HEAT RECOVERY WITH TREATED WASTEWATER AS A LOWER HEAT SOURCE

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Abstract

New technical solutions in wastewater sector are being strongly analyzed due to the increase in energy costs in this field. The aim of the research is to optimize operational costs in wastewater treatment plants as well as their energy independence and neutrality. At first, the main objective in wastewater treatment processes was the adjustment of wastewater quality to the obligatory regulations with no consideration of energy intensity in the system. However, the present requirements in climate protection and energy consumption limitations involve the technological aspects investigations. Therefore, innovative methods are highly respectable. Their purpose is to decrease the energy consumption on one hand, with no negative impact on the environment on the other. One of the approaches involves the heat pump applications with the wastewater as the lower heat source. The energy recovered in the process may be effectively employed in other wastewater treatment processes. The design improves the wastewater treatment plant sustainability. The paper describes the analyzes of obtained thermal energy by means of heat pump supplied with wastewater heat recovery. The studies involve each month of the year for coefficient of performance (COP) calculations. Measurement data were obtained from wastewater treatment plant in Gorzyce, Podkarpackie voivodship in Poland. The research conducted temperature measurements for treated wastewater as well as its flow rates. The results indicate that the heat input ranged between 314.58 kW in January and 2,397.42 kW in August. It proves the seasonal variability in energy potential.

Keywords: *waste heat recovery, heat pumps, wastewater treatment, energy efficiency*

1. INTRODUCTION

The sustainable management in each field of the economy has become mandatory due to the constant energy consumption rise among the whole world. The increase in energy demand, resulting from the life standard growth, causes severe environmental problems concerning the greenhouse gases (GHG) emissions with the temperature rise. Therefore, the necessity to search for the improvements in the applied technologies as well as novel solution in order to optimize the energy production and transformation processes.

The possible answer to solve the issue is the waste heat recovery, including implementing sewage as an alternative form of energy. The research conducted over last two decades contributed to the popularization of waste energy recovery technologies. The studies included several aspects of such an approach.

The implementation of heat conversion from the sewage system requires the decision-making process concerning the possible solutions in case of that issue. The most common techniques were selected and presented in Table 1.

Location	Device type	Wastewater flow rate	Temperature range	Heat recovery efficiency
Directly at the inlet to the sewage system from the drain	Vertical / horizontal heat exchangers	2 - 20 L/min	40 – 50 ºC	< 50%
Sewage pipeline		<10,000 L/min	15 – 30 ºC	40 – 50%
The outlet of sewage treatment plant	Heat pumps	>10,000 L/min	10 – 20 ºC	10 – 30%

Table 1. Characteristics of sewage heat recovery main systems [1-11]

The initial phase of the energy conservation methodology by means of sewage heat recovery is the prediction of the energy utilization potential. Therefore, the analyses involve proposed urban sewage state prediction model (USSPM) [12] that simulates the amount of heat obtained from sewage water through building heat demand, heat source equipment, and heat exchanger models. The simulation process for timely building drainage flow rate and temperature, which are the key factors in simulating the heat flow, include the building information, such as location, building type or building type area, as well as hot water temperature. What is more, the model requires data concerning heat losses in pipelines concerning weather information or sewer system map. The initial analysis enables the wastewater heat recovery potential assessment [13] for several heat recovery scenarios: directly at the facility, from the household, from the precincts or at the wastewater treatment plant level. As concluding, on the basis of data from Swedish city (Linköping) with application of an uncertainty-based approach, heat recovery at showers leads to the highest mean energy recovery (127 MWh/day). Other estimations inform that, every year in the United States alone, 350 TWh of energy is irrevocably expelled with gray water [1].

However, the initial process also involves the optimal support policy. The development of wastewater heat recovery by means of heat pumps as a promising alternative to traditional district heating and cooling sources was widely examined regarding the support policies for local governments [14]. It was discussed that the most significant influence on wastewater heat recovery feasibility present the charges for heating and cooling services. The limited impact was proven for electricity prices, heat pump efficiencies and renewable energy certificates.

