Energy and exergy analysis of waste-water heat recovery in a multi-family residential complex

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Abstract. This article provides an approach to analysing the energy and exergy efficiency of a waste-water heat recovery system. The system studied is installed in a multi-family residential complex in Stockholm, Sweden. The heat recovery unit in question consists of eight coaxial, counter-flow heat-exchangers connected in parallel, with waste-water flowing through the internal pipe and cold brine (propylene glycol 25%) ducted through the external pipe. The analysis was carried out based on data collected by a building monitoring system (BMS) during five winter months (heating season). The energy analysis (using average hourly values) showed that on average 10.7 kW (Span: 1.1 - 38.7 kW) of waste-water heat was delivered to the cold brine. On the other hand, the exergy analysis (using the same data) showed that on average 12% (Span: 3 - 24%) of the exergy contained in the waste-water was delivered to the cold brine, while on average 76% (Span: 60 - 88%) was consumed during the process. Access to accurate and detailed performance measurement data was found to be essential for analysing the exergy and energy performance of the heat recovery system. In conclusion, this article demonstrates that it is vitally important to consider both the first and second laws of thermodynamics to achieve a wholesome understanding of heat recovery from waste-water systems.

1. Introduction

Highly efficient energy system planning and its optimal operation are highly required towards creating sustainable urban development. Focusing on SDGs [1], the rationalization of energy use in building has impacts to achieve the SDGs. In particular, the fields of building construction and energy system engineering are highly related to the SDG No. 9 (Industry, Innovation and Infrastructure), No.11 (Sustainable Cities and Communities), and No.12 (Responsible Consumption and Production). For buildings, the challenge is to utilize renewable potentials at on-site, and apply renewable centred energy management. Then the focus is the minimization of the heat losses and deliver the potential of local heat as much as possible.

There are some researches regarding heat recovery from waste-water. For example, Ramadan, Lemenand, and Khaled studied the experimental method and parametric analysis on the heat recovery systems and they proposed the system performance development and optimization procedure [2]. McNabola and Shields outlined the development and analysis of a horizontal drain water heat recovery system for domestic showers [3]. Ni et al. investigated the potential of energy saving by incorporating heat recovery condenser from waste-water using the heat pump in a residential building [4].

In this article, a heat recovery technology using double coiled heat exchanger was studied. This focused technology is applied to recover the heat from waste-water in buildings such as hotel, apartment buildings in Stockholm. The expectation for this technology is to increase renewable heat application at the demand side and improving thermal performance. Thus, the challenge of this study is to analyse actual performance and have a better understanding of the performance of the whole system.
1.1. Project site
The project site focused in this article is the apartment building blocks in Stockholm, Sweden. The apartment has five buildings, in which three blocks are renovated from hospital buildings and the rest of those are newly constructed. There are 422 units of flats in total and the energy centre is located in one of those buildings.

1.2. Heating system
Figure 1. shows the flow of heating system at the project site. The heating system consists of two large heat pumps (HP, capacity: 197 kW in total, COP: 1.64) to supply heat of both for space heating ($Q_{h_{hp}}$) and domestic hot water ($Q_{hw_{hp}}$) for all building blocks. The cold brine (propylene glycol 25%) is circulated within the heat source loop which connects all building blocks linearly and collect heat through heat recovery from waste-water in each building. At the end of circulation, the cold brine passes through the heat exchanger with ground heat. There are 90 boreholes (200m deep) in the centre of courtyard and heat is charged/discharged into the ground. In case the heat generation from the HPs is not enough, the district heating network supplies as the backup.

1.3. Heat recovery from waste water
The heat recovery system used in this project, consists of eight coaxial, counter-flow heat-exchangers connected in parallel, with waste-water flowing through the internal pipe and cold brine (propylene glycol 25%) ducted through the external pipe (Figure 2). Each building has this heat recovery system at the basement floor and the circulated cold brine passes through one after another. Temperature efficiencies, which were tested at the test bed system, varied between 15% and 40%.

