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13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use

Contribution to Exemplary In-House Wastewater Heat Recovery in Berlin, Germany

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Abstract

Thermal energy recovery from wastewater can be established from centralized wastewater treatment plants and sewage systems. Little attention has been given to In-house wastewater; although it can potentially pave way towards a sustainable heat source. The study was conducted inside student hostels in Berlin, in which water supply, wastewater, and room temperatures variations were observed during winter for one month. It was shown that water supply temperature has insignificant effect on the variations of in-house wastewater temperature as compared to room temperature and water use. The daily average temperature of the in-house wastewater was in a range of 11 °C to 20 °C, with an average of about 15 °C. It was illustrated that by selecting suitable combination of heat exchanger and heat pump, about 40 kWh/h (917 kWh/day) average in-house wastewater thermal heat can be recovered and about 230 €/day saved . This can contribute to reduction of energy needed for hot water provision by about 30% in the targeted hostels.

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Keywords: energy recovery; flow; heat exchager; in-house wastewater; tempreture

1. Introduction

Environmental protection and sustainable management of natural resources stand at the forefront of economic and technological activities worldwide. Current sewage technologies when not focused on resources, nutrient and energy recovery, may not be sustainable[1]. Energy recovered from wastewater is being recognized as a renewable energy resource[2].

Nomenclature

COP	coefficient of performance
Q_F	thermal power (kW)
ΔT_m	temperature drop (K or °C)
c_w	specific heat capacity as 4.186 (kJ/kg K)
ρ_w	density (as 1 kg/l)
V_f	flow rate (l/s)
A_s	heat exchange area (m^2)
L	required external work (kW)
k	heat transfer coefficient (W/m^2 K)

2. In-house wastewater

2.1. Energy carrier

The interrelationship between energy, water and organic content of wastewater can encourage energy recovery operations from many possible sources, including municipal wastewater treatment facilities. The potentials to extract energy from wastewater can be done in a number of ways, including: biomass energy obtained from the biogas produced after anaerobic sludge digestion[3], kinetic energy using micro-hydro systems, chemical energy through sludge incineration, and thermal energy as heat[4] which is related to heated wastewater leaving the houses[5,6]. Therefore, Domestic wastewater is a finite source of thermal energy[7,8,9]and has a true potential of thermal energy recovery from wastewater[4]. The sewer system in Bologna (Italy) investigated the possibility to use sewer water as alternative source of heat[10].

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2.2. Temperature, energy losses and water use

The temperature of tap water can be influenced by soil temperature surrounding the drinking water distribution system, pipe material, pipe diameter and flow velocity[11]. Inside the buildings, water is heated for many purposes and resulting warm wastewater flows into the sewer[12]. This wastewater is characterized by higher temperature than tap water, since 60% of water is heated[10,13].

On account of the ideal source, domestic wastewater temperature ranges from 10°C to 25°C in different seasons of the year[8], resembling a theoretical maximum potential of 56,000 Ton Joule per year (TJ/yr). The actual maximum potential of heat recovery systems in houses is estimated to be 32,000 TJ/yr[9].

On the other hand, estimates by the U.S. Department of Energy (DOE) indicated that the equivalent of 235 billion kWh i.e. 846,000 TJ/yr worth of hot water is discarded annually through wastewater, although large portion of this energy is in fact recoverable[14]. Discharging hot water into sewer system makes domestic wastewater as a carrier of heat[9]. Moreover, looking at heat losses from modern houses, wastewater contributes about 15% - 30% [8], or even 40% of this loss[5,6]. So, a large potential in the amount of heat losses from wastewater leaving buildings[15], need more focus to be recovered and used.

The energy consumption for heating, cooling and domestic hot water supply requires much more energy in residential buildings[16] in countries like Germany[17]. There are a number of uses of hot water in buildings, including showers, tubs, sinks, dishwashers, clothes washers etc. The amount of energy depends on water use inside houses. It was shown that the amount of water use increases in countries with strong economic growth and a high standard of living[8] leading to increase energy demands and to search for sustainable sources, e.g. energy recovery from wastewater.

