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ANALYSIS OF HEAT RECOVERY FROM WASTEWATER USING A HEAT PUMP ON THE EXAMPLE OF A WASTEWATER TREATMENT PLANT IN THE ŚWIĘTOKRZYSKIE VOIVODESHIP IN POLISH

ANALIZA ODZYSKU CIEPŁA ZE ŚCIEKÓW PRZY WYKORZYSTANIU POMPY CIEPŁA NA PRZYKŁADZIE OCZYSZCZALNI ŚCIEKÓW WOJEWÓDZTWA ŚWIĘTOKRZYSKIEGO

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Abstract

Currently, sources from which renewable energy could be generated are being sought worldwide. One of these sources could be wastewater. This article shows how heat can be recovered from wastewater, using a small wastewater treatment plant in Świętokrzyskie voivodeship as an example. It analyses the temperature of wastewater in the reactor, in the sewage system and the ambient temperature for each month. The principle of heat pump operation was presented. Then, the amount of heat energy that can be recovered from wastewater was calculated for each month.

Keywords: heat pumps, heat recovery, waste water as a source of heat pump supply

Streszczenie

Obecnie na całym świecie poszukuje się źródeł, z których można by wytworzyć energię odnawialną. Jednym z takich czynników mogą być ścieki. W niniejszym artykule przedstawiono, jak można odzyskać ciepło ze ścieków na przykładzie niewielkiej oczyszczalni pracującej na terenie województwa świętokrzyskiego. Dokonano analizy temperatury ścieków znajdujących się w reaktorze, w kanalizacji oraz temperatury otoczenia dla każdego miesiąca. Przedstawiono zasadę działania pomp ciepła. Następnie policzono ilość energii cieplnej, jaka może być odzyskana ze ścieków dla każdego miesiąca.

Słowa kluczowe: pompy ciepła, odzysk ciepła, ścieki jako źródło zasilania pomp ciepła

1. INTRODUCTION

Energy is becoming more expansive and the burning of fossil fuels is accelerating global warming. Increased use of renewable energy is the best solution to conserve fossil energy sources, reduce or avoid carbon emissions and slow climate change. Recovering heat from wastewater for heating buildings is possible and has become cost-effective. Wastewater has significant heat energy potential. The temperature of wastewater varies between 7°C and 28°C throughout the year [1]. Even in winter, its temperature does not fall, or at most for a few days, below 7°C. For this reason, wastewater is an excellent heat source for the efficient and economical operation of heat pumps. The recovery and use of this heat is cost-effective for heating large buildings and

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complexes. The recovered heat can also be fed into existing or planned district heating networks [2].

Heat can be recovered in sewage treatment plants. This is technically relatively simple, but wastewater treatment plants are often located far from buildings that could be heated with the recovered heat. Heat recovery from treated wastewater is the best solution where the treatment plant itself needs a lot of heat, e.g. for sludge drying. Recovered heat can also be supplied from the wastewater treatment plant to large nearby heat consumers such as construction sites, business parks or factories [2].

Alternatively, heat can be recovered from sewers and used to heat buildings in their vicinity. In this case, it is important to investigate the impact that wastewater cooling can have on the operation of wastewater treatment plants. Since the technological efficiency of heat pumps depends on the temperature of the heat source, wastewater is one of the most ideal heat sources to power heat pumps [2]. The use of wastewater as an energy source is not a completely new idea, and it is also very environmentally friendly and economical [3].

2. WORKING PRINCIPLE OF HEAT PUMPS

A heat pump is an appliance which extracts heat from the ground, air, water or another heat source with the aid of a small amount of electrical energy and transfers it to heat exchangers [4]. The transport of heat energy takes place in an evaporator and a condenser. The whole process of energy transfer is made possible by thermodynamic transformations (Linde cycle) occurring in a closed circuit [5].

Traditional heat sources such as gas, oil or solid fuel boilers generate heat by burning fuel. The efficiency of such an installation is mainly affected by the calorific value of the fuel used. The efficiency of such boilers varies between 70-110% [5]. Heat pumps are devices that transfer energy from one source to another instead of producing it, thanks to which their efficiency can be as high as 500% [5].

Heat pump components:

- compressor – is used to compress the working medium circulating in the pump circuit. The compression of the vapour causes an increase in pressure and temperature. The compressor is the most energy-intensive component in the system;
- evaporator – is a heat exchanger in which the process of absorbing heat from the environment takes place;
- condenser – is a heat exchanger in which the process of condensation of the working fluid takes place. The change of state of aggregation from vapour to liquid results in an increase in volume, which simultaneously increases the temperature. Thanks to this process in the condenser we obtain high temperature, which can be further transferred to the installation.

