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Energy and exergy analyses of the benefits and limitations of air-to-air heat recovery

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ABSTRACT

The application of air-to-air heat recovery plays an important role in reducing the amount of energy used for heating and cooling the ventilation air. The benefits of heat recovery depend on the outdoor conditions, level of ventilation, and must be evaluated in relation to the amount of energy used by fans. If heat recovery and fans are compared solely from energy viewpoint, a clear benefit might be seen in favor of heat recovery; however, this may or may not be the case from exergy viewpoint. Exergy analysis allows a more holistic and objective comparison of heat recovery and fan than energy analysis alone, and the actual benefits and limitations of applying heat recovery can then be better quantified.

Energy and exergy performances of a warm-air heating system (with and without heat recovery on exhaust air), and a floor heating system were theoretically compared, including the auxiliary energy inputs to pumps and fans. The relative benefits of heat recovery were analyzed.

The exergy input required by the floor heating system was 60% lower compared to warm-air heating without heat recovery, and 15% lower compared to warm-air heating with heat recovery. The floor heating system required 42% less exergy input to the power plant for the auxiliary components compared to warm-air heating without heat recovery, and 68% less compared to warm-air heating with heat recovery.

For the warm-air heating system, applying heat recovery lowered the exergy input to the boiler by 53%, however at the cost of increased auxiliary exergy input. The application of heat recovery in this study was beneficial, since the exergy input reduction to the boiler was considerably larger (2998 W) than the extra exergy input required at the power plant for the additional fan in case of warm-air heating with heat recovery (357 W).

Even though the application of heat recovery might provide clear benefits over the fan energy use in energy terms, the benefits become less significant in exergy terms and fan power becomes a crucial and decisive parameter.

KEYWORDS

Exergy analysis, Cross-flow heat exchanger, Warm-air heating, Heat recovery, Floor heating

INTRODUCTION

Several approaches can be used to heat or cool indoor spaces in buildings. Indoor terminal units are a part of building heating and cooling systems, and they mostly rely on either convection, or a combination of radiation and convection to emit or remove heat (and/or moisture) from indoor spaces (Kazanci and Olesen, 2015).

In HVAC systems used throughout the world (e.g. Europe, North America, Asia, etc.), energy sources and energy generators are similar and the main differences between HVAC systems are often the indoor terminal units (Olesen and Kazanci, 2015). The choice of terminal units has important effects on occupant thermal comfort, the energy use of distribution system, generation plant, and on the usable energy resources.

Different studies have compared the energy and thermal comfort performances of air-based systems with water-based systems (Imanari et al. 1999; Fabrizio et al. 2012; Sastry and Rumsey, 2014). Several authors have indicated that energy analysis alone is not sufficient to have a holistic understanding of the energy utilization (Shukuya, 1994; Yildiz and Gungor, 2009; Dovjak et al. 2010). In order to overcome this limitation, exergy analysis can be used to have a better understanding of the energy utilization in a system, especially when not only thermal energy flows but also the electricity input to different components (e.g. fans, pumps) are involved.

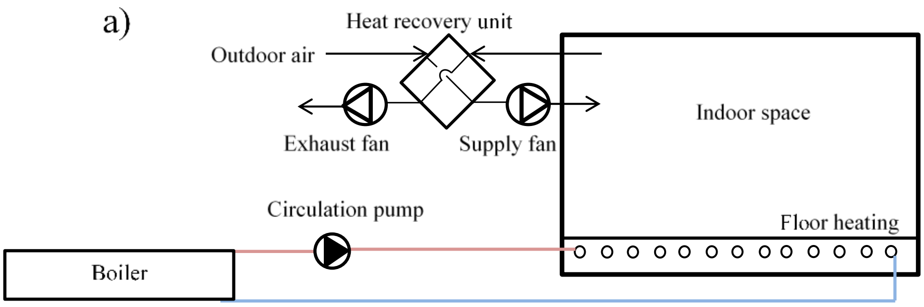
When a warm-air heating system is used to heat an indoor space, applying heat recovery on the exhaust air can result in considerable reductions of the energy used for heating the ventilation air; however, the overall benefits should be evaluated also in relation to the energy requirement by the fan. Exergy analysis allows a holistic comparison of the heat recovered and energy use by fans.

