Unique Integration of Hot Water Heat Recovery into Low Exergy Heating

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ABSTRACT

There are many technologies aimed at reducing energy demand of ventilation systems, but the focus in these designs has remained on the air heating system and exhaust losses. In fact, a typical daily exhaust air requirement for one person has the same quantity of exergy as the water from a typical shower, and thus heating systems must also consider hot water.

This project presents the exergy analysis of integrating wastewater heat recovery into a building heating system. A heat pump provides room conditioning and hot water heating. The “low exergy” heating minimizes the temperature lift required by the heat pump as well as the temperature differences at heat transfer surfaces in the heating system. This maximizes the performance of the heat pump and minimizes the exergy destroyed in the system. An exergy analysis provides a detailed look at the energy demand and the appropriateness of the quality of the energy utilization. The exergy analysis of the system is part of the research in the Swiss participation in the IEA ECBCS Annex 49: Low Exergy Systems for High Performance Buildings and Communities.

The analysis shows that the exergy available in warm wastewater can be used to augment the evaporator temperature of the heat pump. The room heating system functions with large heat transfer surface areas (i.e. TABS) at 30 °C, and when hot water needs to be produced at higher temperatures, the temperature lift of the heat pump remains low by augmentation from hot wastewater. The optimization and performance characteristics of this high performance system are presented.

1. INTRODUCTION

1.1 Motivation

Buildings are like living organisms. They breathe air in and out. They ingest water and materials and excrete waste. They also utilize energy to function. Still, organisms have had millions of years to optimize their systems, and the comparatively short existence of buildings leaves room for their improvement.

Two major improvements that are focused on today are reduced energy requirements and better indoor environmental quality. This brings attention to building ventilation and energy strategies, but often overlooks their integration into a complete system. For example, the energy used to condition air is often considered, but the energy used to condition other incoming flows like water are often not considered. While exhaust air heat is often recovered in modern ventilation systems, the potential of warm wastewater is almost always lost. In fact, it will be shown that the amount of heat in exhaust air for one person for one day is similar to the amount of heat for a typical shower for that person. Therefore a system that captures both of these potential losses should be considered. Here the integration of wastewater heat recovery into this system should be the focus because it is often neglected. The goal is to implement this system into a low exergy building that minimizes the use of high value or high temperature energy. In order to optimally integrate these systems with their various heat fluxes, this concept of exergy is employed to account for changes in both quantity and quality, reducing primary energy consumption.

1.2 Summary

This study will present the exergy analysis of a wastewater heat recovery system. It will model realistic hot water usage data on a fine time scale to allow for optimal heat extraction at the highest possible temperatures. This will show the high exergy content of wastewater. This will be compared to the exergy content of exhaust air. The utilization of this exergy in an integrated system will be described. This will be for the case of a low exergy building in which temperature gradients are minimized and high temperature heat sources are avoided. Therefore the system will incorporate a heat pump. Both the exhaust air and wastewater exergy would be recovered in the system by the heat pump to minimize the temperature lift it must provide.

Using a wastewater heat recovery system minimizes exergy consumption, and is ideal for an integrated low exergy building system.

2. BACKGROUND

2.1 Exergy

Exergy is a concept that combines the first and second laws of thermodynamics by combining the basic energy and entropy balances. This presents a view where it is possible to consider energy quantity as well as *quality* in one value. This improves energy systems and leads to better energy policy (Rosen, 2008)

Exergy is defined by the energy adjusted for the quality as accounted for by entropy. This is given in Equation 1 where *Ex* is the exergy, *Q* the heat transfer, T_0 the reference temperature, and Δs the change in entropy (Ahern, 1980).

$$Ex = Q + T_0 \cdot \Delta s \quad (1)$$

In the case of the exergy change of an incompressible fluid, the energy term can be approximated assuming a constant heat capacity, and the entropy term can be estimated by the natural logarithm of the ratio of the temperature change as shown in Equation 2 where m-dot is the fluid mass flow rate, c_p the fluid heat capacity, T_h the warm input temperature and T_c the cool output temperature (Schmidt, 2004).

$$Ex = \dot{m} c_p \left(T_h - T_c - T_0 \ln \frac{T_h}{T_c} \right) \quad (2)$$

Exergy includes a term, T_0 that accounts for the conditions of the external environment relative to the system. This allows one to evaluate the quality of the energy in a system. A temperature farther away from the environment has more potential, thus more quality or exergy.