From another point of view, fossil fuels are usually used for fulfilment of hot water demands[10], which has clear carbon footprint and causes greenhouse gas emission. Although the water sector has only a very small contribution to greenhouse gas emissions compared to other sectors like energy production or mobility. The energy use in water sector needs to be optimize to reduce the carbon footprint of the water sector, and eventually limiting greenhouse gas emissions[5,6,9,18,17]. Optimizing energy use can be through making essential improvements for orientation of future energy demands and quality standards[9]; and innovative technologies that include renewable energy[19].

Energy has a great role in water use. On average, the energy needed for heating water is eight times higher than energy needed for producing, treating and transporting water[9]. Other estimates indicated that such purposes reaches ten times more. Therefore, reducing hot water use and application of heat recovery from wastewater can have a large contribution for further optimization of energy demands [12].

2.3. Energy recovery options

Thermal energy can be recovered from raw wastewater[5,6], or effluent by exploiting temperature differences between wastewater and ambient conditions. This temperature differences can be recovered for use in heating and cooling purposes[2]. The heat available in raw and effluent wastewater is described as low-grade heat, which can be recovered through the application of heat pump technology[15].

Heat pump technology uses a reverse refrigeration cycle to factor low temperatures to useable heating levels[20]. The heat pump technology is simple and proven. Over 500 wastewater heat pumps are in operation worldwide[8]. The first heat pump was built more than 20 years ago. A heat pump system using wastewater as heat source allows for usage of low-cost off-peak electricity with neither noise nor spoil the appearance of the building where it is installed. In addition, it has outstanding energy saving effect since it is operated at high coefficient of performance (COP) without air pollution[21].

Heat exchange technology is another option to recover the heat energy. A heat exchanger is a heat transfer device that is used for transfer of internal thermal energy between two or more fluids available at different temperatures. In most heat exchangers, the fluids are separated by a heat transfer surface without mixing or crossing over[22]. Heat transfer occurs between two fluids of different starting temperatures, such as wastewater and refrigerant. Typically used heat exchangers include pumped heat exchangers, in-tank heat exchangers, and in-pipe or in-trench heat exchangers[20]. On particular, most of the liquid–liquid heat exchangers are shell, tube, and plate type. Both fluids are pumped through the exchanger, so the principal mode of heat transfer is forced convection[22].

The heat exchanger can be used to recover the thermal energy from the wastewater [14]. The heat exchanger can be installed in the sewer system[5], or in the effluent of WWTP[7]. For thermal energy from wastewater, it is estimated that about 50% may be recovered by use of heat exchangers in sewers[5,6].

A combination between heat pump and heat exchanger is other option for the thermal heat recovery[7]. The challenge for coming years is to choose combinations of all possibilities to fulfil the energy demand[6].

3. Scope of work

Generally more heat can be recovered from the wastewater in the sewer than from the wastewater treatment plant (WWTP) effluent. Furthermore, in the sewer, the heat usually is recovered at a location where is close to the consumers[7] However, in practice, the use of wastewater as a source for heating systems is not often considered. The value of higher temperature recovery has not been exploited, and is available only close to the point of use[15]. Therefore, the main scope of this work is to investigate the potentials of wastewater heat recovery inside a house in Berlin, Germany or any other countries of similar climatic conditions.

The amount of thermal energy that can be obtained from wastewater and optimal design of heat recovery systems depend on knowledge of the flow rate and wastewater temperatures[13]. Through this research study, the temperature of in-house wastewater effluent pipeline, drinking water supply, room temperature, and water supply flow rate were observed. The temperature and flow rate were measured for a period of one month starting from Jan. 9th, 2015 till Feb. 8th, 2015. Students' hostel owned by Bürgermeister-Reuter-Stiftung "house of nation" was selected to perform the research study. The hostel is located in Triftstr. 67, 13353 Berlin, Germany. The hostel "Ernst-Reuter-Haus-Altbau" contains 330 rooms, café-restaurant, and a kindergarten. A boiler of 6 m^3 capacity is used to heat the water up to 60°C before pumping into the hot water network. From time to time, the hot water is heated up to 70°C for hygienisation purposes and harmful pathogens removal.