The global warming and the GHG emissions to the atmosphere necessitate the strong concern for the natural environment situation. Therefore, the reduction of carbon emissions from buildings has become crucial. Sewage heat may not only be valued as a clean energy source, but also analyzed in case of reducing carbon emissions in an urban built environment. Studies integrate sewage pipe network data with urban geographic information system (GIS) data for implementing sewage heat recovery systems in urban buildings in a northern Chinese city [15]. When endeavour to carbon neutrality, the conducted examinations focused on the changing relationship between the dynamic state of sewage and the characteristics of building heat demand, proving that the proportion of building types impacts the carbon emission reduction rates. With number of residential buildings in the urban sewage pipe network exceeding 60 %, office and retail buildings were considered suitable as the main bodies of heat recovery and utilization with the CO_2 emission decrease over 60%. Not only the urban area may influence the global warming, but the energy reduction processes at the sewage plant itself as well. Several possible processes were tested, concerning the heat pumps and photovoltaics systems installed in a sewage plant, in order to classify the best solution to be implemented. The examination proved that the reclaimed water source heat pump is very effective when used for district heating, even though the whole system requires additional heat exchange station in order to supply the heat-to-heat users or plant [16].

The wastewater heat recovery systems involve either heat exchangers [17] or heat pumps [18] implementation. Heat exchangers technical solutions may be varied. When they are applied directly on the sewage pipelines the system required may involve horizontal, spiral heat exchanger [17] or counter-flow heat exchanger. Both devices were compared on a representative experimental test setup using three different fillings (100%, 50%, 33%) and study revealed that the correction factor, which quantifies the deviation from ideal behavior, falls within the range of 0.78 to 0.83, with an average value of 0.81.

Sewage water source heat pump present several problems such as scale formation, difficulty in cleaning, and rapid decrease of their heat transfer coefficient with time. Therefore, the recovery of heat from sewage using a waste water bath experimental platform, and applying a new, rare earth element non-metallic immersion sewage heat exchanger was recognized [18]. The results show that the system can produce hot water at 40.4–60.6 ºC, and the highest system coefficient of performance (SCOP) of the system is 5.65. The study shows that varying the depth of immersion of the heat exchanger in the water pool affects the heat transfer ability of the heat exchanger. The continuous operation of the system for one year was analyzed and energy saved was determined to be equivalent to that of burning 4.29×10^4 kg of standard coal.

The heat recovered from sewage system may not only be applied in heating or cooling installation in buildings. Other methods utilizing wastewater energy may include injecting it into borehole fields in order to prevent the rapid temperature decline that follows reduction of the spacing between boreholes. Simulations concerning that issue were conducted with the aim of seasonal waste heat storage for improving the sustainability of geothermal heating systems in urban environments. For a tightly spaced borehole field, decreasing the distance between boreholes and thus the surface area requirement of a borehole field, will make it feasible to design geothermal heating systems even in urban areas with very little space near the buildings [19]. Other possibility was presented at As Samra wastewater treatment plant in Jordan, where waste heat was applied for water desalination process [20].

Many researchers conduct their analyzes and calculation procedures including economic aspects of waste heat recovery systems [14, 16], since the issue importance does not only derive from ecological aspects. Heat pumps supplied with the wastewater as a lower heat source cause financial benefits for the plant operator. The raw sewage source heat-pump system with the coefficient of performance 4.0 in China was examined and proved that yearly saving cost is about 53,100 euros [21].

Most research results concerning sewage recovery development involve analyzes of municipal wastewater. However, the sewage produced by industry processes are known to be more effective energy source due to their higher temperature. Performance of an evaporative condenser supplied with the sewage heat recovery from the petrochemical industry was proposed in order to improve the efficiency of energy conversion [22]. The economic and ecologic benefits were calculated and the investment payback period was estimated to be 2.3 years with the emission reduction of CO_2, SO_2 and NOx is 1513.02 t, 46.89 t and 23.45 t per year, respectively.