For energy alone, a balance can always be made. But in the case where one has a volume with the same amount of energy but with different temperatures, the potential to do something useful with the higher temperature volume is greater, even though it has the same amount of energy. This higher potential is quantified by exergy. Exergy accounts for the potential for an amount of energy to do work based on its state as compared to the state of its surrounding environment (Ahern, 1980) (Moran, 2000).

The definition of the external environment, T_0, is fixed for most systems operating in controlled environments, but for large scale systems like buildings it can be assumed to be fixed for certain systems, but in most cases it is taken as the outside conditions. For steady state analysis of heating systems or cooling systems this can be the design or the average conditions (Shukuya, 1994) (Schmidt, 2004).

Another term that is often used along with exergy is anergy. This refers to exergy that has been destroyed or is at the environmental state. It is no longer able to do work relative to the defined environment, and therefore another name for the environmental state is the dead state. Although work cannot be created from this state, work can be done in a thermodynamic cycle to extract anergy from the dead state as is done by heat pumps.

2.2 Low Exergy Buildings

Buildings that are considered to have low exergy systems utilize the concept of low temperature heating and high temperature cooling. This minimizes the temperature gradient between the room air and the heat source, thus minimizing exergy destruction. In order for adequate heating or cooling to be supplied with low temperature gradients a large surface area is needed like TABS or chilled beams along with a well insulated envelope. An extensive overview is found in the IEA Annex 37 Guidebook (2003) and at www.lowex.net.

In this study an important aspect of low exergy buildings is the elimination of the use of high temperature heat. This clearly makes combustion technologies undesirable. High efficiency heat pumps are the ideal solution, and therefore it is of interest to optimize them for use in low exergy systems.

2.3 Heat Pumps

The laws of thermodynamics allow a heat pump to transport up to a certain amount of heat per unit of work input into the system. This performance (heat moved/energy input) is the coefficient of performance (COP) and it has a theoretical maximum defined by a reversible Carnot cycle given in Equation 3 with T_H being the hot condenser temperature and T_C being the cool evaporator temperature (Moran, 2000).

$$COP = \frac{T_H}{T_H - T_C} \quad (3)$$

A real heat pump has an efficiency less than the Carnot efficiency due to losses in the system. Still, it is clear that the potential of heat pump performance is dependent on the temperature lift it must provide. The exergetic performance of heat pumps has been studied by Gasser et. al. (2008), Ozgener (2007), and Bilgen (2002) among others, which show the potential for better optimization of heat pump systems through the use of exergy analysis.

The use of heat pumps for the production of hot water is well known (IEA Heat Pump Centre, 1993). The application of heat pumps for hot water production is expanding as fossil fuels become more costly (Waide, 2008). New methods of measuring seasonal efficiency of integrated hot water and space conditioning heat pumps have been developed, and consider exergy (IEA Heat Pump Centre, 2006).

2.4 How Water Usage

Most hot water usage is found in domestic systems, with the most concentrated usage found in large hotels or apartment complexes.

In order to realistically consider the potential of using energy from hot wastewater, one must consider how and when hot wastewater is produced. Unlike ventilation, the usage is sporadic and unpredictable (Shove, 2003). For an accurate look at the recovery of exergy from this system, realistic usage must be considered (Jordan, 2001).

