647: Exergy recovery from warm wastewater for an integrated low exergy building system

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Abstract

The energy for water heating is often overshadowed by space heating and cooling, but as well-insulated buildings like zero energy buildings become more common, the water heating takes on a larger role in the building energy demand. A system to recover heat from warm wastewater has been studied. The analysis optimizes the heat recovery using the concept of exergy in order to maximize the quantity and quality. Statistical data for hot water usage at 6-min intervals has been used to create a realistic model of heat recovery. A model assuming a recovery-tank with completely mixed conditions has been analyzed and an extension has been made to approximate a stratified tank. An optimal flow rate for the mixed tank has been found using exergy analysis of 1.3 L/min for the mixed model and 0.35 L/min for the stratified model. The energy recovered at these optimal operating conditions was 3000 kWh or 68% of the hot water demand. In terms of exergy, higher quality is found in the stratified model with 150 kWh exergy compared to 85 kWh from the mixed model. The model differences are discusses as well as the potential losses in the system.

Keywords: exergy, heat recovery, wastewater, LowEx, low-exergy

1. Introduction

Zero energy buildings will never be realized unless every aspect of building energy demand is considered. Not only does each aspect have to be recognized, but also ways to integrate and optimize these systems simultaneously must be considered. This should all be done without overlooking the second law impacts of entropy production by utilizing the concept of exergy analysis.

The heating of buildings has become a focal point of research into creating zero energy buildings. Still, this focus is often limited to only space heating. But buildings are more than just warm spaces. Buildings have much in common with living organisms. They breathe air in and exhaust it out, materials and water come in and waste goes out, and they utilize energy to perform these among other functions. Organisms have optimized their systems over millennia, but buildings have existed for a relatively short time. This leaves much room for improvement. As organisms have done, improvements can be found by integrating the various systems, and by paying close attention to what is lost in the system that could still be used.

An area that deserves more attention is hot water production and usage. Heat recovery systems for exhaust air are becoming more common, but if the exhaust is to be recovered in a building, so should the water flow. It has significant potential for recovery. The most recent Residential Energy Consumption Survey in the United States showed that hot water production represents 17% of total energy consumption [1]. In almost every case the hot water, which has a high exergetic value, is flushed directly out of the building.

An exergy analysis has been done on the operation of a wastewater heat recovery system. A model was used based on realistic annual hot water usage data on a 6-minute time scale. Analysis is therefore carried out such that high temperature flows on short timescales can be captured. The exergy recovery in the system is maximized for a heat exchanger operation. This exergy is used in an integrated “low exergy” building. The operation of such a system is approximated along with the potential impact of wastewater heat recovery.

A wastewater heat recovery system can be optimized to extract a maximum amount of exergy from wastewater for integration in a heat pump system as part of a low exergy building.

2. Background

2.1 Exergy

Exergy (Ex) is a concept that combines the first and second laws of thermodynamics. Usually the first law, which is the basis for energy balances and heat flow calculations, is used in building analysis. By incorporating the second law, a better understanding of the value of the energy being used is gained. Both the quantity and the *quality* are expressed by exergy. This is considered to be a better way to improve energy systems and make better energy policy [2]

Exergy is defined by adjusting the energy or heat, Q, by a term representing the change in entropy, Δs relative to the external environmental conditions with temperature T_0. This is given in Equation 1 [3].

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

In order to calculate the exergy change for water flows one assumes an incompressible fluid with mass flow rate, mdot and a constant specific heat at different temperatures, c_p. The entropy term is estimated with the natural logarithm of the ratio of the temperature change from hot to cold in the fluid, T_H/T_C. This provides the exergy change in the water flow, Ex, as shown in Equation 2 [4].

$$Ex = mdot \cdot c_p \cdot [(T_H - T_C) - T_0 \ln(T_H/T_C)] \quad (2)$$

If only the energy in water or air is of interest, it can be calculated based on the temperature and properties of the substance alone. This gives an absolute amount. In the case of exergy, a relative quality is included. This is relative to the external environment. This describes the actual potential of the energy available to perform useful work within the relative surroundings of the system. The relative surroundings are accounted for by the reference state including the reference temperature T_0. In this way the loss of quality is exposed by the exergy lost in the use of high temperature systems relative to their environment and in heat exchanges across large temperature gradients [2,5].

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 individual systems, or it can be taken to be the outside conditions. For steady state analysis of heating systems or cooling systems this can be the design or average condition [4,7].

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 can no longer 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. Anergy is also used to quantify the amount of exergy destroyed in optimization problems.

2.2 Low Exergy Buildings

Buildings require only low temperatures for comfort so high temperature combustion sources are not needed. In general exergy analysis tells us that large temperature gradients in any system should be avoided.