This paper demonstrates a comparative study on the energy and exergy performances of an air-based and a water-based heating system assumed to be installed in a single-family house.

DESCRIPTION OF THE STUDIED SPACE HEATING SYSTEMS

The studied systems were assumed to be installed in a detached, one-story, single-family house with a floor area of 66.2 m^2 and a conditioned volume of 213 m^3. The house was assumed to be located in Copenhagen, Denmark. Detailed description of the house and its systems can be found in (Kazanci and Olesen, 2014).

The studied space heating systems were warm-air heating with and without heat recovery on exhaust, and floor heating. Figure 1 shows the schematic drawings of these systems.



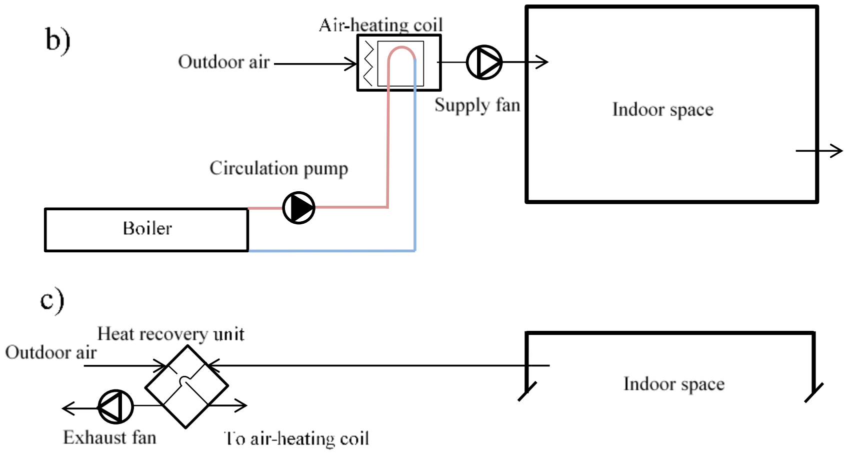


Figure 1. Schematic drawings of the analyzed heating systems: a) Floor heating (FH), b) Warm-air heating without heat recovery (WAH_NoHR), c) Warm-air heating with heat recovery (WAH_HR).

The calculations were carried out under steady-state conditions. The outdoor air temperature was -5°C (Olesen et al. 1980), and the indoor temperature was 20°C. The heat recovery unit had a heat recovery efficiency of 85% (sensible heat). This meant that the temperature of the intake air leaving the heat recovery unit was 16.3°C. Airflow rate in warm-air heating cases was determined based on the space heating load, while the ventilation rate was 0.5 ach in floor heating case.

The resulting space heating loads were 30.9 W/m^2-floor area for warm-air heating, and 32.9 W/m^2-floor area for floor heating. Further details of the load calculation procedure are given by Kazanci et al. (2016).

Floor heating

The load calculations showed that a specific heat output of 48.4 W/m^2-floor heating area with an average floor surface temperature of 24.7°C was required to satisfy the space heating demand. The required mass flow rate was 469 kg/h. The supply and return water temperatures to and from the floor loops were 33°C and 29°C, respectively. The calculations of the heat output, surface temperature, and the flow rate was based on Babiak et al. (2009), EN 1264-2 (2008), and EN 1264-3 (2009).

Warm-air heating

The supply air temperature to the indoor space was limited to 35°C (DS 469, 2013). The necessary heating rate needed for bringing the outdoor air at -5°C to the supply air temperature of 35°C was 5460 W when there was no heat recovery, and it decreased to 2559 W with heat recovery. The necessary heat was supplied to the air by an air-heating coil, which was connected to a boiler. The supply and return water temperatures to the air-heating coil were 50°C and 39°C, respectively (ASHRAE, 2000).