Expansion valve – serves to expand the working medium in the heat pump circuit from liquid to steam. Its two most essential functions are throttling of the working medium so that the compressor can reach the required working pressure in the condenser, and expansion when the thermodynamic cycle is required to be repeated [5].

Figure 1 shows a simplified schematic of an effluent heat pump installation.

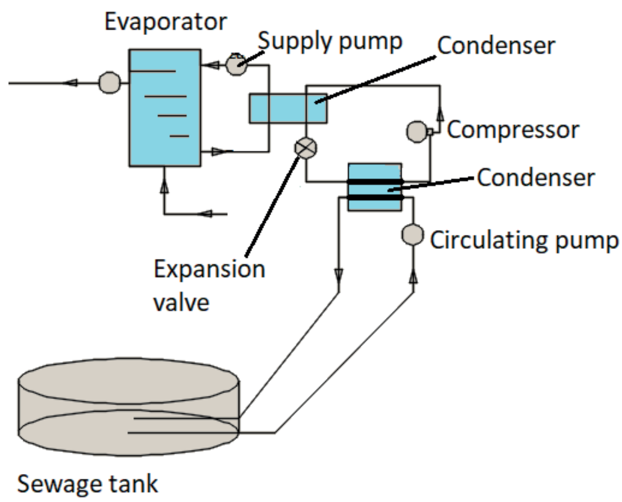

Fig. 1. Schematic of the operation of a heat pump fed with wastewater (own study)

The COP (coefficient of performance) is the basic performance parameter of a heat pump. It defines the ratio of the amount of heat delivered to the amount of energy (usually electrical) consumed during a given operating point. The higher the coefficient, the cheaper the pump is to operate as it uses less energy to produce the same amount of heat. The COP is calculated based on the EN 255-3 standard. The higher the COP value, the higher the heat pump efficiency [5, 6].

3. CASE STUDY

Typically, modelling heat recovery from wastewater presents several difficulties. Firstly, appropriate input data has to be generated or obtained based on the highly variable wastewater temperature statistics [7]. Since wastewater heat is

Table 1. External temperature values for location of wastewater treatment plant X [°C] [8]

	January	Fabruary	March	April	May	June	July	August	September	October	November	December
Avarge Temperature (°C)	– 5.8	– 4.3	1.8	8	12.5	15.5	17.3	16.7	13.1	8.8	2.8	– 2.5
Min. Temperature (°C)	– 8.8	– 7.5	– 2	3.1	7.2	10.3	12.1	11.5	8.3	4.5	0	– 5
Max. Temperature (°C)	– 2.8	– 1.1	5.7	13	17.8	20.7	22.5	21.9	18	13.1	5.7	0.1

almost never taken into account, there are very few statistics available for wastewater temperature data. In order to implement wastewater temperature data, the sewage system at wastewater treatment plant X operating in the Świętokrzyskie Province was analysed and monitored.

At the site of the analysed facility in 2020, the average annual ambient air temperature was 7°C. Temperature values for the location are presented in Table 1.

As an example, wastewater treatment plant X operating in a mechanical-biological system, located in the Świętokrzyskie voivodeship, was taken for calculation. The plant operates with a sequencing batch reactor (SBR) system. The facility serves 890 inhabitants. Wastewater temperature was measured in the sewerage system supplying wastewater to the plant, and inside the SBR reactor, in which wastewater was subjected to biological treatment processes using the activated sludge method. Measurements were taken periodically at the beginning of each month of 2020. The result sarepre sented in Figure 2.

As can be seen, the effluent temperature correlates strongly with the outdoor temperature, but is significantly higher for the coldest months. It ranges from 7.5°C to 18.4°C for the temperature in the reactor. It can therefore be seen that when the outside temperature is high, the effluent maintains a similar value, while at minus temperatures the effluent remains positive and oscillates between 7°C and 8°C.

Figure 2 shows a graphical plot of wastewater temperatures in the sewer and in the reactor during the different periods of the study.