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, usually a large surface area is needed as in the case of TABS or chilled beams, while also maintaining a well-insulated envelope that minimizes the heat flow. This allows small temperature gradients to supply adequate conditioning. An extensive overview is found in the IEA Annex 37 Guidebook [6] along with introductory exergy material at www.lowex.net, and is being further developed in the IEA ECBCS Annex 49.

In this project an important feature of a low exergy building is how well suited it is for heat pump applications. Heat pumps can provide both low temperature heating and high temperature cooling, and by doing so achieve their maximal efficiency. But in these systems hot water must still be produced at a higher temperature. Therefore it is very interesting to find ways to augment the efficiency of this heating process such as through wastewater heat recover.

2.3 Heat Pumps

The laws of thermodynamics allow a heat pump to transport a certain amount of heat per unit of work input into the system. This performance (heat moved per energy input) is the coefficient of performance (COP) and it has a theoretical maximum defined by a reversible Carnot cycle given in Equation 3 [4].

$$COP = T_H / (T_H - T_C) \quad (3)$$

A real heat pump has a COP less than the maximal Carnot COP 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 extensively studied [8,9,10], 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 [11]. The application of heat pumps for hot water production is expanding as fossil fuels become more costly [12]. New methods of measuring seasonal efficiency of integrated hot water and space conditioning heat pumps have been developed [13]. Increasing the source temperature of heat pumps (T_C) with a high exergy source such as wastewater will increase the heat pump performance [8].

2.4 Domestic Hot 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 [14]. For an accurate look at the recovery of exergy from this system, realistic usage must be considered [15].

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 [16]. This engine was used to produce usage profiles based on statistics gathered at the US National Renewable Energies Laboratories (NREL). The data was produced from the engine based on usage profiles for showers, bathes, sinks, laundry, and dishwashers for the typical year [17]. Each usage type was generated based on statistics from survey data for profiles of a two, three, or four bedroom residence. The software generated a random set based on the statistical distributions of hot water events on a 6-minute time scale for an entire year. The output includes data for pure hot consumption or for the hot-cold mixes of bathes, showers and sinks. The temperatures of the usage are taken from [17]. The data for four bedrooms was used to model the wastewater heat recovery tank, and the entire year was compiled into one input into the models created in Matlab.

3.2 Mixed Tank Model

The simulation uses the flow of hot water over time along with its temperature from the data mentioned above. The simulation sends hot water to a recovery tank with a set diameter, volume, and wall heat transfer coefficient. The tank contains a heat exchanger having a flow rate, fixed supply temperature of 10°C, and pipe diameter, and is shaped in a spiral. The spiral width is sized relative to the tank diameter, and the spacing between turns is relative to the pipe width.

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 according to [17] and the losses during flow to the tank and losses during usage are subtracted. 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. A valve is simulated that activates if the tank fills 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 the current volume in the tank. This calculates the new temperature of the tank assuming it is completely mixed. The heat extraction by the heat exchanger is modelled as a laminar flow through a pipe with constant surface temperature equal to the tank temperature [18]. The heat extracted from the tank and the heat loss from the walls are calculated at each step 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 above the inlet temperature of the heat exchanger the tank is flushed completely and waits for the next event.

3.3 Stratified Tank Model

A second model was derived that allowed for an approximation of a tank with stratified conditions. The same setup for the input of data was used in the mixed model. In this case the wastewater volume is broken up into discrete layers within the tank. The heat exchanger is modelled using the same equations only the heat is removed separately from each layer during each time-step. Because the heat exchanger flows in from the bottom, the heat is removed there first creating a stratified state. Thus the temperature at the top stays warmer and the output temperature of the heat exchanger at the top is higher (more exergy). The conduction between each layer is included as the stratification develops, and the temperature differences are monitored such that unrealistic extreme cases can be avoided. In this case a valve is simulated that would be at the bottom of the tank and empties the bottom layers that drop below a set temperature at each time step. The tank is also emptied at its maximum fill as done in the mixed model.

3.4 Exergy and Energy Analysis

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. The reference state for the exergy comparison is 1 atm and 5°C. The optimal heat exchanger flow rate and tank size are probed, and the relative amount of heat recovered is determined

The heat pump is assumed to have a given performance providing 55°C hot water. 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 [8]. This provides a rough 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.

Finally the application of the system is considered by estimating the pumping cost and the running time of the exchanger system.