The presented recent research study implies that the sewage heat recovery issue is highly investigated but still requires several aspects examination. Therefore, the paper presents the numerical analyses of heat recovery potential by means of a heat pump from wastewater in sewage treatment plant in Gorzyce, Poland.

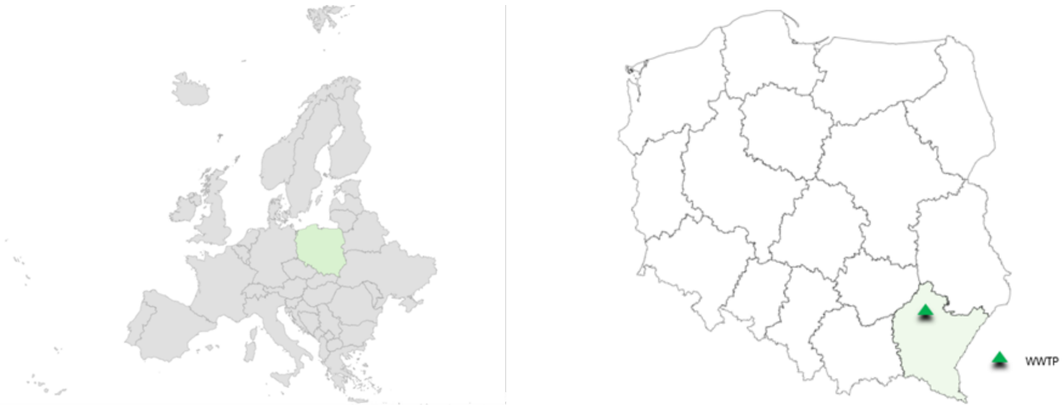
2. METHODOLOGY

2.1. The sewage treatment plant characteristics

The study is based on the data from Gorzyce Wastewater Treatment Plant that operates on system with mechanical and biological installations. The sewage treatment process applies activated sludge technology, with enhanced nutrient removal. The average daily flow is 4,200 m^3/d, with a population equivalent (PE) of 11,593.

The facility is located in Poland, in the northern part of the Podkarpackie Voivodeship, in the Gorzyce commune (Fig. 1). It is situated on the River Łęg, which is a receiver for the treated wastewater.

The immediate vicinity includes industrial plants and residential buildings, as well as a flood embankment 50 meters from the facility.



a) b)

Fig. 1. The location of the wastewater treatment plant:

(a) in Europe, (b) in Poland, Podkarpackie Voivodeship.

The treatment plant receives municipal wastewater: a mixture of wastewater from households and industrial plants. Sewage from septic tanks is also delivered to the facility. The sanitary wastewater collection system is primarily based on pressure sewers, equipped with domestic and collective pumping stations. However, the residential wastewater is discharged by means of gravity sewers. In some parts of the metropolitan area a mixed system collects the sewage, combining gravity and pressure sewers.

Raw sewage enters the treatment plant through three main collectors: two pressure collectors with diameters of 280 mm and 225 mm, and one gravity collector with a diameter of 600 mm. All these collectors connect at an expansion well located on the treatment plant premises.

The mechanical wastewater treatment process begins in the screen building, which is equipped with a 6 mm stepped mechanical screens, known as "screenings". These retain the largest contaminants, which are then transferred to a hydraulic feeder and collected in waste containers. Pre-cleaned wastewater on the other hand flows to the sanitary sewage pumping station, where three pumps with a capacity of 212 m^3/h operate as a retention facility. This stage is important for balancing the flow to subsequent sites.

The wastewater then flows into a vertical grit chamber equipped with a ring-shaped aeration grate, which separates mineral particles from the wastewater, and a grit separator. The grit from the separator flows into a drainage area, where the water is drained.

The next facility that receives wastewater is the Imhoff settling tank used for sedimentation and anaerobic digestion. It consists of two settling tanks that operate independently of each other. Each settling tank is equipped with two flow troughs and two digestion chambers.