3. METHODS

3.1 Data Acquisition

The data used for the simulation of the hot water usage came from a probabilistic simulation engine developed at the University of Kassel (Jordan, 2003). The data was produced from the engine for the US DOE based on usage profiles for showers, bathes, sinks, laundry, and dishwashers (Hendron, 2007). This provided randomized data at 6-minute intervals for each use that fit the statistics developed for each profile for a two, three, or four bedroom residence. The data is provided for bathes, showers, sinks, laundry, and dishwashing loads. There is data for pure hot consumption or for the hot-cold mixes of bathes, showers and sinks. The temperatures of the usage are taken from Hendron (2007). The data for four bedrooms was used and the entire year was compiled into one input for simulation in Matlab.

3.2 Analysis

The simulation uses the flow of hot water over time along with its temperature from the data mentioned above. This is sent into a modeled recovery tank with a set diameter, volume, and wall heat transfer coefficient. The tank contains a heat exchanger having a set flow rate, supply temperature and pipe diameter, and is modeled in a spiral. The spiral width is sized relative to the tank diameter, and the spacing between turns is set at three pipe widths.

At each time step the simulation checks if a hot water event occurred and the amount of water going into the tank. The temperature of the incoming water is adjusted from the given values (Hendron, 2007) so that losses during flow to the tank and losses during use are considered. These are estimated to be 5, 3, 2, 5, and 2 percent for bath, shower, sink, clothes and dishes respectively.

If an event has occurred, the new volume of the tank is calculated. There is a valve that is activated if the tank is filled to capacity. It removes liquid from the bottom of the tank, so if the new volume is greater than the capacity, the previous water is removed to make space for new input.

New events are combined using an energy balance with what is in the tank. This calculates the new temperature of the tank assuming it is completely mixed. The heat exchanger in the tank is assumed to have a heat transfer coefficient, which depends on the depth of liquid in the tank. The actual heat transfer rate depends on the calculated temperature in the tank and the heat transfer coefficient. The heat extraction is modeled as a laminar flow through a pipe with constant surface temperature equal to the tank temperature. The heat extracted from the tank and the heat losses through the walls are removed from the tank using an energy balance to determine the new temperature. This provides the temperature of the tank for the next time step. If the temperature has dropped below a set point that is two degrees above the heat exchanger supply temperature, the tank is flushed completely and waits for the next event.

The amount of exergy available from the wastewater is calculated from equation 2 and the amount of heat extracted by the heat exchanger at each step. This is compared to what would be available from exhaust air at room temperature. The reference temperature for the exergy comparison is 5 degrees Celsius.

The heat pump is assumed to have a given performance. The operating temperature and pressure of the evaporator temperature can be raised using the heat recovered. Thus the heat pump COP can be improved based on the simple Carnot (equation 3) multiplied by a performance factor of typical exergetic efficiencies of heat pumps (Gasser, 2008). This provides an estimation of the performance increase that could be obtained in a heat pump from the reduced exergy needed to provide the high temperature lift for water heating. It shows the overall exergy used by the system with and without the heat recovery and subsequent temperature lift reduction.

4. RESULTS

4.1 Recovery of Wastewater Exergy

The dynamic filling and emptying of the of a 600 L recovery tank for each 6 minute time step over the model year is shown in Figure 1. The variations shown are due to complete emptying of the cooled tank, while the overflow happens only while the tank is completely full.

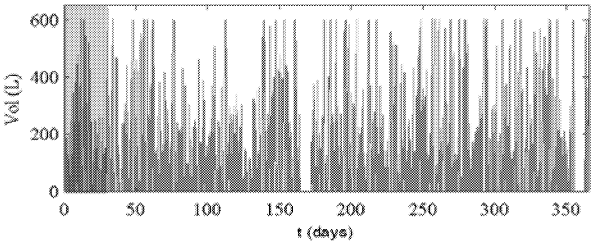

Figure 1. Volume in the recovery tank over the course of the modeled year with the month of January highlighted.

