W], and through warm-air, $\Delta X_{WAH,out}$ [W], can be determined with Eqs. (3) and (4), respectively.

$$X_{FH,out} = Q_{heating}\ (1 - \frac{T_o}{T_{S,FH}}) \tag{3}$$

$$\Delta X_{WAH,out} = V_{sa} c_a \rho_a \left\{ (T_{sa} - T_i) - T_o \ln \frac{T_{sa}}{T_i} \right\} \tag{4}$$

where $T_{S,FH}$ is average temperature of the heated floor surface [K], V_{sa} is volumetric flow rate of supply air [m³/s], c_a is specific heat capacity of air [J/kgK], ρ_a is air density [kg/m³] and T_{sa} is temperature of the supply air [K]. The calculation procedure for the radiators is similar to the floor heating. Exergy consumed in the indoor space is the difference between the exergy supplied to the indoors and the heating exergy load.

The exergy consumption in the floor structure, X_c [W], is obtained from the exergy balance as

$$\Delta X_W - X_c = X_{FH,out} \tag{5}$$

$$\Delta X_w = X_{w,supply} - X_{w,return} \tag{6}$$

where ΔX_w is the difference in the rate of exergy between the supply and return water flows [W]. The exergy of the supply and return water flows, X_w [W], are calculated as

$$X_w = V_w c_w \rho_w \left\{ (T_w - T_o) - T_o \ln \frac{T_w}{T_o} \right\} \tag{7}$$

where V_w is volumetric flow rate of water [m³/s], c_w is specific heat capacity of water [J/kgK], ρ_w is density of water [kg/m³] and T_w is temperature of water [K]. Eq. (7) can also be used to calculate the exergy of the air flows by replacing the necessary flow, physical parameters, and temperatures of water with those of air.

The exergy consumption in the air-heating coil in the air handling unit is obtained as

$$\Delta X_{w,coil} - X_c = \Delta X_a \tag{8}$$

$$\Delta X_{w,coil} = X_{w,supply,coil} - X_{w,return,coil} \tag{9}$$

$$\Delta X_a = X_{a,out} - X_{a,in} \tag{10}$$

where ΔX_a is the difference in the rate of exergy between the air leaving ($X_{a,out}$) and the air entering the air-heating coil ($X_{a,in}$) [W].

It was assumed that the natural gas fired condensing boiler had an efficiency, η_{boiler}, of 90% (Shukuya 2013; Kilkis 2012). The ratio of the chemical exergy to the higher heating value of natural gas, r, was taken as 0.93 (Shukuya

2013). The exergy input to the natural gas fired boiler, $X_{in,boiler}$ [W], is calculated using Eq. (11).

$$X_{in,boiler} = \frac{Q_{boiler}}{\eta_{boiler}} r \tag{11}$$

where Q_{boiler} is the amount of heat to be provided by the boiler [W].

It was assumed that the electricity provided to the heat pump, pumps, and fans was generated in a remote, natural gas fired power plant. The conversion efficiency at the power plant, transmission and distribution efficiencies combined, η_{TOT}, was 0.35 (Shukuya 2013). The exergy input to the power plant by natural gas, $X_{in,power\ plant}$ [W], is calculated as follows.

$$E_{HP} = \frac{Q_{heating}}{COP} \tag{12}$$

$$X_{in,power\ plant} = \frac{E_{HP}}{\eta_{TOT}} r \tag{13}$$

Exergy input required at the power plant for the pump and fans is also calculated using Eq. (13) by replacing the electricity input to the heat pump (E_{HP}) with respective pump power (E_{pump}) and fan power (E_{fans}). E_{HP} is replaced with E_{total} in Eq. (13) to calculate the necessary exergy input to the power plant for auxiliary components ($X_{in,pp,aux}$, [W]).

RESULTS

Heating Season

Figure 2 shows the pump power, fan power, their total, and the necessary exergy input to the power plant for auxiliary components in the studied heating systems.

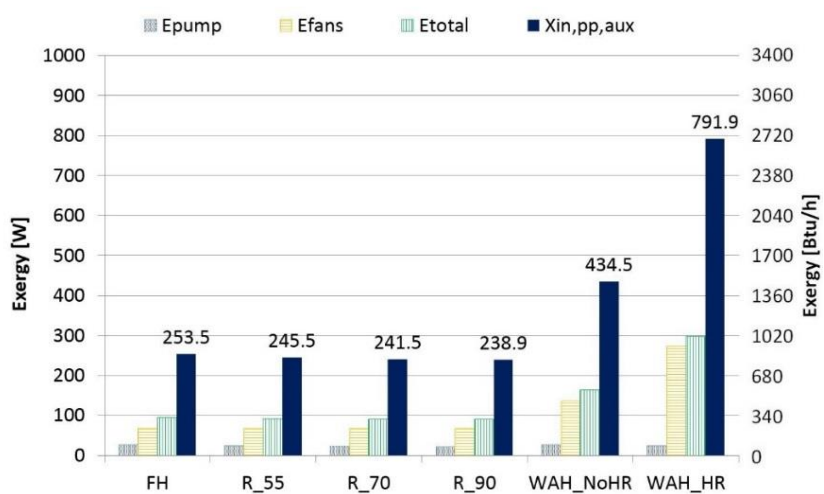


Figure 2 Exergy input to the auxiliary components and to the power plant, heating season

Table 2 shows the comparison of the energy and exergy use for auxiliary components and space heating.