The biological wastewater treatment process involves two denitrification tanks operating in series and four nitrification tanks operating in parallel, as well as two secondary settling tanks. The tanks, which reduce nitrates to gaseous nitrogen, are located at the beginning of the secondary treatment process. This process is a primary denitrification stage. To ensure the homogeneity of the wastewater in the denitrification tanks, sludge from the secondary settling tanks is recirculated and mixed with the wastewater using mixers. A fine-bubble aeration system is used in the nitrification process.

The modern biological system is an independent process line, which includes a Sequential Biological Reactor (SBR), operating in a cycle consisting of stages: filling, aeration (nitrification), mixing (denitrification), sedimentation, decantation, and a shutdown period with the possibility to remove an excess sludge. The reactor is equipped with blowers, mixers, and measuring probes. A continuous inflow and batch outflow system ensures high pollution reduction efficiency. The mechanically treated wastewater stream is managed in a separation chamber, where some of the wastewater is directed to traditional biological chambers, while the remaining wastewater is transferred to the SBR. Treated wastewater from the secondary settling tanks and the biological reactor is mixed in the outflow channel and directed to the discharge channel.

The sludge section of the wastewater treatment plant includes a sludge dewatering station, which receives digested sludge from the Imhoff settling tank. This facility is equipped with a belt filter press with a rotary flocculator, and a coagulation agent preparation with dosing system. A sludge sanitization unit is located directly adjacent to the building. After mixing with lime, the dewatered sludge is directed to a storage yard.

Rainwater and meltwater flow is handled by a separate process system. This wastewater is transported to the wastewater treatment plant by means of an independent stormwater drainage system located in the study area.

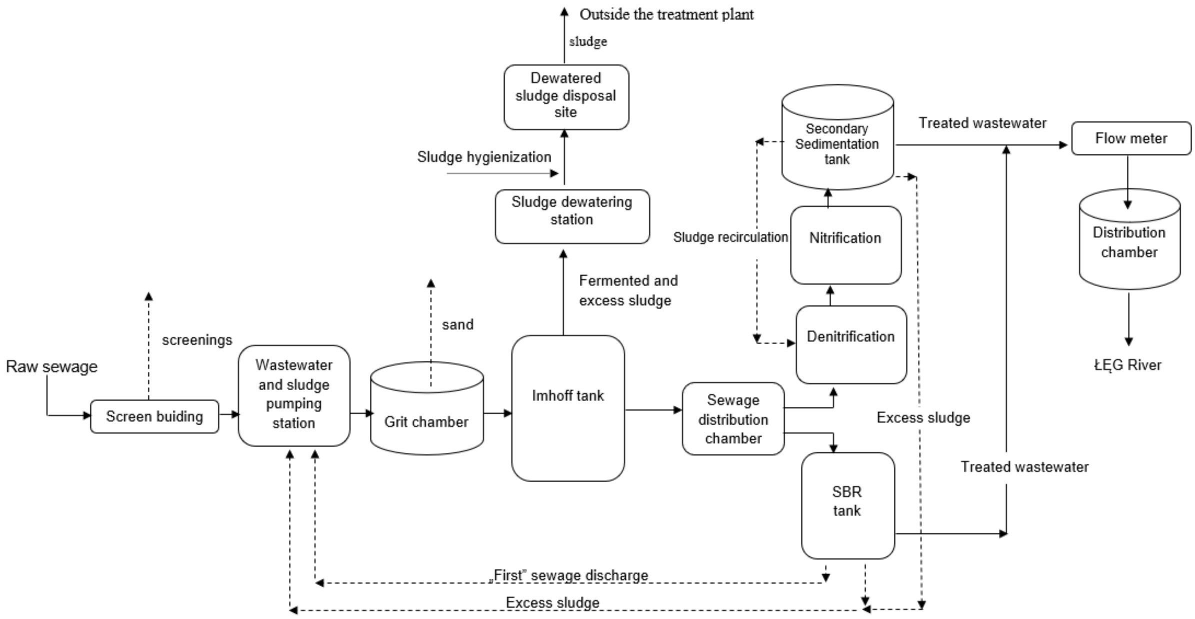


Fig. 2. Technological diagram of the wastewater treatment plant in Gorzyce.