1.4. Data accessibility and data reliability
To analyse the actual performance of heat recovery from waste-water, the measurement data at on-site is collected. In general, the on-site measurement of this project site is implemented by the building monitoring system (BMS) for operational purpose. This is the reason why the measurement points are not designed suitable for analysing the performance in post processing process. For instance, the temperature of both waste-water and cold-brine are measured to check the status of heat exchangers. However, the values of volumetric flow are not measured. In addition, to measure the accurate volumetric flow rate of waste-water is technically difficult. Thus, the methods to detect unmeasured values or missing values are highly demanded to understand the performance. Moreover, there are some limitations caused by the monitoring system errors. As a result, the available data for the analysis were prepared only five months in winter season.
2. Methodology
2.1. Modeling of Heat Exchanger
Figure 3. shows the schematic model of the heat exchanger to investigate its performance. The temperatures of cold brine \(T_{c.in}, T_{c.out}\) and those of waste water \(T_{w.in}, T_{w.out}\) are taken from the measured values. To understand the behaviour of the system, the averaged values of on hourly basis are used to clarify the general profile of the system. \(V_c\) is assumed from the recorded values of the pump output because the pump operated constant flow rate. Since \(V_w\) was not measured, the reason for which is mentioned above, the value of \(V_w\) was estimated from the energy balance equation to be described in the next section.

![Figure 3. The schematic model of the heat exchanger](image)

2.2. Energy Balance
The following equations are set according to the first law of thermodynamics that is the conservation of energy. The balance of energy input and output has to stand valid within the system. This means energy coming in through the system boundary \(E_{in}\) has to be equal to the sum of stored energy \(E_{store}\) and outgoing energy \(E_{out}\) as shown in eq (1).

\[
E_{in} = E_{store} + E_{out}
\]  

The system boundary in this study includes the heat exchanger (eight sets of pipelines) and pump. Incoming energy \((Q_{in}+E_p)\) and outgoing \(Q_{out}\) are totally balanced.

2.3. Entropy Balance
To see how the thermal dispersion takes place, the entropy balance is set up by applying the second law of thermodynamics. Entropy is the concept, which exactly quantifies the dispersion. Entropy contained by a certain matter is expressed by eq (2). Entropy flowing into the system, \(S_{in}\), and that flowing out
from the system, $S_{out}$ are given, then the steady state entropy balance can be written as eq (3). The difference between $S_{out}$ and $S_{in}$ is the entropy, $S_g$, generated is the whole of heat transfer process within the heat exchanger.

Entropy ($S$) is determined by considering reference temperature $T_{ref}$ [K]. In this study, the outdoor temperature ($T_o$ [K]) is applied.

$$S = C \rho V \ln \frac{T}{T_{ref}}$$

(2)

where $C$ is the heat capacity of fluid object [kJ/kgK], $\rho$ is the density of the object [kg/m$^3$], and $V$ is the volume [m$^3$].

$$S_{in} + S_g = S_{out}$$

(3)

Note that $S_g$ is necessarily greater than zero; in other words, there is no spontaneous phenomena, in which entropy is decreased.

2.4. Exergy Balance

The exergy analysis requires the following calculation process. First, the energy balance incoming energy ($E_{in}$) and out-going ($E_{out}$). In the case of this project, delivered heat energy from wastewater to the cold brine, and it is assumed that no energy is stored ($E_{store}$) in the study boundary.

