Possibilities of using wastewater in sewage treatment plants as a source of heat

Ścieki jako źródło ciepła w oczyszczalniach ścieków

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DOI 10.36119/15.2022.5.2

Preventing climate change is a priority for the European Union. In order to reduce CO_2 emissions into the atmosphere and thus the negative impact of human activity on the environment, the European Parliament and the Council of the European Union have developed and enacted a number of directives. Improving the energy efficiency of systems used by people is a priority task included in the European Union policy.

Energy obtained from the combustion of biogas and sewage sludge is widely used at wastewater treatment plants, while the heat recovered from wastewater is used only to a small extent.

The article presents methods of heat recovery from wastewater and possibility of its application at wastewater treatment plants. The heat contained in the wastewater is discharged into the sewage system and further into the wastewater treatment plant. In most wastewater treatment plants in Poland, the heat is not utilized and flows with the treated wastewater to the reception tank. The lack of utilization of this heat is due to the low temperature of the wastewater, which is higher than the temperature of cold water supplied to buildings by only a few to several degrees Celsius. This limits the direct use of the heat contained in them with heat exchangers. In wastewater treatment plants, the higher temperature heat is used for heating, hot water preparation and technological needs. A higher temperature of the heated medium than in heat exchangers may be obtained with heat pumps, where wastewater can be used as lower heat source. Unfortunately, this temperature cannot be too high as the efficiency of heat pumps (COP) decreases with the increase of the temperature in the condenser. The basis of any analysis of the possibility of using heat from wastewater is the determination of its temperature. The analysis is based on the example of the Zdroje Wastewater Treatment Plant in Szczecin, for which the results of wastewater temperature measurements are presented for individual days in 2020. Analysis was also performed for water taken at the Miedwie intake, which feeds the wastewater treatment plant's inflow areas, and for the average daily outdoor air temperature. The average daily efficiency of heat extraction with heat pumps from sewage at the plant and from outdoor air was determined for selected months. The efficiency of heat extraction depends on the temperature of the lower and upper heat source. The paper presents the results of performance calculations when the lower heat sources are wastewater and outside air. The efficiency of heat extraction from wastewater is higher than that of heat extraction from air. The relative increase in pump efficiency was also determined when wastewater is the lower heat source instead of the outside air.

Keywords: wastewater treatment, wastewater heat recovery, wastewater treatment plant heat management

Zapobieganie zmianom klimatu jest strategicznym priorytetem Unii Europejskiej. Aby ograniczyć emisję CO_2 do atmosfery i przez to niekorzystny wpływ działalności człowieka na środowisko Parlament Europejski i Rada Unii Europejskiej opracowała i uchwaliła szereg dyrektyw. Poprawa efektywności energetycznej użytkowanych przez ludzi systemów jest priorytetowym zadaniem polityki Unii Europejskiej.

W oczyszczalniach ścieków szeroko wykorzystywana jest energia uzyskiwana ze spalania otrzymywanych w nich: biogazu i osadów ściekowych, w niewielkim stopniu ciepło odzyskiwane ze ścieków.

W artykule przedstawiono sposoby odzyskiwania ciepła ze ścieków i możliwości ich zastosowania w oczyszczalniach ścieków. Ciepło przekazywane w budynku zużywanej wodzie odprowadzane jest ze ściekami do kanalizacji i dalej do oczyszczalni ścieków. W większości oczyszczalni w Polsce, nie zostaje ono w żaden sposób zagospodarowane i odpływa z oczyszczonymi ściekami do odbiornika. Brak spożytkowania tego ciepła wynika z niskiej temperatury ścieków, jest ona wyższa od temperatury zimnej wody dostarczanej do budynków od kilku do kilkunastu stopni Celsjusza. Ogranicza to bardzo bezpośrednie wykorzystanie zawartego w nich ciepła za pomocą wymienników ciepła. W oczyszczalniach ścieków znajdują zastosowanie czynniki grzejne o wyższej temperaturze, potrzebne do ogrzewania, przygotowania ciepłej wody i na potrzeby technologiczne. Wyższą temperaturę podgrzewanego czynnika niż w wymiennikach ciepła można uzyskać za pomocą pomp ciepła, ścieki wtedy stanowią dla nich dolne źródło ciepła. Niestety temperatura ta nie może być zbyt wysoka ze względu na malejącą, wraz ze wzrostem temperatury w skraplaczu efektywność (współczynnik COP) pomp ciepła. Podstawą każdej analizy możliwości