2.2. Calculation procedures

The aim of the research was to determine the amount of thermal power obtained from the treated wastewater stream for individual months using actual measurement data, including the calculation of the thermal power obtained in the heat pump evaporator and condenser as well as the determination of the coefficient of performance COP.

The empirical data used in the analysis included monthly ambient temperature values, treated wastewater temperature values, and corresponding wastewater flow rates. Measurements were conducted in 2023 in the outflow channel, right before the discharge into the receiving water body. This data collection method ensures the determination of the actual energy potential of treated wastewater without the influence of factors occurring within the sewer system.

The heat recovery process was proposed for a heat pump, where the lower heat source was a stream of treated wastewater with temperature varying depending on the season. The calculation model was recommended with the assumption that the wastewater temperature is equal to the temperature of the working fluid at the inlet to the heat pump evaporator. This means that the refrigerant in the evaporator has the same temperature as the treated wastewater in the outflow channel. This assumption simplifies the heat balance and direct use of wastewater temperature measurements to determine the thermal conditions in the evaporator. Furthermore, a constant temperature (6°C) was assumed for the working fluid at the outlet of the evaporator.

The heat recovery process using a heat pump involves the refrigerant, circulating at low pressure, which evaporates in the evaporator, extracting heat from the wastewater. It is then compressed to condensing pressure in the compressor, with the increase in its temperature. The compressed refrigerant then flows through the condenser, where it releases heat to the heating system and condenses. After expansion in the expansion valve, the refrigerant decrease in temperature and pressure is obtained and the fluid returns to the evaporator, completing the cycle (Fig. 3). This process enables effective heat recovery from wastewater and raises its temperature to a value useful in the heating system.

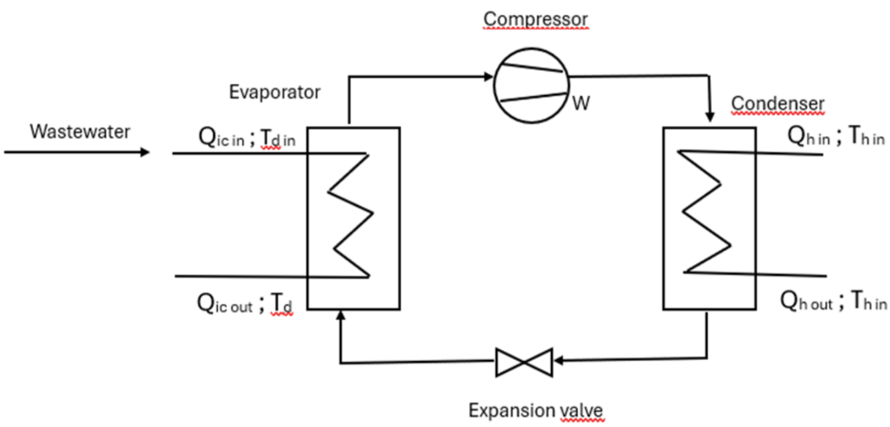


Fig. 3. Heat pump operation diagram.

The calculations were performed using standard thermal energy balance equations, taking into account the density and heat capacity of the wastewater.

The temperature difference and flow rate were included in order to calculate the thermal power of the evaporator ($Q_{ic\ in}$). The assumed compressor power allowed the thermal power of the condenser ($Q_{h\ out}$) estimation and COP determination.

The thermal power of the evaporator was calculated based on the formula [24]:

$$Q_{ic\,in} = V \cdot \rho \cdot C_p \cdot (T_c - T_z), \;\; kW \tag{1}$$

where:

$Q_{ic\ in}$ – evaporator thermal power, kW

V – volume flow rate, m^3/s

ρ – density, kg/m^3

c_p –heat capacity, 4,18 kJ/(kg·°C)

T_z – wastewater inflow temperature, °C

T_c - wastewater outflow temperature, °C

The thermal power of the condenser was calculated based on the formula [24]:

$$Q_{h\,out} = Q_{ic\,in} + W, \quad kW \tag{2}$$

where:

$Q_{h\,out}$ - condenser thermal power, kW

$Q_{ic\,in}$ - evaporator thermal power, kW

W – compressor electric power, kW

To evaluate heat pump efficiency, the Coefficient of Performance (COP) is used. This is the rate that measures the device's energy efficiency, defining the ratio of the heating power delivered by the heat pump to the electrical power required to operate it. The COP is expressed using the following formula [24, 25]:

$$COP = \frac{Q_{h\,out}}{W} \tag{3}$$

3. RESULTS

The temperature of treated wastewater presents a visible dependence on the outside temperature. It is higher in summer months, while a noticeable decrease is observed in winter months. Despite this, even during the lowest air temperatures, treated wastewater presents a relatively high temperature. The relation between the treated water and ambient temperature in each month is presented in Figure 4.

In each figure below the summer period (May – August) is marked, since this paper mainly discusses the heating potential of heat pump with treated sewage as the lower heat source. Therefore, the heating season (September - April) is the period analyzed during the studies.

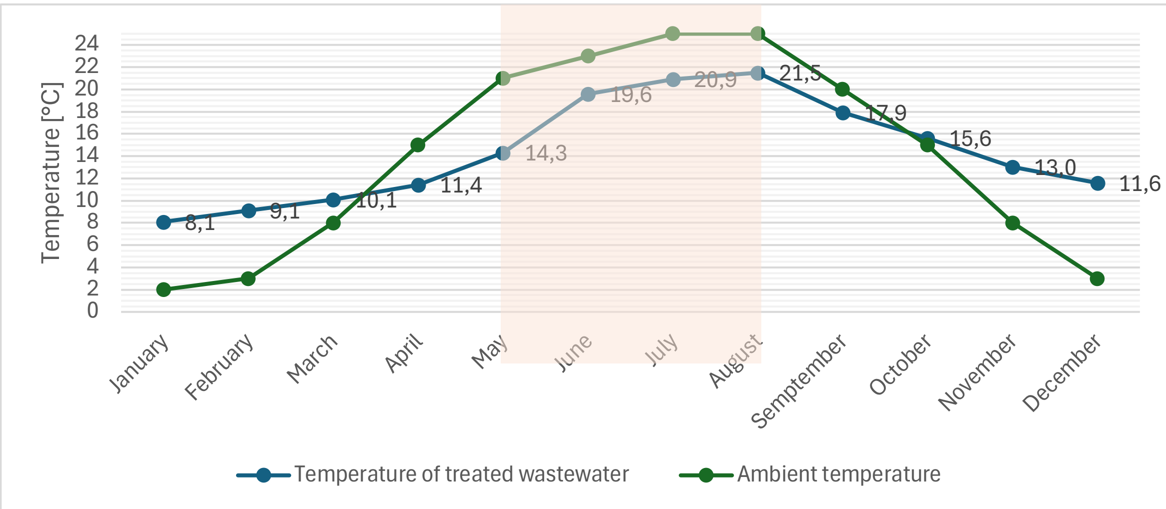


Fig. 4. Average monthly temperatures.

Based on the obtained treated wastewater temperature measurements, it can be seen that their value ranges from 8.1°C in January to 21.5°C in August. In winter, despite sub-zero ambient temperatures, the treated wastewater temperature remains above zero and ranges from 8.1°C to 11.6°C, making it a potential source of thermal energy.

The other factor that is required to be measured in order to calculate the operation of heat pump powered by sewage, is its flow. Therefore, the collected values for Gorzyce Sewage Treatment Plant are presented in Figure 5.