January is highlighted in Figure 1, and is shown in Figure 2. The top plot shows the total volume as well as the overflow volumes. The middle is the tank temperature. The bottom is the exergy output based on an environmental reference temperature of 5 degrees Celsius.

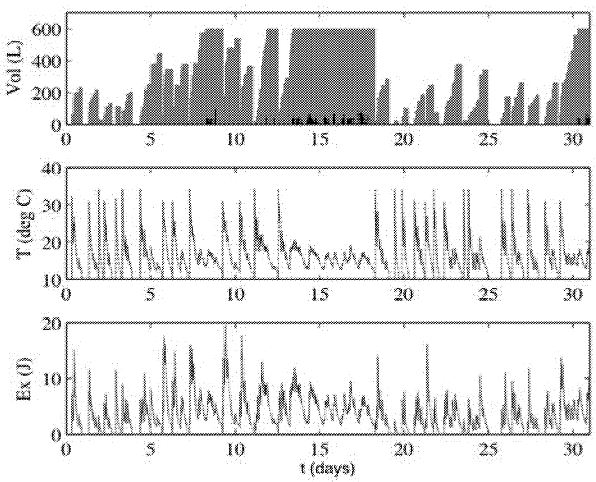

Figure 2. January data for the recovery tank total volume (grey) and overflow volume (black) on top, tank temperature in the middle, and exergy recovered on the bottom.

It is clear that a normal fill and recovery cycle takes about one to two hours. The exergy recovered follows the temperature with an order of magnitude greater amount being extracted at steps when the tank is fresh and warm.

The heat exchanger flow rate was adjusted to optimize the total exergy recovered over the year. This proved that a flow rate of 1.3 L/min was optimal as shown in Figure 3. This maximum was then check across different tank volumes and it was found to be consistently within 0.1 L/min of this value.

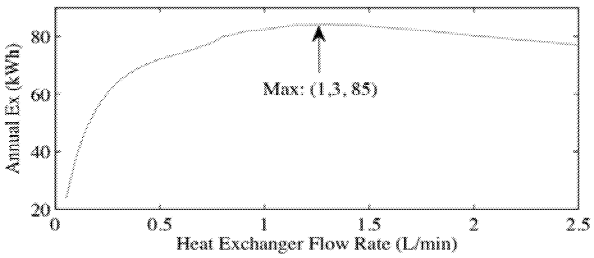

Figure 3: Total exergy recovered over the year versus the heat exchanger flow rate.

The exergy output was also observed for the different values to find the optimal tank size, as shown in Figure 4.

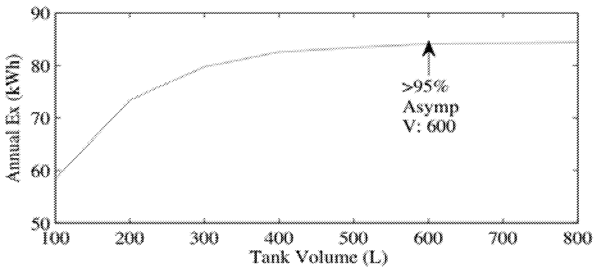

Figure 4. Total exergy recovered over the year versus the size of the tank for the flow rate of 1.3 L/min.

In this case the output approaches a maximum asymptotically, and it with a 600 L tank greater than 95% of this maximum is achieved and is an acceptable value.

At this state the model system recovers 85 kWh (0.31 GJ) of exergy. The energy demand reported by Hendron (2007) for this hot water usage year scenario was 4800 kWh (17 GJ) and the tank model simulation gave a similar demand of 4400 kWh (16 GJ) for the year. The simulation gave a total exergy consumption for the annual hot water production 350 kWh (1.2 GJ).

On an energy basis 3000 kWh (11 GJ) are brought out with the heat exchanger, which is 68% of the demand supplied. This would increase with higher heat exchanger flow rates but the quality of the energy would go down, reducing exergy. This is why Figure 3 has a maximum.