The necessary airflow rate was 410 m^3/h (1.9 ach) for both of the warm-air heating cases. The mass flow rate required in the air-heating coil was 428 kg/h and 201 kg/h for the case without and with heat recovery, respectively.

Fan and pump powers

Power requirements for pumps and fans were determined as described by Kazanci et al. (2016). Table 1 summarizes the pump and fan powers for the studied cases.

Table 1. Summary of the pump and fan powers for different heating cases.

	E_{pump} [W]	E_{fans} [W]	E_{total} [W]
FH	27.5	67.9	95.4
WAH_NoHR	27	136.5	163.5
WAH_HR	25	273	298

Heat and power generation

It was assumed that the heat generation for space heating in all cases was through a natural gas fired condensing boiler with an efficiency of 90% (Shukuya, 2013). The ratio of chemical exergy to the higher heating value of natural gas was 0.93 (Shukuya, 2013).

The electricity provided to the 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 was assumed to be 0.35 (Shukuya, 2013).

Kazanci et al. (2016) provide further details regarding the studied cases.

EXERGY CALCULATION METHODOLOGY

For any system, it is possible to obtain the exergy balance equation from energy and entropy balances. In its general form, exergy balance equation is obtained from the energy and entropy balance equations as follows (Shukuya, 2013):

$$[Energy\ input] = [Energy\ stored] + [Energy\ output] \quad (1)$$

$$[Entropy\ input] + [Entropy\ generated] = [Entropy\ stored] + [Entropy\ output] \quad (2)$$

In its general form, exergy = energy – entropy · T_o. Therefore it is possible to obtain the exergy balance equation as Eq. (1) – Eq. (2) · T_o.

$$[Exergy\ input] - [Exergy\ consumed] = [Exergy\ stored] + [Exergy\ output] \quad (3)$$

where [Exergy consumed] = [Entropy generated] · T_o, and T_o is the environmental (reference) temperature [K]. The storage terms in Eqs. (1), (2), and (3) disappear under steady-state conditions.

Eqs. (1), (2), and (3) indicate that every system consumes a part of the supplied exergy and in the meanwhile entropy is generated. This applies to heating and cooling systems in buildings as well.

The detailed calculation methodology for the studied systems was described by Kazanci et al. (2016), therefore they are not described further in this paper. Here, the exergy balance for the heat recovery unit is given. The exergy consumption in the heat recovery unit is obtained through the exergy balance equation set up for the heat recovery unit:

$$X_{outdoor\ air} + X_{exhaust\ air} - X_c = X_{inlet\ air} + X_{discharge\ air} \quad (4)$$

where $X_{outdoor\ air}$ is the exergy of the intake air from outdoors (=0) [W], $X_{exhaust\ air}$ is the exergy of the exhaust air (from the indoor space) [W], $X_{inlet\ air}$ is the exergy of the inlet air (supply air for the floor heating case, and the air entering the air-heating coil in the warm-air heating with heat recovery) [W], and $X_{discharge\ air}$ is the exergy of the discharge air (discarded to the environment after the heat recovery) [W].

Eq. (5) is used for calculating $X_{outdoor\ air}$, $X_{exhaust\ air}$, $X_{inlet\ air}$, and $X_{discharge\ air}$ with respective airflow temperatures.

$$X_a = V_a c_a \rho_a \left\{(T_a - T_o) - T_o \ln\frac{T_a}{T_o}\right\} \tag{5}$$

where X_a is the exergy of the airflow [W], V_a is the volumetric flow rate of air [m^3/s], c_a is the specific heat capacity of air [J/kgK], ρ_a is the density of air [kg/m^3], and T_a is the temperature of the air flow [K].

In addition to the exergy consumption due to heat transfer in the heat recovery unit, the discharged air also contains a certain amount of exergy. This exergy is totally consumed while the discharged air is completely discarded into the environment.

RESULTS AND DISCUSSION

Figure 2 shows the whole chains of exergy flows from the exergy input to the boiler to the environment. Figure 3 shows the exergy consumption in the heat recovery unit, and Figure 4 shows the required exergy inputs to the pump, fans and to the power plant.