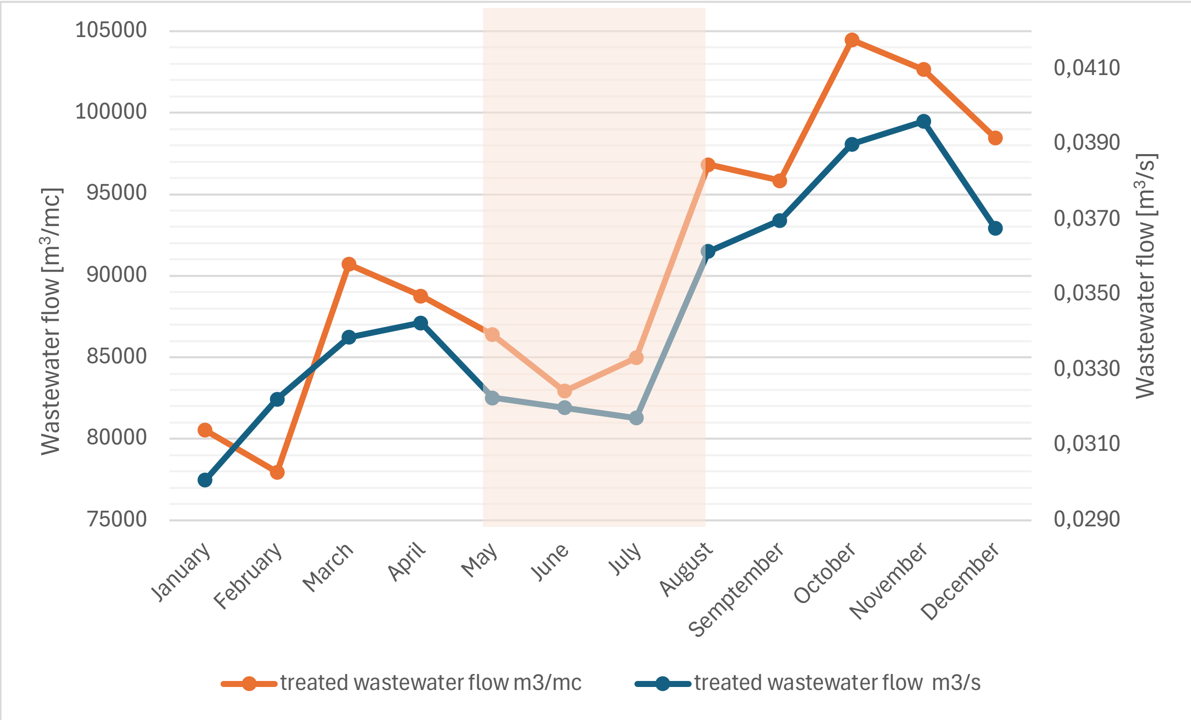


Fig. 5. Average monthly wastewater flow rate.

The highest treated sewage flow in relation to month was observed in October and amounted to 104,463 m^3/month, while the lowest in February – 77,961 m^3/month. The average flow value in the summer months, i.e. from May to August, was 87,779 m^3/month. However, it should be noted that the highest instantaneous flow values [m^3/s] differ from the monthly flow totals. In this case, the highest instantaneous flow was recorded in November at 0.0396 m^3/s, and the lowest values in January at 0.0301 m^3/s (Fig. 5).

Considering all the data given, the possible thermal powers of the evaporator and condenser as well as the COP value were calculated. All the results are presented in Figure 6.