From an exergy perspective 85 kWh (0.31 GJ) are recovered compared to the 350 kWh (1.2 GJ) supplied. This is only 25% because the temperature recovered is lower than the temperature supplied, thus the exergy demonstrates the loss in quality. This is what allows for the optimization in Figure 3 where the exergy has a maximum. In the energy case, the energy would increase continuously with increasing heat exchanger flow rate because more heat is removed, but because the tank would decrease in temperature faster, there is less high quality energy (exergy) available.

4.2 Exhaust Air Comparison

A simple comparison to heat recovery from exhaust air demonstrates the relative significance of wastewater recovery. For the 4-bedroom case, the assumptions for exhaust air are five people with 30 cubic meters per person, and a temperature of 25 degrees Celsius.

Making the approximation that air is heated for 5 months from 10 degrees Celsius and using the same reference conditions as used for the water, the total exergy in this stream is about 100 kWh (0.36 GJ). This is an approximation, but it is clear that the potential from wastewater is on the same order of magnitude or higher.

4.3 Integrated Air and Water Recovery System

It has been shown that heat recovery from wastewater is a significant potential source of exergy. Therefore it should also be integrated into high performance systems, especially those that already recover heat from exhaust air.

The recovery can be part of integrated domestic hot water and space conditioning heat pump system. There are many options readily available (IEA Heat Pump Center, 1993). But the valuable potential shown above of exergy recovery from wastewater for use in the heat pump must be integrated. This could be optimally done by directly reducing the exergy demand of the heat pump. Ideally a heat pump with a compressor that could operate at two different temperature lifts could be designed. The heat pump could then provide low temperature lift space heating with exhaust air heat recovery, and the wastewater heat recovery could allow a low temperature lift for water heating as well. This would be done by augmenting the evaporator side of the heat pump. This would have a direct impact on the COP as shown in equation 3.

4.4 Estimated Heat Pump Savings

A simple estimation of the increase in heat pump performance can be achieved by substituting the evaporator temperature with the recovery temperature. For a typical ground source heat pump the incoming temperature is about 10 deg Celsius. The average temperature coming out of the heat exchanger in degrees Celsius was 15 with a maximum of 30.

For a typical exergetic efficiency of 0.4 (Gasser, 2008), the COP of a typical ground source heat pump would increase from 3 to 3.2 on average. This would decrease the electricity demand by 6%. Depending on how the dynamic heat pump system can be modulated for different inputs, the higher temperature outputs could increase performance to a COP close to 5.

5. CONCLUSIONS

5.1 Overall System Potential

The potential recovery of exergy from hot wastewater has been analyzed. There is an optimal savings in a year for a typical 4-bedroom residence of 85 kWh (3.1 GJ/year). This is for 68% recovery of heat, but is 25% of the exergy. A potential concept for integration of this system is presented and an estimate of the performance increase in the heat pump during recovery is shown to increase the COP significantly with a potential to nearly double the performance during high temperature recovery outputs.

5.2 Applications

This research is part of work in the IEA ECBCS Annex 49 (www.annex49.com). The work provides the basis for the development of new heat recovery systems that consider exergy. Collaboration is underway with the large sanitary systems firm of Geberit AG, working toward eventually producing a product for market. The goal is to have a pilot project ready to be implemented in a 4 floor, 4 apartment, building project that will begin construction in 2009.

5.3 Future Work

Further analysis will include better modeling of tank stratification dynamics as well as heat exchanger characteristics. Also, a wider range of hot water usage profiles should be used to clarify how larger scale systems such as hotel and multifamily systems might function. Also, the system could be compared to a fully mixed one taking cold and hot sources. Finally, the current view of the heat pump is very simplified. Collaboration is being developed with a group to look at the real potential operation of a heat pump using the waste heat recovery scheme described. A more comprehensive model is currently being developed.

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