In general, the proportions of daily generated wastewater vary between the night minimum during summer and the day maximum during winter by a factor of up to ten. Consequently, when planning and designing wastewater energy recovery, it is very important to have careful measurements related to water use inside houses[8], besides the two liquids temperatures i.e. water supply and wastewater effluent.

The temperature and flow rate measuring devices were selected in order to provide robust and consistent readings. The main selection criteria of measuring devices were: the ability to record readings in short time; the ability to store recorded data for long period; the flexibility during installation; the high accuracy; and the low costs. The selected devices were connected with data loggers to store recorded readings for the monitoring period.

For temperature measurements, thermometers used were "VOLTCRAFT DL-111K USB-Temperatur-Datenlogger, Messschreiber mit KTyp-Fühler". These thermometers can record a reading every 2 minutes for 44.4 days, i.e. about 32,000 readings can be taken and stored into the data logger.

In this study, temperature measurements were taken every two minutes for the whole study period of 1 month. Three thermometers were used, the first was installed and fixed on the outside bottom of 50 cm diameter sewage pipeline, as shown in figure 1 (a). The second one was fixed on the outside bottom of 3.81 cm diameter water supply, as shown in figure 1 (b). The third thermometer was installed in the basement where the water supply and wastewater effluent pipelines are located. This third thermometer was used to measure the ambient room temperature.

For water consumption measurements, the used flow meters were "FAST EnergyCam data logger". This flow meter can take a reading every 2 minutes for 13.8 days, i.e. about 10,000 readings can be taken and stored into the data logger.

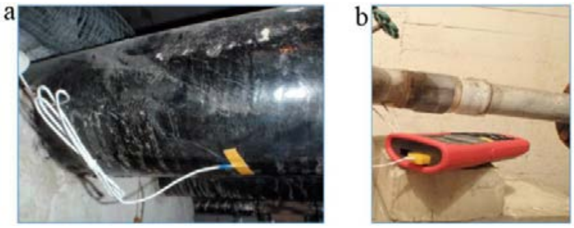

Fig. 1. (a) thermometer fixed on wastewater pipeline; (b) thermometer fixed on the drinking water supply pipelines.

In this study, all temperatures and flow measurements were taken every 2 minutes during the monitoring period. Inside the targeted house, the main water supply pipe was divided into two pipes as shown in figure 2 (a). Two flow meters "Fast EnergyCam" were installed on top of the existent two water meters as shown in figure 2 (b). The existent flow meters were used by the house owners to measure the accumulated water consumption.

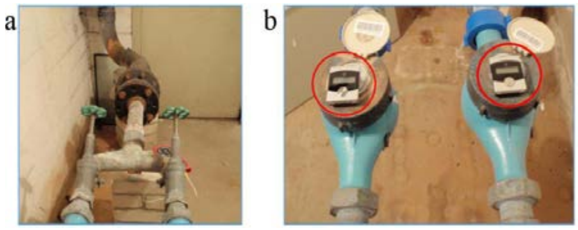

Fig. 2. (a) drinking water supply pipelines; (b) flow meters fixed on the drinking water supply pipelines.

4. Data analysis

All devices were calibrated and tested based on the provided manuals of the devices before their usage. After installation of the thermometers and flow meters, a period of 7 days from Dec. 4^{th} 2014 till Dec. 11^{th} ,was set as testing period (testing readings are not shown) before starting the real measurements.

The main water supply was divided into two pipelines. Consequently, the records of flow rates from the two water pipelines were summed up in order to obtain the total water flow rate.

