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Use of Heat from Wastewater

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Abstract. There are increasing demands on energy efficiency at all areas of life e.g. heating, cooling and hot water supply. Using waste water is meeting requirements of sustainability and environmental protection. Waste water has great energy potential. The article deals with the optimization of sewer heat exchanger and economic efficiency. Heat exchanger effect is depending on shape and geometry of heat exchanger. Also temperature of waste water affects heat exchanger effect. Usual temperature of sewage is about 20 degrees Celsius in summer and about 10 degrees Celsius in winter. Cooling for a maximum about 1 degrees Celsius and flow at least 10 liters per second is required for seamless operation. To pass requirement of minimum flow is this system suitable for bigger buildings. It is also necessary for positive economic effect. For proper design and optimization it is necessary to use three basic methods: diagnostics, heat balance calculations and modelling. Numeric simulations are made for selection of the best sewer heat recovery. Recovered heat energy was used for heating, cooling also for hot water supply. Positive economic effect is provided in case study of administrative building.

1. Introduction

As the society is developing, there are greater demands on reducing energy performance in all areas of life. The European Union has pledged to reduce the greenhouse gas emissions by 40% by 2030 compared to the level from 1990 and to increase the proportion of renewable energy to at least 27%.

The energy plan for 2050 aims to further reduce the greenhouse gas emissions by more than 80% compared to 1990 [1]. One of the possibilities of using renewable sources is reusing waste products. Wastewater constitutes considerable thermal potential, which is not used much in the Czech Republic. Wastewater ranges from 10 to 25°C, which is an ideal source for thermal pumps. Thermal pumps using air or soil as the source of energy are commonly available, however, the air temperature oscillates and recovering energy from soil can be very expensive due to expensive drilling or large land grabbing. Heat pumps using air or soil as the source of energy are commonly available, however, the air temperature oscillates and recovering energy from soil may be very expensive whether it is due to expensive drilling or extensive land grabbing. The hydraulic conditions for groundwater flow may not ensure the necessary, reliable and cheap operation as it is often necessary to draw water from great depths, which is where groundwater is found. That is why it is necessary to look for a cheap and accessible source, which could be, for example, sewage or waste water from showers. The amount of energy which could be recovered in the form of waste heat from wastewater is enormous.

The first installation of a sewage heat exchanger was performed more than 20 years ago and there are over 500 systems using heat pumps to recover energy from wastewater all over the world. Their performance ranges from 10 kW to 20 MW. Swiss and German studies prove that up to 3% of all



buildings may recover heat from the sewage system. The studies carried out in Switzerland [2] also show that up to 15% of thermal energy gets lost from buildings through the sewage system and this value increases in well insulated buildings with low consumption. Since hot water is drained into the sewage system, sewage systems in buildings are a major source of heat loss. In many countries, engineers try to recover energy from wastewater using heat pumps and heat exchangers [2, 3, 4, 5], which enable the air-conditioning of buildings. Heat recovery from wastewater is also common in Europe, where there are, for example, water treatment plants in Oslo and Zurich [2]. There are two main factors which are important for a proposal of heat recovery: the wastewater temperature and flow rate. For suitable use of a heat exchanger, it is necessary to know the sewage system type and to take into consideration the following factors: 1) wastewater temperature of at least 10 °C, 2) short distance between the recovery system and the consumption point, 3) minimum wastewater flow rate of 10 ls⁻¹, 4) sufficient pressure dimensions in the pipeline, 5) wastewater flow, 6) optimal heat exchanger values, 7) minimal cleaning of the exchanger, 8) minimal maintenance of the system during operation, 9) maximal economic profitability [6]. Temperature in a sewage system is quite stable. Fluctuations mostly occur only in the summer and winter. In the summer, the temperature is around 20°C and in the winter it ranges from 10-13°C. Wastewater is the warmest immediately after leaving the building where it is consumed.