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wykorzystania ciepła ze ścieków jest znajomość ich temperatury. Analizę przeprowadzono na przykładzie Oczyszczalni Ścieków Zdroje w Szczecinie, dla której, w poszczególnych dobach 2020 roku przedstawiono wyniki pomiarów temperatury ścieków. Pokazano też temperaturę wody ujmowanej w Ujęciu Miedwie zasilającym tereny spływu ścieków do tej Oczyszczalni, oraz średnią dobowej temperatury powietrza zewnętrznego. Dla poszczególnych miesięcy określono średnią dobową efektywność pozyskiwania ciepła za pomocą sprężarkowych pomp ciepła ze ścieków w oczyszczalni oraz z powietrza zewnętrznego. Efektywność pozyskiwania ciepła zależy od temperatury dolnego i górnego źródła ciepła. W artykule przedstawiono wyniki obliczeń efektywności, gdy dolnym źródłem ciepła są ścieki oraz powietrze zewnętrzne. Efektywność pozyskiwania ciepła ze ścieków jest większa niż w przypadku pozyskiwania ciepła z powietrza. Określono również względny wzrost efektywności pompy w przypadku gdy dolnym źródłem ciepła są ścieki a nie powietrze zewnętrzne.
Słowa kluczowe: oczyszczalnie ścieków, odzysk ciepła ze ścieków, gospodarka ciepłem w oczyszczalniach ścieków

Notations:

- COP – coefficient of performance of a heat pump [–]
- Q_b – heat from combustion of biogas [MJ],
- Q_{ss} – heat from combustion of sewage sludge [MJ],
- Q_r – heat recovered from wastewater [MJ],
- Q_a – heat from additional heat source [MJ],
- Q_h – heat for space heating [MJ],
- Q_{ww} – heat for hot water preparation [MJ],
- Q_{ds} – heat for drying of sludge [MJ],
- Q_{hs} – heat for heating the sludge directed to digestion chamber [MJ],
- T_e – temperature of evaporator [K]
- T_k – temperature of condenser [K]
- η_d – efficiency of the heat pump, [–],
- ϕ_c – counter-clockwise Carnot coefficient of performance, [–],

Introduction

Preventing dangerous climate change is a top priority for the European Union. The EU is working hard to reduce its own greenhouse gas emissions while encouraging other countries and regions to do the same. In the European Parliament and of the Council Directive of 11 December 2018 it was stated that "Improving energy efficiency throughout the full energy chain, including energy generation, transmission, distribution and end-use, will benefit the environment, improve air quality and public health, reduce greenhouse gas emissions…". One significant way to improve energy efficiency can be waste heat recovery. An example is the heat contained in wastewater.

The heat discharged along the wastewater can be recovered within the buildings, sewers and at wastewater treatment plants. The paper discusses, the possibility of recovering the heat from wastewater at the treatment plants. The temperature of wastewater is always higher than the temperature of intake cold water. During cold periods of the year it is also higher than the outside air temperature. However, low temperature of the wastewater poses an issue with recovery of the heat. The maximum temperature of wastewater at treatment plant is observed in summer reaching over 20°C. The temperature in winter rarely falls below 10°C [6, 13, 15]. In theory, this heat can be recovered through heat exchangers. Wastewater treatment plants are not interested in such a low temperature heat source. It is possible to use the wastewater as a lower heat source for heat pumps. Currently available heat pumps allow to heat the medium to 60°C [3, 12] or even 80°C [4] without any trouble.