The temperatures variations of the observed parameters: water supply temperature, wastewater temperature, room temperature and water flow rate were analysed. The recorded measurements every 2 min, were averaged with a time step of one hour. The flow rate and temperature variations were shown in figure 3

The box-plots and histogram were used to manipulate the recorded data in each hour of the day. In statistics, box-plot and histograms are convenient graphical demonstration for generating a conclusion among the gained quantitative data. In the box-plot and through quartiles, bottom and top of the box are the differences in first and third quartiles respectively. The top end of the whiskers represents the difference between maximum values and upper quartile, while the lower end represents the differences between lower quartile and minimum values.

The water supply temperatures had insignificant variations in whole measurement period. The average temperature of water supply was 11.24 °C with the standard deviation of 0.17. The minimum temperature was 10.50 °C, while the maximum temperature was 11.80 °C. The wastewater temperature varied between 10.60 °C as minimum and 19.80 °C as maximum. The average temperature was 14.68 °C with the standard deviation of 0.55.

The ambient room temperature was in the range of 12.30 °C and 16.10 °C as minimum and maximum respectively. Average temperature was 14.36 °C with standard deviation of 0.65.

The flow rate of drinking water indicates water consumption, which finally generates wastewater flow, since measuring wastewater flow is so difficult inside the house.

The average hourly water flow rate was 5.16 m^3/h with a standard deviation of 0.30. The daily consumption of water supply falls in the range of 112 m^3 and 145 m^3. Therefore daily average consumption of water was 128.22 m^3 for both cold and hot water.

5. Results and discussions

For the purpose of examining the potentials of in-house thermal energy recovery, it is important to identify the main factors that might affect the wastewater temperature behaviour.