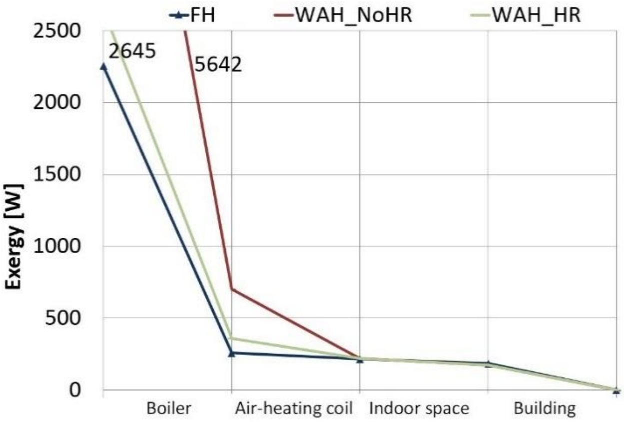


Figure 2. Exergy flows for different heating strategies.

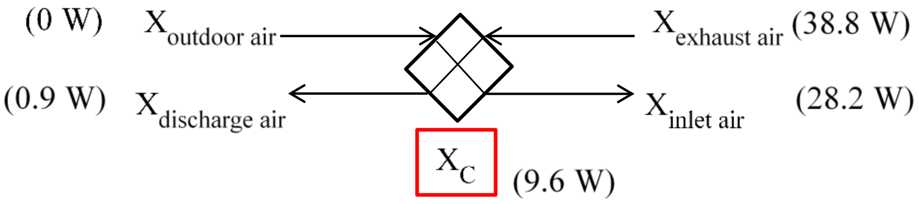


Figure 3. Exergy consumption in the heat recovery unit (cross-flow heat exchanger), shown for 0.5 ach (values in the parentheses indicate the exergy values, X_c is the exergy consumption).

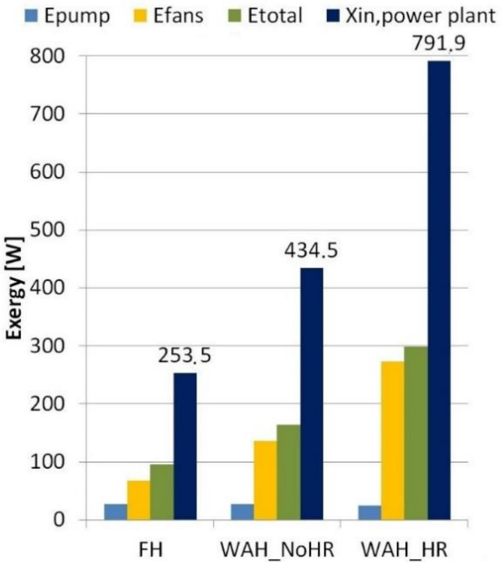


Figure 4. Required exergy inputs to the pump, fans and to the power plant (four bars in each case indicate, from left to right, the exergy input to pump, to fans, their total, and the exergy input to the power plant).

The heating exergy load (input to the “Building” in Figure 2) consists of the heat loss from the building envelope (transmission loss) and the heat required for bringing the fresh air at 16.3°C to the indoor temperature of 20°C. The heating exergy load is 186 W for the floor heating case, and 174.6 W for the warm-air heating case (this load is different since the supply air has to be warmer than the indoor air).

Exergy consumption in the indoor space varies with the heating strategy chosen. For floor heating, the exergy consumption in the space is 31.2 W, and this is lower than that of warm-air heating case (46.3 W). This is because of the low temperature heating possibility and the low surface temperature of the floor.

The application of heat recovery on the exhaust air resulted in a significant decrease in the exergy consumption within the air-heating coil, from 479.6 W to 137 W, (71% decrease, Figure 2), because with heat recovery, the air temperature should be increased from 16.3°C to 35°C in the air-heating coil compared to no heat recovery when the air temperature should be increased from -5°C to 35°C. This is also reflected in the necessary energy and exergy inputs to the boiler.