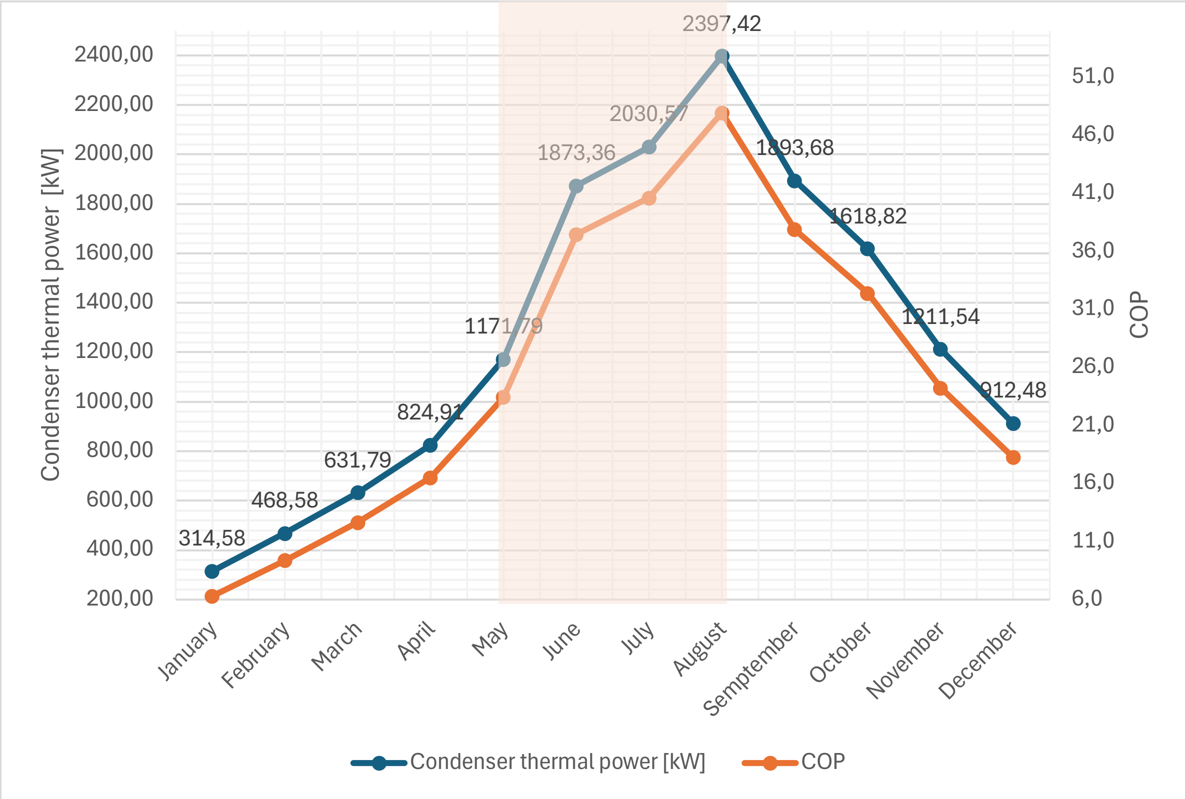


Fig. 6. Average monthly condenser heat output and coefficient energy efficiency.

Based on the thermal power obtained in the condenser in each month, it can be seen that the highest values were achieved in August (2,397.42 kW), while the lowest were obtained in January (314.58 kW). The average condenser power output was 1,279.13 kW. It should also be noted that in the winter (heating) months, the average value was 984.55 kW, while in summer months it ranged from 1,171.79 kW to 2,397.42 kW with the average value of 1,868.28 kW.

The COP reached a median value of 23.8. The value ranges between 6.3 and 47.9. The lowest value was achieved in January, and the highest in August. Furthermore, in the summer, the average value was 37.4, while in the heating season period it was 19.69 (Fig. 6).

4. DISCUSSION AND CONCLUSIONS

Taking into consideration the calculations and analysis of data on the temperature and flow of treated wastewater, as well as the obtained thermal power and COP, it was concluded that wastewater can be an effective and stable lower heat source for heat pump systems dedicated both to heating purposes and the production of domestic hot water.

The results indicate that during the heating season from September to April, an average of approximately 985 kW of thermal power can be recovered, effectively meeting the thermal demand of the analyzed facility. During the summer months, from May to August, this power increases to values exceeding 1,870 kW, making the system particularly attractive for domestic hot water preparation or seasonal thermal energy storage.

Moreover, the surplus of recovered thermal energy can also be used to satisfy the needs of other facilities located in the vicinity of the treatment plant, such as industrial plants.

To meet the treatment plant's energy needs, a system consisting of 10 heat pump units with a nominal power of 100 kW each could be used. The high energy efficiency coefficient achieved confirms the viability of using treated wastewater as a renewable energy source in low-temperature systems.

An additional benefit is the ability to seamlessly control wastewater flow in order to optimize the heating system's operation depending on current heat demand. Implementing this type of solution can contribute to reducing the operating costs of wastewater treatment plants and achieving goals related to improving energy efficiency and reducing greenhouse gas emissions.

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