The aim of the article is first to show the heat potential of wastewater compared to the heat potential of air and water drawn at the intake and to present the possibility of using the heat contained in them.

Methods of wastewater heat recovery

Heat from the wastewater can be recovered using heat exchangers. The heat flow rate can be determined by using classical heat exchanger calculation equations [2]. In heat exchangers the temperature of the heated medium is lower than the temperature of the inflowing wastewater. For low temperatures of the wastewater their usability is limited. When required temperature of the heated medium is not too high, not exceeding 60°C, wastewater can be used as the lower heat source in heat pumps [14].

Among the heat pumps types, compressor heat pumps are the most commonly used. The coefficient of performance (COP) can be determined using a simplified relation [5, 15]:

$$COP = \eta_d \cdot \varphi_c \tag{1}$$

The COP of a heat pump is a coefficient that determines the efficiency of the heat pump. It is the ratio of the amount of heat delivered by the pump to the amount of electricity consumed by the work done by the pump. Industrial compressor heat pumps achieve the efficiency of η_d = 50 – 60% of perfect Carnot heat pump φ_c. The performance (COP) of a heat pump working in contraclockwise Carnot cycle φ_c can be calculated from the following formula:

$$\varphi_c = \frac{T_k}{T_k - T_p} \tag{2}$$

For a given lower heat source temperature, the performance of the heat pump decreases as the upper heat source temperature increases. If the lower heat source is sewage, deposits and biological film build up on the evaporator heat transfer surface, reducing the heat pump efficiency. It is assumed that the use of heat pump is efficient for values of COP above four [5]. Wastewater heat recovery (WWHR) takes place when wastewater flows through heat exchangers and heat pump evaporators within the building or heat exchangers located in the sewage system. It is also possible to use an intermediate medium between the heat pump and the wastewater, but this increases the cost of the investment and reduces the performance of the heat pump [15].

Untreated domestic wastewater contains a large amount of suspended solids which cover the surfaces of channels increasing the hydraulic resistance and reducing the flow. Suspended solid cover also the surface of heat exchangers, reducing their effective area. The precipitates on the surface also create additional thermal resistance lowering the value of the heat transfer coefficient and the heat flux extracted from the wastewater [9, 10]. Because of this, heat at wastewater treatment plants is most often extracted from treated wastewater, which practically containing no solids. Heat exchangers should be designed, constructed and located so their surfaces can be easily cleaned from the sewage.

Low temperature heating demand

The overall heat balance of a wastewater treatment plant for a given period of time can be represented by the relation:

$$Q_b + Q_{ss} + Q_r + Q_a = \\ = Q_h + Q_{ww} + Q_{ds} + Q_{hs} \quad (3)$$

Heat at the wastewater treatment plant can be obtained from combustion of biogas obtained from methane fermentation in the digestion chambers $\mathbf{Q_b}$ and from sewage sludge combustion $\mathbf{Q_{ss}}$, recovered from sewage $\mathbf{Q_r}$ and obtained from another heat source $\mathbf{Q_a}$. This heat is used for heating of administrative, social and technological facilities $\mathbf{Q_h}$, preparation of hot water $\mathbf{Q_w}$ for heating of sewage sludge directed to the digestion chambers $\mathbf{Q_{hs}}$ and for drying of sewage sludge $\mathbf{Q_{ds}}$ [8].

Heating installations designed for use of wastewater heat should be designed for low-temperatures. For a medium with a design temperature of up to 45°C, the compressor heat pumps can be used to achieve the thermal potential. The heat pump will operate at a relatively high coefficient of performance. The heat pumps can also be used for the hot water preparation.

The low-temperature heat from heat pumps can also be used to heat sewage sludge directed to separate digesters where mesophilic sludge digestion is conducted.