Table 2. Comparison of Energy and Exergy Use for Auxiliary Components and Space Heating*

Case	FH	R_55	R_70	R_90	WAH_NoHR	WAH_HR
$Q_{heating}$, W (Btu/h)	2180 (7439)	2180 (7439)	2180 (7439)	2180 (7439)	2048 (6988)	2048 (6988)
$X_{heating}$, W (Btu/h)	186 (635)	186 (635)	186 (635)	186 (635)	175 (597)	175 (597)

$E_{pump}/Q_{heating}$, %	1	1	1	1	1	1
$E_{pump}/X_{heating}$, %	15	13	12	12	15	14
$E_{fans}/Q_{heating}$, %	3	3	3	3	7	13
$E_{fans}/X_{heating}$, %	37	37	37	37	78	156
$E_{total}/Q_{heating}$, %	4	4	4	4	8	15
$E_{total}/X_{heating}$, %	51	50	49	48	94	171
$X_{in,pp,aux}/X_{in,fuel}$, %	12	11	11	11	8	30

*: E_{pump}, E_{fans} and E_{total} are given in Table 1. $X_{in,pp,aux}$ for different cases is given in Figure 2 . $X_{in,fuel}$ corresponds to $X_{in,power\ plant}$ for FH and it corresponds to $X_{in,boiler}$ for other cases.

Cooling Season

Figure 3 shows the pump power, fan power, their total, and the necessary exergy input to the power plant for auxiliary components in the studied cooling systems.

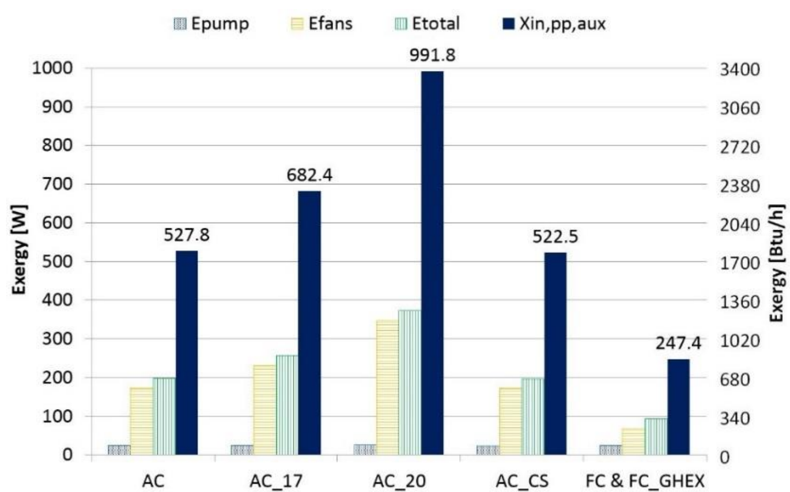


Figure 3 Exergy input to the auxiliary components and to the power plant, cooling season

Table 3 shows the comparison of the energy and exergy use for auxiliary components and space cooling.

Table 3. Comparison of Energy and Exergy Use for Auxiliary Components and Space Cooling*

Case	AC	AC_17	AC_20	AC_CS	FC	FC_GHEX
$Q_{cooling}$, W (Btu/h)	1042 (3556)	1042 (3556)	1042 (3556)	1042 (3556)	876 (2989)	876 (2989)
$X_{cooling}$, W (Btu/h)	14 (48)	14 (48)	14 (48)	14 (48)	12 (41)	12 (41)
$E_{pump}/Q_{cooling}$, %	2	2	2	2	3	3
$E_{pump}/X_{cooling}$, %	180	182	187	165	215	215
$E_{fans}/Q_{cooling}$, %	17	22	33	17	8	8
$E_{fans}/X_{cooling}$, %	1246	1662	2493	1246	580	580
$E_{total}/Q_{cooling}$, %	19	25	36	19	11	11
$E_{total}/X_{cooling}$, %	1426	1844	2680	1411	795	795
$X_{in,pp,aux}/X_{in,fuel}$, %	40	48	60	87	36	184

*: E_{pump}, E_{fans} and E_{total} are given in Table 1. $X_{in,pp,aux}$ for different cases is given in Figure 3. $X_{in,fuel}$ corresponds to $X_{in,power\ plant}$ for all cases except for FC_GHEX, where it corresponds to the sum of exergy flow from the ground and the necessary exergy input to the power plant for the brine pump.