The floor heating requires the smallest fuel (exergy) input to the boiler (2253 W) while the required fuel input is largest for the warm-air heating without heat recovery (5642 W), followed by the case with warm-air heating with heat recovery (2645 W). The exergy input required by the floor heating is 60% smaller compared to warm-air heating without heat recovery, and 15% smaller compared to warm-air heating with heat recovery. It should be noted that this is only the thermal exergy flow and does not consider the exergy input to auxiliary components.

Regarding the exergy inputs to the heating plant, the use of a boiler does not allow taking advantage of the low exergy demand of the radiant floor heating system. The largest exergy consumption through the whole space heating process occurs in the boiler and this is mainly due to the combustion process.

The results in Figure 4 show that an air-based heating system requires large fan powers, resulting in a further decrease of the system energy and exergy performances. This is mainly because larger flow rates and volumes are required to transport the same amount of heat with air compared to water, and this emphasizes an advantage of water-based heating and cooling systems over air-based systems. The floor heating system requires 42% less exergy input to the power plant for the auxiliary components compared to warm-air heating without heat recovery, and 68% less compared to warm-air heating with heat recovery.

There is a trade-off between the exergy gain with the heat recovery unit and the electricity necessarily supplied to the additional exhaust fan (also the extra fan power needed to cover the additional pressure drops). Depending on the local climate, ventilation rate and on the efficiency of the heat recovery unit, it might not always be beneficial to have heat recovery. If the exergy input to the fan exceeds the exergy recovered from the exhaust air, this indicates that there is a threshold for which the heat recovery is beneficial. This issue should be carefully considered before applying heat recovery on ventilation systems.

When considering the warm-air heating cases with and without heat recovery, extra exergy input for the exhaust fan is the crucial parameter to consider when evaluating the benefits of heat recovery. The extra exergy input required at the power plant for the additional fan in the case of warm-air heating with heat recovery is 357.4 W, which is significantly less than the saved exergy input to the boiler due to the application of heat recovery (2998 W), therefore the application of heat recovery is justified for this application.

During the heat recovery from the exhaust air, the exergy consumption in the heat recovery unit is inevitable. Due to heat transfer between air streams, there is exergy consumption in the heat recovery unit and due to the efficiency being less than 100% (exergy is necessarily consumed even if the 100% energy-wise efficiency is possible), it is not possible to fully recover the thermal exergy from the exhaust air. A certain amount of air with exergy is discarded into the environment after the heat recovery, and hence it is lost. This amount of exergy would vary in different locations: in the present case of Denmark, due to low outdoor temperature, it has higher exergy compared to another location with a mild climate.

The exergy consumption in the heat recovery unit for the warm-air heating case is 37.2 W (40.6 W including the exergy of the discharge air), and it is 9.6 W (10.5 W including the exergy of the discharge air) for the floor heating case.

CONCLUSION

Exergy performances of floor heating and warm-air heating were compared in this study. In addition to the thermal exergy, these systems were also compared in terms of auxiliary exergy used for pumps and fans. The relative benefits and penalties associated with the application of heat recovery in the ventilation system were identified.

The floor heating system had the lowest exergy consumption and it performed better than the warm-air heating systems in terms of required exergy input, and exergy consumption. The overall performance of the floor heating system could have been improved further by coupling it to another heating plant than a natural gas fired condensing boiler (e.g. a ground coupled heat pump), because the boiler does not allow taking advantage of the low exergy demand of the radiant floor heating system.

The water-based floor heating system required lower auxiliary exergy input than the warm-air heating systems. This shows a clear benefit for water-based systems over air-based systems.

For a heat recovery unit to be beneficial, the thermal exergy gained from the heat recovery (from the exhaust air) must be greater than the exergy supplied to the exhaust fan, and this analysis should be carried out before deciding on the application of heat recovery. In the current case, the application of heat recovery proved to be beneficial: the extra exergy input required at the power plant for the additional fan in case of warm-air heating with heat recovery was 357.4 W, which is significantly smaller than the reduced exergy input to the boiler due to the application of heat recovery (2998 W).

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