In the balance of the digestion chamber, the heat flux needed to heat the raw sludge has the highest value (usually it is more than 80% of the total heat demand of the SCC). The remaining heat flux is used to cover the heat losses of the piping and digester. Mesophilic fermentation of sewage sludge takes place at a temperature of 30-40°C. In winter, the sludge temperature is around 10°C. It is possible to preheat the sludge fed to the digestion chamber with the sludge discharged from it. Such a solution is practically not applied due to the fact that these sludges contain considerable amounts of organic substances and relatively quickly settle on the surfaces of heat exchanger building up a biological film, that increases the thermal resistance of the exchanger partition and thus decreasing the heat transfer coefficient and the heat stream transferred in the exchanger. When the heat flux decreases, the exchangers need to be cleaned. To supplement the heat flux, the sludge in the WKF can be heated to the right temperature with heat from other sources, e.g. with heat from cogeneration or heat pumps.

Wastewater, cold water and air temperatures

The temperature of the wastewater leaving the apartment building is higher than the temperature of the cold water supplied. This is due to the fact that part of the water supplied to the residential building and used by the tenants of the buildings is heated to a temperature of about 55°C. On average35% of hot water used in residential buildings has this temperature [7]. The temperature of wastewater does not exceed 25°C during the summer and rarely drops below 10°C during the winter [4, 5]. Figure 1 presents the average temperatures during a year of water at the Miedwie intake [16], treated wastewater temperature at Zdroje WWTP [16], and air temperature at meteorological station in Szczecin during 2020 [1]. The average annual temperature of water taken from the intake was 8.8°C [16], of wastewater at the treatment plant 19.0°C [16], and of air 10.7°C [1]. It can be seen that the wastewater has the highest temperature (except for a few days where the air was higher). The 24-hour average air temperature is characterized by largest daily amplitudes. In cold period it is basically lower than the cold water temperature, while in the summer it is higher than it.

Figure 2 shows the difference between the temperature of the wastewater at the Zdroje WWTP in 2020 and the temperature of the water at the Miedwie intake. The annual average temperature difference is 10.2°C, the wastewater temperature is significantly higher than the intake water temperature. This temperature difference varies throughout the year. The highest occurs during the summer in August (about 14°C), while the lowest differences occur in the autumn-winter period in November

Fig. 1.
Daily average temperature of water at the Miedwie intake [16], wastewater at the Zdroje WWTP [16], and average daily air temperature in 2020 [1]
Rys. 1. Średnia dobowa temperatura wody pobieranej w ujęciu Miedwie [16], ścieków w oczyszczalni Zdroje [16] i powietrza w poszczególnych dniach 2020 roku [1]

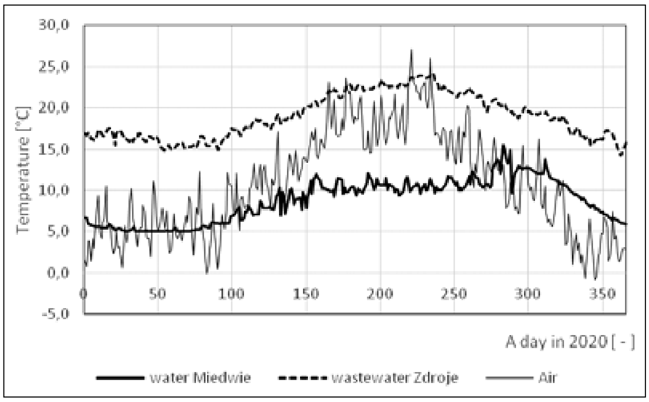


Fig. 2.
Daily differences between wastewater temperature at Zdroje WWTP [16] and water temperature at Miedwie intake [16] in 2020
Rys. 2. Dobowe różnice temperatury ścieków w oczyszczalni Zdroje i temperatury wody pobieranej w ujęciu Miedwie w roku 2020