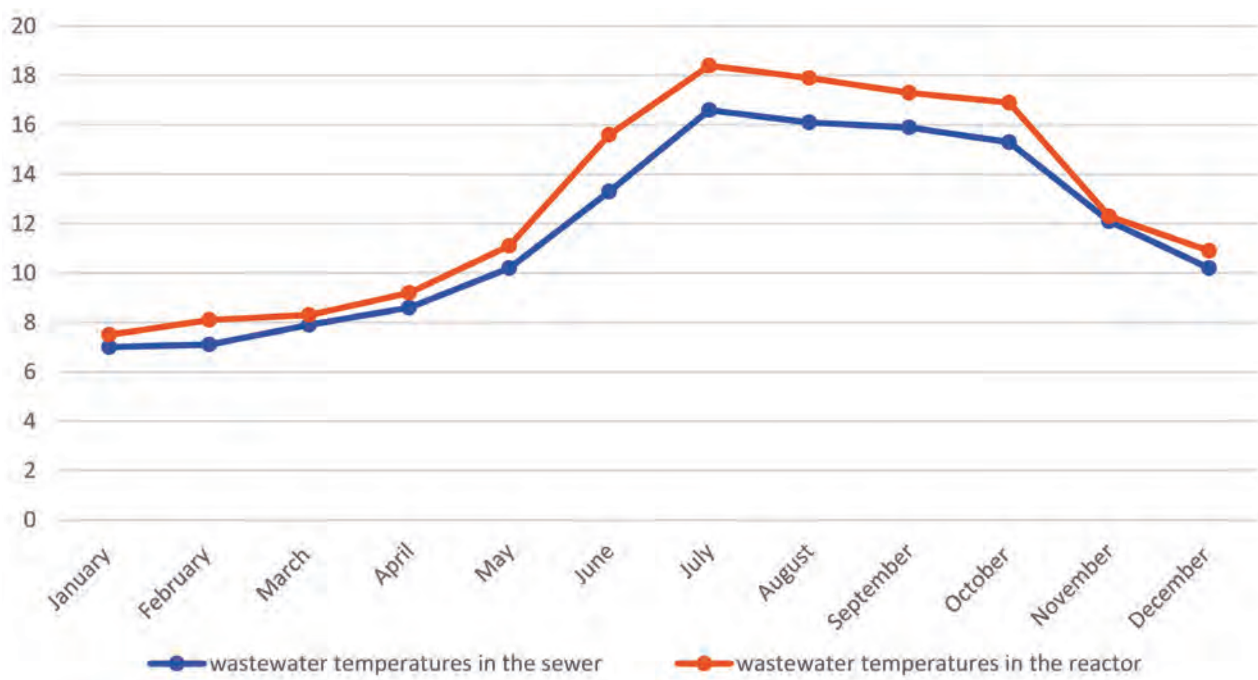

Fig. 2. Graph of wastewater temperature values at treatment plant X

environment

4. CALCULATION OF HEAT OUTPUT FROM WASTE WATER

This paragraph presents an example of the calculation of the extracted heat power from wastewater for the temperature data analysed. The input data come from a statistical analysis carried out for wastewater treatment plant X in the Świętokrzyskie region. The principle of operation is as follows: a waste water heat exchanger extracts heat from municipal waste water filtered through a block filtration unit (to reduce corrosion and extend the life of the waste water heat exchanger) and sends it to the evaporator side of a heat pump as a low grade heat source. The compressor side of the heat pump system extracts heat from the condenser side and sends it to the heat supply system [9]. The design of the system starts with setting the inlet (*Tc*) and outlet (*Tz*) temperatures and the effluent flow rate [6].

The determination of the heat output extracted from the grey sewage flow rate, can be determined by the following formula [6]:

$$Q_F = q_{h\acute{s}r} \cdot c_{\acute{s}\acute{c}} \cdot \rho_{\acute{s}\acute{c}} \cdot (Tc - Tz) \tag{1}$$

where:

$q_{h\acute{s}r}$ – average flow of grey sewage assumed 8000 dm^3/h,
$c_{\acute{s}\acute{c}}$ – specific heat of grey sewage: assumed 4.186 kJ/(kg·K);
$\rho_{\acute{s}\acute{c}}$ – density of grey sewage, assumed 1.15 kg/dm^3;
Tc – temperature at inlet, °C;
Tz – outlet temperature, °C.