4. Results

4.1 MIxed Tank Model

The dynamic filling and emptying of the 400 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. January is highlighted in Figure 1, and is shown in Figure 2. In Figure 2 the top plot shows the total volume given in Figure 1 with better resolution, as well as the overflow volumes for the cases where the tank is filled to capacity and dumps an overflow amount, shown in black. The bottom plot is the tank temperature. The temperature decreases quickly after each fresh input to the tank, and then decreases slowly until it is emptied.

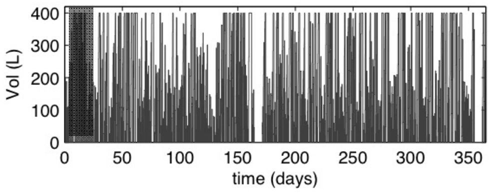

Fig 1. Volume in the recovery tank over the course of the modeled year with the month of January highlighted

A normal fill and recovery cycle appear to take about one to two hours as shown in Figure 2. The exergy recovered follows the tank temperature as expected. The maximum amounts of exergy being extracted are about an order of magnitude greater right after events than what is extracted at steps when the tank has not had a recent event.

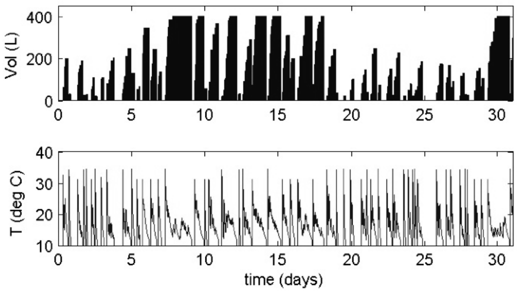

Fig 2. January data for the recovery tank total volume (grey) and overflow volume (black) on top, tank temperature in the middle, and exergy recovered on the bottom.

The heat exchanger flow rate was adjusted to optimize the total exergy recovered over the year. This exposed an optimal flow rate of 1.3 L/min was optimal as shown in Figure 3.

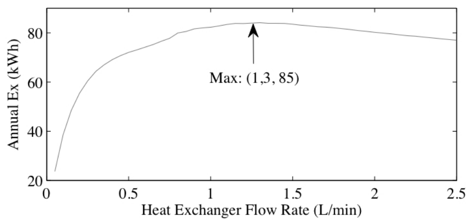

Fig 3. Total exergy recovered over the year versus the heat exchanger flow rate.

This maximum was then check across different tank volumes and it was found to be consistently within 0.1 L/min of this value. The exergy output was also observed for the different tank volume values to find the optimal tank size. This varied slightly for different time periods and models, but 400 L provided a maximal output or at least above 90% of the maximum in various simulations. Other parameters of the heat exchanger, such as pipe diameter and spacing were varied but the impact was not as significant.
At this state the model system recovers 85 kWh of exergy. The energy demand reported by [17] for this hot water usage year scenario was 4800 kWh and the tank model simulation gave a similar demand of 4400 kWh for the year. The simulation produced a total exergy consumption for the annual hot water production 350 kWh.

On an energy basis 3000 kWh are brought out with the heat exchanger, which is 68% of the demand supplied. The losses are just the energy that is flushed down the drain, and on an energy basis they can be reduced by simply increasing the flow rate and removing more of the heat before it is flushed. From an exergy perspective 85 kWh are recovered compared to the 350 kWh supplied. This is only 25% because the temperature recovered is lower than the temperature supplied, thus this is an example where exergy shows a loss in quality that would not be captured by energy analysis alone. This is what allows for the optimization in Figure 3 where the exergy has a maximum. The energy increases continuously with increasing heat exchanger flow rate because more heat is removed, but because the tank would lose its temperature faster, there is less high quality energy, and thus exergy available.

4.2 Stratified Tank Model

The stratified tank model required much more computation time, and due to small variations in the filling of the top layer, the long simulations were not always stable. Therefore the month of January was used to explore various flow rates for the optimal heat exchanger setting, instead of using an entire year. This is shown in Figure 4.

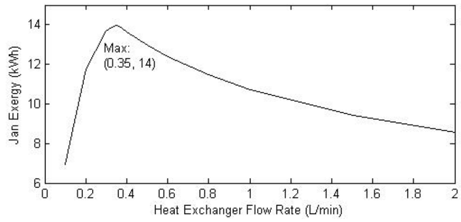

Fig 4. Exergy recovered over the month of January versus the heat exchanger flow rate