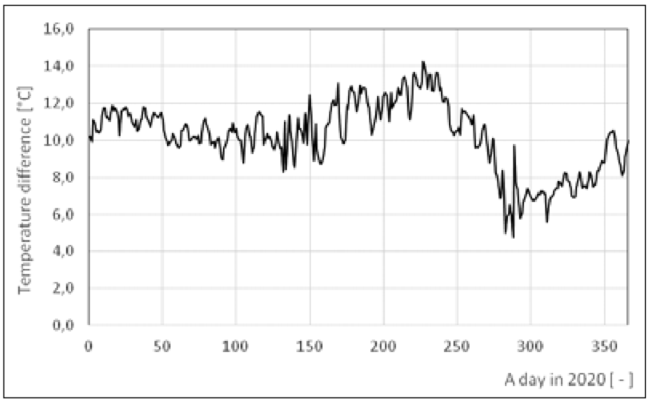
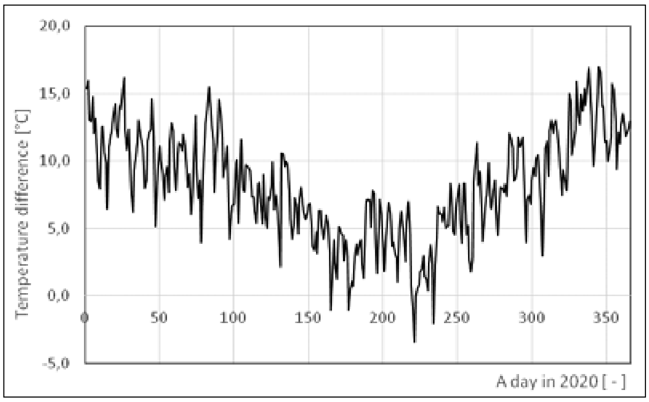


Fig. 3.
Daily differences between wastewater temperature at Zdroje WWTP [16] and average air temperature in Szczecin in 2020 [1]
Rys. 3. Dobowe różnice temperatury ścieków w Oczyszczalni Ścieków Zdroje i średniej temperatury powietrza w Szczecinie w 2020 roku



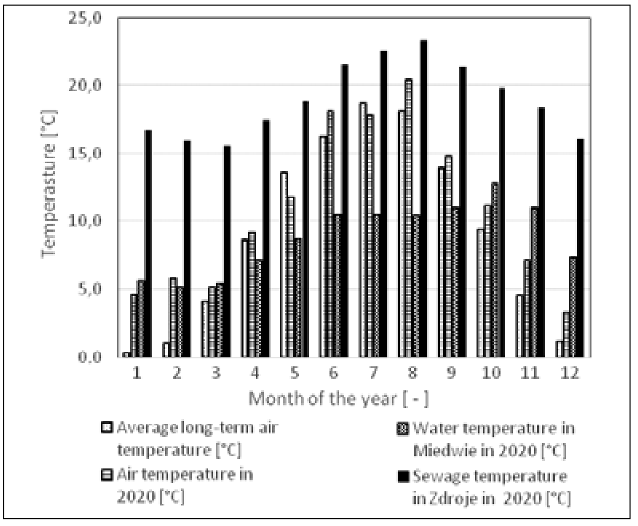


Fig. 4.
Monthly average long-term air temperatures [1] and in average daily temperatures in 2020 [1] in relation to temperature of water at Miedwie intake [16] and wastewater at Zdroje WWTP [16]
Rys. 4. Średnia miesięczna długoterminowa temperatura powietrza [1] i średnie dzienne temperatury w 2020 r. [1] w stosunku do temperatury ujęcia wody w Miedwie [16] i ścieków w Zdrojach [16]

(about 7°C). The average temperature difference in the heating season (January – April, October – December) is 9.4°C.

Figure 3 shows daily temperature differences between treated wastewater at Zdroje WWTP and air in Szczecin in 2020. Average temperature difference was 8.2°C, while in the heating season (October – December, January – April) it was 10.6 °C.