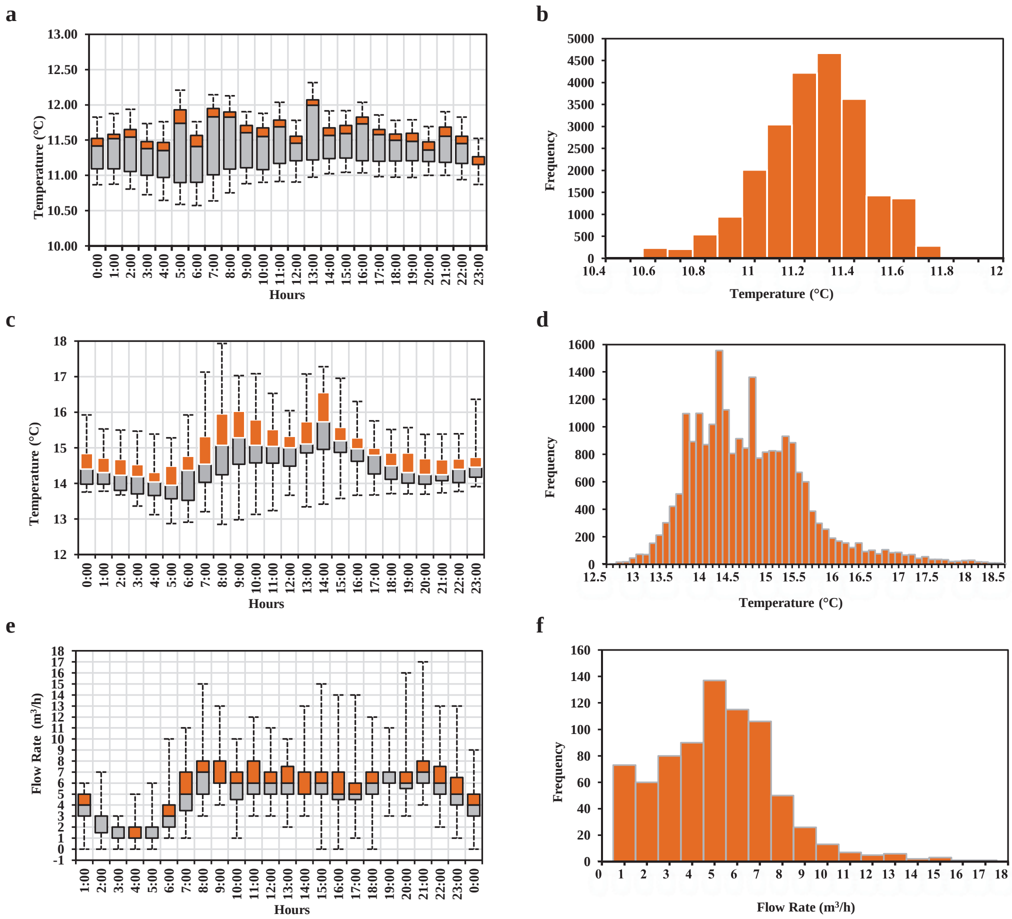

Fig. 3. (a), (b) box-plot and histogram of frequency of water supply temperature respectively. (c), (d) box-plot and histogram of frequency of wastewater temperature respectively. (e), (f) box-plot and histogram of frequency of flow rate respectively.

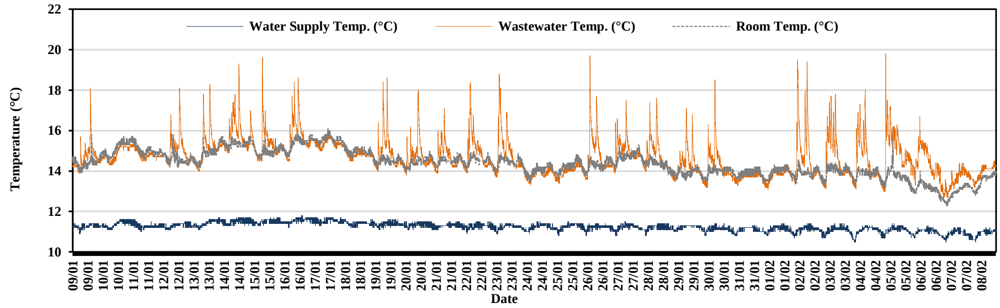

Fig. 4. trend of water supply temperature, wastewater temperature, and ambient room temperature every 2 minutes

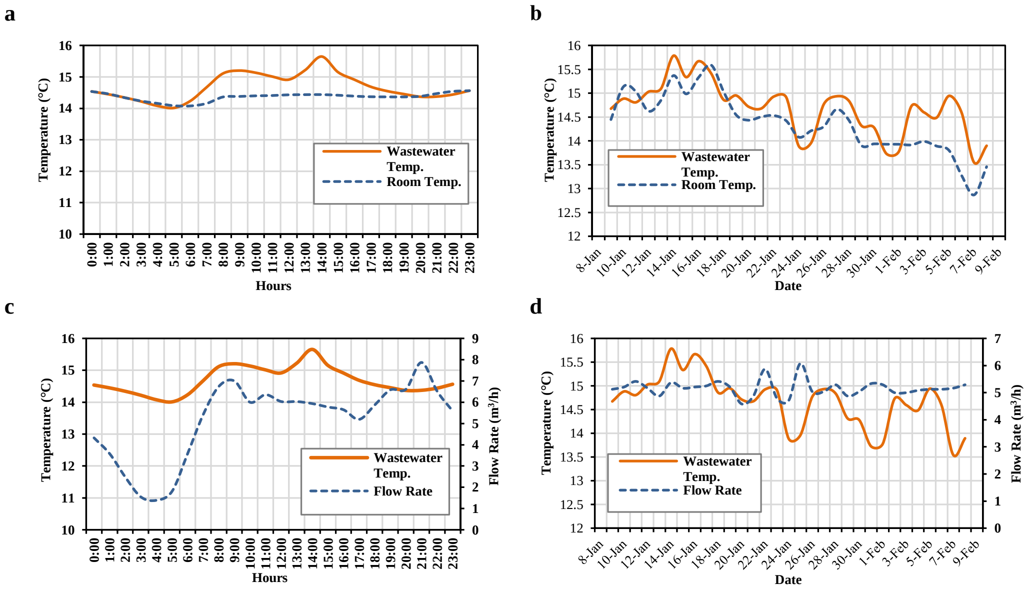

Fig. 5 data analysis comparisons (a) hourly average & (b) daily average for wastewater and ambient room temperature respectively. (c) hourly average & (d) daily average for wastewater temperature respectively