The total exergy consumption for the entire year was computed on an individual basis for this optimal flow rate of 0.35 L/min and also for 0.3 and 0.4 L/min to check that it is still a maximum for the whole year. The values for 0.3, 0.35, and 0.4 L/min were found to be 146.0, 147.4, and 147.0 kWh respectively. Thus 0.35 L/min is probably a good estimate for the maximum.
Compared to the mixed tank model this is a much lower flow rate. However, this should be expected as the stratified model allows higher temperatures to be present and remain longer in the top of the tank. The heat exchanger flow gain more exergy from the high temperature fluid at the top using a lower flow rate.
As for the quantity of energy recovered in the stratified tank, it is the same as the mixed tank at 3000 kWh hours of energy, or 68% of the hot water energy recovered. This agreement helps to verify accuracy of the independent models.
As expected, the exergy recovery is higher because a higher temperature is maintained at

the top of the tank. By routing the heat exchanger from the bottom of the tank to the top, a stratified system is setup that helps increase the quality of the energy extracted. In this case 145 kWh of exergy are recovered from the original 350 kWh, nearly double that from the mixed tank model.

4.3 Estimated Savings and Costs

A simple estimation of the increase in heat pump performance can be achieved by substituting the evaporator temperature where the heat pump receives its heat with the recovery temperature from the wastewater. For a typical ground source heat pump the incoming temperature is about 5-10°C. The average temperature coming out of the heat exchanger is 15°C with a range going up to 30°C (Figure 2).

For a typical exergetic efficiency of 0.4 [8], the COP of typical ground source heat pumps would go from 2.6-2.9 to 3.3 for the average supply of 15°C. Depending on how the dynamic heat pump system can be modulated for different inputs, the higher temperature outputs could increase the COP to close to 5.

Nevertheless, this project is focused on the heat recovery from the wastewater. The heat recovered could be used for a variety of systems. Here the focus is on the integration with a heat pump where the high quality energy in the form of exergy can be best utilized as calculated above. Still, the integration with a heat pump would influence the operating parameters, and as an integrated system the optimization could be different. The COP calculations above are rough estimates. In collaboration with the Lucerne University of Applied Sciences and Arts the heat pump analysis will be extended to include its influence on performance, and the system will be tested in an experimental setup, providing more reliable heat pump results.

The additional operating costs of the system also must be estimated. They would consist of the heat exchanger pumping costs along with any maintenance costs. In this case a rough estimate of the pumping was on the order of a few Watts. The pumping power at these flow rates is miniscule, making the cost in this case insignificant. Still, further optimization incorporating the heat pump operation may show an increase in pumping demand of the system, although this not likely to be dramatic.

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 when a mixed tank is modelled, and 145 kWh when a stratified tank is modelled. This is for 3000 kWh or 68% recovery of hot water heat, and is for flow rates of 1.3 L/min and 0.35 L/min for the mixed and stratified models respectively. A potential concept for integration of this system is presented. An estimate is made of the performance increase in the heat pump during recovery. This is shown to be on average over a 10% increase with a potential to nearly double the performance if the higher temperature heat recovery outputs can be utilized. This could significantly reduce the primary energy demand for hot water supply in low exergy buildings.

5.2 Applications

This research is part of work in the IEA (International Energy Agency) ECBCS (Energy Conservation in Buildings and Community Systems) Annex 49 (www.annex49.com). The work provides the basis for the development of new heat recovery systems that consider exergy. Collaboration is also underway with the largest sanitary systems firm in Europe, Geberit AG, They will use the theory and concept developed here to eventually produce a product for market. The goal is to have a pilot project ready to be implemented in a 4 floor, 4 apartment, building project in Zurich that will begin construction in 2009. The cost of installation of such a system will include the cost of the tank, the heat exchangers between the tank and the heat pump, and any piping required. This should not create a barrier to implementation, but the payback would have to be detailed in order to convince people to make the investment. Finally, this system is ideal for use in conjunction with grey water systems as these naturally separate out the warm wastewater sources and the large cold wastewater sources (i.e. toilets). This reduction in overall water usage combined with the reduction in energy demand make a good integrated system.

5.3 Future Work

Further analysis will include improved modelling of tank stratification dynamics as well as heat exchanger characteristics using better approximations of the system. This includes finite difference analysis for the transient temperatures between time steps and also a CFD analysis of the tank. Also, a wider range of usage profiles should used to understand how larger scale systems like multifamily and hotel systems might function. The system could be compared to a fully mixed one taking cold and hot sources, as well as to a simple analysis of the pass-through heat exchangers used to pre-heat the cold-source input of shower water. Finally, the current view of the heat pump is very simplified. The pumping costs and equipment costs for integration into the heat pump system will be considered in detail in the future. The collaboration with the Lucerne Univ. of Applied Science and Arts will lead to a more realistic evaluation of the integration with the heat pump, both analytical and experimental. This will lead to a better understanding of the real potential operation of a heat pump using the waste heat recovery scheme as described for single to multi-family residence scales.

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