Figure 4 shows the average long-term monthly air temperature [1] and the average daily temperature of air in 2020. The data presents also the temperature of water at Miedwie intake [16] and treated wastewater from Zdroje Wastewater Treatment Plant (WWTP) [16] in particular months of the year.

By analyzing the temperature values during the year, it can be concluded that wastewater is a much more favorable lower source of heat pump than air, because its temperature during the heating period is much higher than that of the outside air. The temperature of wastewater during the heating period is much higher than the temperature of other possible lower heat sources such as ground or water drawn from the ground, or water from watercourses or reservoirs [14].

Efficiency of heat recovery with heat pumps

Heat pump performance calculations were performed. The relations (1) and (2) given in the introduction were used. It has been assumed that the performance of the actual heat pump circuit is equal to 0.5 (η_d = 0.5) [5, 13, 15]. Calculations were performed for wastewater as a lower heat source or air and for an upper heat source temperature from 30°C to 60°C. Calculation were performed for two months with the lowest and highest temperature in the heating season. The calculations took into account the multi-year average monthly air temperature and the average monthly wastewater temperature in 2020. The average monthly air temperature during the heating season was lowest in January (T=0.3°C), while the highest was in April (T= 8.6°C). Figures 5 and 6 present the results of the calculations. When the lower heat source is wastewater (WW) the pump efficiency is higher than for the outdoor air (A).

Results shown in Figure 7 prove that wastewater is a better heat source than outdoor air. In January, for an upper heat source temperature between 30°C and 60°C, the performance of the heat pump is

Fig. 5.
Coefficient of performance (COP) for average monthly temperature in January, lower heat source air COP(A) T(A)=0,3 [°C] and wastewater COP(WW) T(WW)=14,2 [°C] as a function of upper heat source temperature
Rys. 5. Efektywność pomp ciepła (współczynnik COP) dla średniomiesięcznej temperatury w styczniu, dolne źródło ciepła powietrze T(A)=0,3 [°C] i ścieki T(WW)=14,2 [°C] w funkcji temperatury górnego źródła ciepła

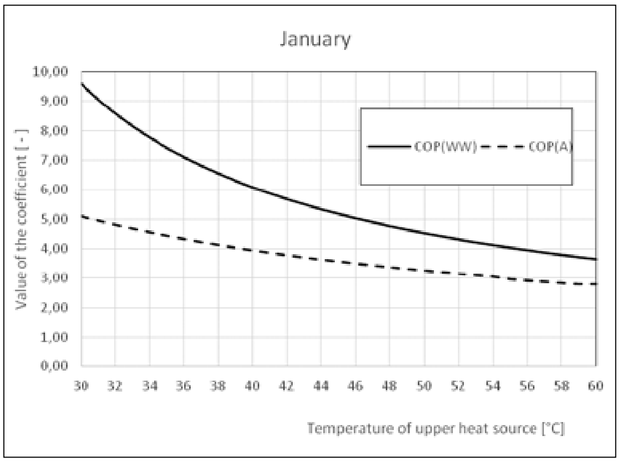
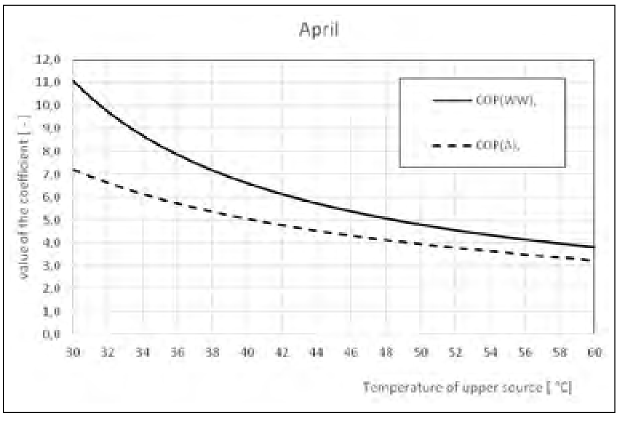