DISCUSSION

The results show that the water-based systems require considerably lower exergy input to the auxiliary components than the air-based systems for providing the same space heating and cooling. Air-based systems require larger flow rates and volumes to transport the same amount of heat and exergy compared to water-based systems because of the air's smaller specific heat capacity and density than water. This causes a larger power requirement for air to be transported and it emphasizes the advantage of water-based heating and cooling systems. In water-based heating and cooling systems, the heat transfer medium is water and the ventilation system is used only to provide the necessary amount of fresh air without the goal of providing space heating or cooling, so the required airflow rates can be reduced. On the other hand, in air heating and cooling systems, high airflow rates are needed to address the space heating and cooling loads, which results in high auxiliary power requirements.

In the heating season, water-based systems required 43% lower auxiliary exergy input than the warm-air heating system without heat recovery and 68% lower auxiliary exergy input than the warm-air heating system with heat recovery. The increase in the auxiliary power requirement for the warm-air heating system with heat recovery is due to the extra fan power needed for the heat recovery unit. For the water-based systems, the temperature difference between the supply and return water flows to and from the terminal units and the corresponding flow rates make a difference in the required pump power. This is the main reason for the radiator cases having a lower auxiliary exergy input (3% to 6%) than the floor heating case.

In the cooling season, different supply air temperatures for space cooling, which required different airflow rates, were compared and the effects of different airflow rates on auxiliary exergy input can be seen in Figure 3. The auxiliary exergy input required for AC_20 was 88% higher than AC, and for AC_17 it was 29% higher than AC. The slight difference between AC and AC_CS is due to the difference in circulation pump power. The floor cooling system required 53% lower auxiliary exergy input than the air cooling systems (AC and AC_CS).

These results indicate a clear benefit for water-based systems over air-based systems. Further investigations are needed to quantify the effects of pump power on system energy and exergy performances in heating and cooling systems that are characterized by a low temperature difference between the supply and return water flows (e.g., low temperature heating and high temperature cooling systems).

The importance of auxiliary components is more evident in air-based heating and cooling systems compared to the water-based systems (mostly due to the high fan power), though it is also important for water-based systems to minimize the pump energy use (particularly for low temperature heating and high temperature cooling systems).

In heating cases, the pump powers (1%) and fan powers (between 3% to 13%) might seem negligible when compared to space heating and cooling loads in energy terms; however, they become crucially important when compared to space heating and cooling exergy loads. The necessary exergy input to the power plant for auxiliary components can be as high as 30% of the necessary exergy input to the boiler, as in WAH_HR, as shown in Table 2.

In cooling season, the systems behave similarly to the studied systems in heating season. It can be seen in Table 3 that the pump and fan powers become even more critical when the actual space cooling loads are low, as compared to the heating season. The required total exergy input to the auxiliary components (E_{total}) could exceed the space cooling exergy demand ($X_{cooling}$) by several times.

The required exergy input to the power plant for auxiliary components is comparable to the exergy input to the boiler and to the power plant for the heat pump. When naturally available heat sinks were used (ground heat exchanger, GHEX, and crawl-space, CS), this effect became more pronounced, as in FC_GHEX and AC_CS. This clearly shows that in order to benefit truly from the "free" cooling opportunities using renewable energy sources, the natural resources should be used wisely and the auxiliary energy input to utilize these sources should be minimized.

It should be noted that optimizing a system by lowering the pressure drops (e.g., for floor systems having more loops or a larger pipe diameter) will increase the initial costs, and this issue should also be considered carefully. Further investigations could consider the effects of the electricity mix (e.g., a certain part of the electricity delivered to the components is generated by renewables) on the overall results. Although this paper focused on the distribution system, a complete assessment of the system and improvement possibilities are necessary (e.g., the effects of improvements in the power plant vs. increased distribution system exergy use).

CONCLUSIONS

The studied water-based systems required significantly lower exergy input to the auxiliary components compared to the air-based systems. Water-based heating systems required 43% lower auxiliary exergy input than the warm-air heating system without heat recovery and 68% lower auxiliary exergy input than the warm-air heating system with heat recovery. Floor cooling system required 53% lower auxiliary exergy input than the air cooling system. These results show clearly the benefits of water-based systems over air-based systems in terms of auxiliary component energy use and exergy consumption.

Pump and fan powers might seem negligible in comparison to space heating and cooling loads in energy terms, but they become critical in exergy terms. Their importance becomes even more pronounced when space heating and cooling loads are small. In exergy terms, the required exergy input to the power plant for space heating and cooling purposes is comparable to the required exergy input for auxiliary components.

In order to effectively integrate the naturally available heat sinks and sources (e.g., ground, lake, sea-water, nocturnal radiative cooling, etc.) to building heating and cooling systems, the auxiliary exergy input to utilize these sources should be minimized.

For the optimal design of a heating and cooling system, all three parts of the system (generation, distribution, and heat emission/removal) should be considered holistically. Exergy analysis provides the required holistic analysis tool to achieve the optimal design.

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