Figure 4 represents the time series of 2 min in the observation period for water supply temperature, wastewater temperature, and room temperature. It is evident that the temperature variations of the in-house wastewater are not affected by the temperatures of drinking water supply.

For better understanding the behaviour of wastewater temperature, the wastewater temperatures were compared with room ambient temperature and water flow rate. The comparisons were arranged on daily average basis and hourly average basis as shown in figure 5. The wastewater temperature fluctuate in a range of 0.5 -1.5◦C. Based on the hourly average, it was evident that the wastewater temperature variations were significantly affected by the ambient room temperature and to some extent affected by water flow. The daily average data showed that the room temperature is the most significant factor affecting the wastewater temperature.

From another point of view, the obtained and analysed data can be considered as the input data required for designing in-house wastewater heat recovery system. Thermal power transferred from the wastewater Q_F through heat exchanger to heat transfer fluid is determined by heat balance equation[10]

$$Q_F = \Delta T_m \, . c_w \, . \rho_w \, . V_f$$

Based on the obtained measurements, the wastewater flow rate was analysed to be 1.23 *l/s*. The water enters the heat exchanger at a temperature of 14.68 ◦C and will come out at a temperature of 9 ◦C. The average acquired thermal power from wastewater is about 30.21 kWh/h, (about 676.81 kWh/day), assuming that a shell heat exchanger was used. The heat exchange surface was estimated by:

$$Q_F = k \, . \, A_s \, . \, \Delta T_m$$

Taking into account wastewater heat transfer coefficient as 850 W/m^2 K [23]. The obtained heat exchanger area equals to

6.1 m^2. For safety, exchanger area will be increased by 50% to consider the efficiency reduction due to biofilm formation. Therefore, the area becomes 9.15 m^2. If the length of the pipe is 3 m and pipe diameter is 20 mm, about 48 pipes are required inside the shell and tube heat exchanger.

Considering COP =4 as recommended[10], the power transferred from the heat pump for heating and producing hot water equals the sum of power acquired from heat transfer fluid and external work supplied to the heat pump by electricity, which is estimated as 10 kWh/h. The recovered thermal power in-house wastewater will reach 40.21 kWh/h (916.81 kWh/day). Considering the kWh cost as 0.25 € in Berlin, the cost of recovered thermal power could be about 10 €/h, which equals to 230 €/day.

Observed records of hot water consumption were analyzed to be about 46% of the water supply. Hot water boils up to 60 ◦ C, which needs about 138.07 kWh/h (about 3136.54 kWh/day). Therefore, the in-house wastewater energy recovery can contribute significantly to a reduction of hot water provision up to 30% by suitably adopting the heat exchanger and heat pump in a combined system.

6. Conclusion

The study has analyzed the temperatures variations of wastewater, drinking water supply at ambient room, and cold water and hot water flow rates on daily basis for a period of 1 month in winter season in Berlin.

In particular, it has been illustrated that wastewater temperature varied significantly based on the room temperature, and water use rather than water supply temperature. It has also been shown that wastewater temperatures have high values in day hours as compared to late night hours and early morning hours.

The in house wastewater energy approved to be a valuable source of energy that can be recovered as it can contribute to about 30% of thermal energy needed for hot water provision.

The in-house wastewater heat recovery has fewer concerns, therefore, further research is needed and it is recommended to observe the variation of wastewater temperature in different seasons of the year. In addition to optimize the best combination between the heat exchanger and heat pumps for sustainable in-house wastewater heat recovery.

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