Fig. 6.
Coefficient of performance (COP) for average monthly temperature in April, lower heat source air COP(A) T(A)=8,6 [°C] and wastewater COP(WW) T(WW)=16,3 [°C] as a function of upper heat source temperature
Rys. 6. Efektywność pompy ciepła dla średniomiesięcznej temperatury w kwietniu, dolne źródło ciepła powietrze T(A)=8,6 [°C] i ścieki T(WW)=16,3 [°C] w funkcji temperatury górnego źródła ciepła



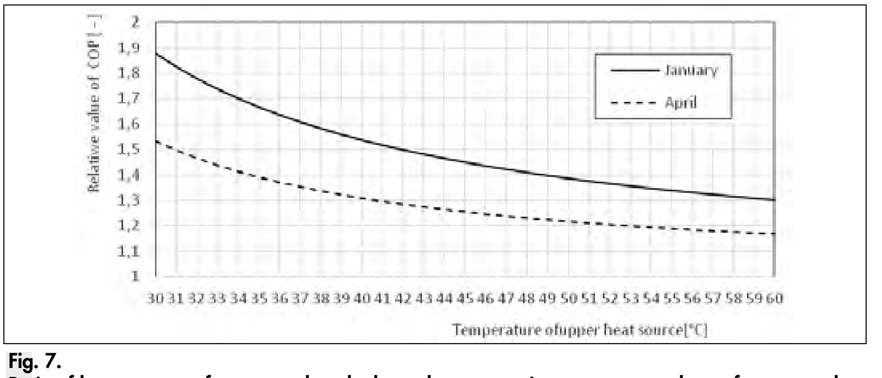


Fig. 7.
Ratio of heat pump performance when the lower heat source is wastewater to the performance when the lower heat source is outdoor air in relation to the upper heat source temperature
Fig. 7. Stosunek wydajności pompy ciepła, gdy dolnym źródłem ciepła są ścieki do wydajności, gdy dolne źródło ciepła to powietrze zewnętrzne w stosunku do temperatury górnego źródła ciepła

higher by 88%to 30% when heat is extracted from wastewater than when it is extracted from outdoor air. In April, on the other hand, the value is 53% to 18% higher.

Figure 7 presents the ratio of heat pump performance when the lower source is wastewater to efficiency when that source is outdoor air in relation to upper heat source temperature for January and April.

Summary

The article presents the results of comparison of heat pump performance at a wastewater treatment plant when the lower heat source is the wastewater and outside air. The comparison was made for Waste Water Treatment Plant Zdroje in Szczecin.

As the temperature of the upper heat source increases, the performance of heat pumps decreases. In January, for a heat source temperature between 30°C and 60°C, the performance of a heat pump with wastewater as the lower heat source is 88% to 30% higher than for air as the lower heat source. In April, the performance is 53% to 18% percent higher for studied lower heat sources.

It can be concluded that at wastewater treatment plants, the most advantageous lower heat source for the heat pump is the wastewater, as its temperature during the heating period is much higher than the temperature of other possible lower heat sources such as air, ground or water drawn from the ground, or water from watercourses or reservoirs.

The performance of heat pumps, for a heat source at a given temperature, depends on the temperature of the upper heat source. As the temperature of the upper heat source increases, the performance of the heat pump and economic efficiency decreases. Above a certain temperature of the upper heat source a heat pump is not economically justifiable. Therefore, they are mainly used at low heat pump temperatures. The problem of heat utilization in wastewater treatment plants lies in the limited possibilities of heat utilization with heat pumps, due to their low thermal potential.

To utilize heat pump for heating purposes, the heating medium should have low temperature, while the central heating should be designed to utilize systems with low heat such as floor heating.

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The author would like to express his gratitude to the Management of ZWiK in Szczecin (Water and Sewage Company) for providing the data on water temperature at Miedwie intake and sewage temperature at Zdroje Water Treatment Plant. I would also like to thank them for their unlimited help and kindness.

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