Combining the energy balance equation, eq. (1), and entropy balance equation, eq. (3), together with the environmental temperature brings about eq. (4) as exergy balance equation. This equation describes a portion of the input exergy ($X_{in}$) is consumed at the rate of $X_c$ ($= S_g T_o$) through the process and thereby the exergy output $X_{out}$ is generated as the purpose of the system.

$$X_{in} - X_c = X_{out}$$

(4)

$X_{in}$ and $X_{out}$ are calculated from

$$X_{in} = C \rho V \left\{ (T_{in} - T_o) - T_o \ln \frac{T_{in}}{T_o} \right\}$$

(5)

$$X_{out} = C \rho V \left\{ (T_{out} - T_o) - T_o \ln \frac{T_{out}}{T_o} \right\}$$

(6)

3. Results

3.1. Energy balance at the heat exchanger

Figure 4. shows the trend of energy from wastewater ($Q_{out}$) and electricity input to the pump ($E_p$). The result of the heat exchanger were applied in the study. Since the flow rate of wastewater ($V_w$) is not measured, the delivered energy was estimated with the temperatures of cold brine ($T_c$), wastewater ($T_w$) and the flow rate of cold brine water ($V_c$). The amount of generated wastewater and its flow rate affect the deliverable energy. The result showed that energy delivery overnight was high through the day. The flow rate of wastewater decreased because of low activity and it resulted that there was enough time to transfer the heat to the cold brine. Consequently, there is a tradeoff relationship between the amount of generated wastewater and delivered heat energy, making moderated wastewater generation a key focus.
of the next coming study. Energy study clarified that 10.7kW (on average, 1.1 - 38.7kW) of heat from wastewater was delivered to the cold brine side.

![Energy flow graph](image)

**Figure 4.** The variation of energy input and output through the heat exchanger

### 3.2. Exergy balance at the heat exchanger

Figure 5. shows the exergy balance of the heat exchangers in one building of the project site. The positive side of the Y-axis indicates the incoming exergy into the system, and the negative side indicates the amount of outgoing exergy and consumed exergy although all of exergy values never become negative; “negative” signs are used for presenting all values together on one single graph.

![Exergy balance graph](image)

**Figure 5.** Exergy balance

The exergy of incoming cold brine water \(X_{c.in}\) (light blue) increased after exchanging heat \(X_{c.out}\) (dark blue). The exergy of incoming wastewater \(X_{w.in}\) (dark orange) decreased \(X_{w.out}\) (light orange) because some parts were delivered to the cold brine and other parts were consumed \(X_{cons}\) (green). The exergy input \(E_p\) (grey) and consumption \(X_{cons.ep}\) (light green) at the pump were included in this balance. In both cases, the wastewater overnight has more exergy than at other times. The exergy analysis brought the understanding of actual system performance and practical knowledge when applying values from BMS. Exergy analysis clarified that 12% (on average, 3–24%) of exergy contained in the wastewater was delivered to the cold brine and 76% (on average, 60–88%) was consumed during the process.
4. Conclusion

In conclusion, this article demonstrates that it is vitally important to consider both the first and second laws of thermodynamics to achieve the comprehensive understanding of heat recovery from waste-water systems. Conventional energy analyses clarify the flow rate of wastewater which passes through the heat exchanger is the influential factor. But even when large amounts of wastewater are generated, the high flow rate doesn’t necessarily realize the heat transfer from wastewater side to the cold brine side being always efficient. This tradeoff relationship can be the next research question to maximize heat gain from wastewater. The exergy analysis clarified that 12% (in average, 3 - 24%) of exergy contained in the wastewater was delivered to the cold brine. 76% (in average, 60 - 88%) was consumed during the process. We concluded there are two ways to increase the exergy efficiency. The flow rate of wastewater is one of the focuses as mentioned above. Another focus can be the electricity input at the pump which is dominant at exergy consumption. Thus, optimizing the scale of wastewater heat recovery application is needed as further study. The possible strategies can be, for example, to reduce the capacity of the pump by optimizing the flow rate of the cold brine or optimizing the scale of heat collection and supply. In the case of the project site, the length of the cold brine pipe network is too long. Since the development of the heat exchanger technology based on the energy concept is almost matured, the next coming challenge is the way of designing the heat system which manage collected heat optimally on the basis of exergy concept.

References

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