Table 2. Obtained thermal power from wastewater for individual months

Month	*T* [°C]	*T* [K]	*ΔT* [K]	Q_F [KW]
January	7.5	280.5	1.5	16.05
Fabruary	8.1	281.1	2.1	22.47
March	8.3	281.3	2.3	24.61
April	9.2	282.2	3.2	34.23
May	11.1	284.1	5.1	54.56
June	15.6	288.6	9.6	102.70
July	18.4	291.4	12.4	132.66
August	17.9	290.9	11.9	127.31
September	17.3	290.3	11.3	120.89
October	16.9	289.9	10.9	116.61
November	12.3	285.3	6.3	67.40
December	10.9	283.9	4.9	52.42

The above formula shows that to increase the available power, the flow rate or the temperature difference must be increased. In this example, the available wastewater flow rate was assumed to be about 8000 dm^3/h, (average flow rate generated by about 1000 inhabitants) [10]. It was also assumed that the wastewater will cool to a temperature of 6°C. It is therefore possible to recalculate the heat output for different variants of effluent temperature depending on the season, as shown in Table 2.

The wastewater heat output ranged from 16.05 kW for January to 132.66 kW for July. Retrofitting the wastewater treatment plant with a heat pump reduces maintenance and operating costs, with the least possible impact on the environment.

5. HEAT PUMP EFFICIENCY

To evaluate the performance of a heat pump, the *COP* (coefficient of performance) was introduced. It describes the ratio of the heating power to the electrical power input required for the pump operation and is expressed by the formula [11];

$$COP = \frac{Q_F}{Q_E}[-] \tag{2}$$

where:

Q_F – heating capacity of the heat pump, kW;
Q_E – electrical power needed to drive the compressor, kW.

The efficiency coefficient of a heat pump can also be calculated using the reverse Carnot cycle [11]:

$$COP = \frac{Tg}{Tg - Td} = \frac{Tg}{\Delta T} \tag{3}$$

where:

Td – temperature of the lower heat source, K;
Tg – temperature of the upper source (heating system) K;
ΔT – temperature difference between the upper source temperature and the lower source temperature, K.

A *COP* = 5 therefore means that the pump gives back as heat five times the electrical energy that was supplied to the pump. The lower the temperature difference between the heating water and the lower heat source, the higher the *COP* and the efficiency of the heat pump [4]. Depending on the heat source, modern heat pumps achieve an efficiency ratio of between 3.5 and 5.5 [3]. This means that for every kilowatt hour of electricity consumed, 3.5 to 5.5 kWh of heating heat will be generated.

So a heat pump using 1000 watts of electrical power to absorb 4000 watts of heat from the external environment, and then adding 1000 watts of heat to that total, for a total of 5000 watts of heat transferred to the building, with only 1000 watts of electrical power actually being used by the heat pump to facilitate this transfer. The *COP* in this example will be 5:1, or 5, meaning, for every 1000 watts of electrical input power supplied to the heat pump, the heat pump transfers 5000 watts of heat output power to the house, or 5:1 – output power divided by input power. This is the ideal *COP* value that can be obtained using heat pumps calculated from the $Tg/(Tg - Td)$ equation.

6. OTHER METHODS BASED ON MEASUREMENT

The measurement-based approach relies on measurements and mathematical models to capture the relationship between the relevant input and output parameters. Various measurements, such as waste water temperature, ambient temperature, waste water discharge, etc., were made over a period of time and the relationships between these variables were established using mathematical tools. Between these variables using mathematical tools such as correlation analysis. An example of such an approach can be found in the work of Escalas-Cañellas et al. [12]. The authors used the method of time series modeling in which the future temperature of the wastewater is predicted on the basis of historical temperature, average daily ambient temperature and rainfall. Modeling error A modeling error of 0.5°C (RMSE) was found between the predicted and measured temperature. Abdel Aal et al. [13] used a different approach in which the wastewater temperature was modeled using the inductive abduction mechanism (AIM), a supervised learning technique. Two parameters were used as input, the sewage temperature at the top and the air temperature at the bottom of the channel. The study compares it with the model developed by Abdel et al. [14] and it has been shown that the proposed AIM estimates the temperature of waste water with greater accuracy. In a recent study by Golzar et al. [15] used an artificial neural network to predict the temperature of the wastewater flowing into the treatment plant. The model included as input parameters the ambient temperature, temperature and flow rate of waste water from the building, storm water flow rate, infiltration water flow rate, hour of day and day of the year [12, 15].

7. CONCLUSIONS

The paper analysed the seasonal variation of wastewater temperature in the sewage system of wastewater treatment plant X in the Świętokrzyskie Province, and analysed the amount of power extracted using a heat pump. Studies of this type can be useful in designing heat recovery systems, which require the knowledge of temperature trends. Special attention was paid to the seasonal value of waste water temperature and outdoor temperature. During the coldest period, the heat pump was able to generate 16.05 kW of power to heat the building. In contrast, during the summer periods, the power was as high as 132.66 kW, where this power could be used for drying the sludge.

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