A change in the temperature may occur at night or when it is raining. The flow rates must be at least around 10 ls⁻¹. Wastewater flow rate is related to the variability of consumer demand for water. The water flow has a daily and weekly cyclic trend, which is different during working hours and at the weekend. A change in the trend is affected by climatic conditions, work, and consumer activities and habits. In larger cities, these irregularities are slighter. Some processes in water treatment plants are temperature-sensitive. Heat recovery from wastewater must not affect the biological processes taking place in water treatment plants. For this reason, wastewater may be cooled after heat exchange by approximately 1-3°C. A big problem related to the installation of sewage heat exchangers is the formation of a biofilm on the walls of the exchangers. The formation of a biofilm leads to reduction in the heat exchange efficiency. This is one of the reasons why a larger number of sewage heat exchangers are proposed than needed. Another essential element of the recovery is a heat pump [7]. By installing a heat pump in a system for recovering energy from wastewater, the wastewater potential is increased many times. A heat pump may be used both for heating and cooling. The performance of a heat pump is characterized by a heating factor (COP – coefficient of performance). It is the ratio of heat transferred to the heat transfer medium to the work carried out (supplied). The heat factor increases with a higher temperature of the source – the wastewater temperature [8].

2. Experimental setup

The project in question is carried out at a water treatment plant at the altitude of 167 m. It is an older building used as an office building. The heat will be recovered from wastewater using a sewage heat exchanger. The exchanger will be inserted into a single circular-shaped sewage system. The pipeline is DN 1200. The paper optimizes several types of sewage heat exchangers. The models were created in the CalA software and there are heat exchangers of various types, dimensions, and made of various materials. The simulations are carried out for an average, minimal, and maximal flow rate.

2.1. Input information

The simulations were based on real data measured at the water treatment plant over a one-year period. To make the work easier and to reduce the number of models, the data were averaged to obtain the annual average temperature and the winter average temperature.

$$W_{OP} = c \cdot \rho \cdot Q \cdot \Delta T \quad (1)$$

where: Δ – wastewater cooling [°C]
 W_{OP} – amount of heat removed [kW]
 c – specific heat capacity of water, 4,18 [kJ.kg⁻¹.°C⁻¹]

- ρ – specific weight of water [kg.l^{-1}]
 Q – wastewater flow [l.s^{-1}]

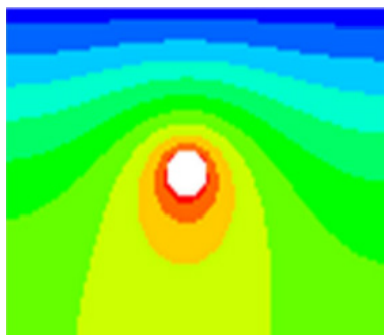
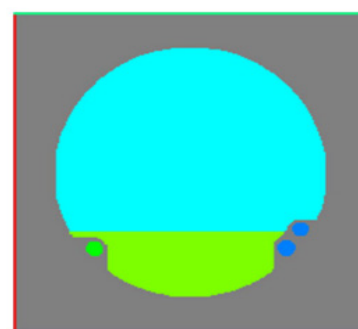
Table 1. Input data

Sewage system type	Single sewage system
Shape of pipeline	circular
Dimensions of pipeline	DN 1200
Average dry water flow	75 l.s^{-1}
Minimal dry water flow	13 l.s^{-1}
Average annual temperature of wastewater	$14.3 \text{ }^{\circ}\text{C}$
Average winter temperature of wastewater	$9.7 \text{ }^{\circ}\text{C}$
Depth of the pipeline laying	3 m

It follows from the equation that the cooling of wastewater is mainly caused by the removal of thermal energy. As the flow rate increases, the cooling of wastewater decreases. The amount of low-potential heat removed for a heat pump is affected by the wastewater flow rate. For the sewage heat exchanger calculation, the heat transfer coefficient must be calculated. The heat transfer coefficient depends on the Nusselt criterion, thermal conductivity, and characteristic dimensions.

2.2. Simulation

The behaviour of the sewage heat exchanger is simulated using the cross section. The geometric model of a pipe surrounded by soil is as precise as possible. The calculation network selected is $3 \times 3 \text{ mm}$. The simulated circular DN 1200 pipeline is made from reinforced concrete. The pipeline is laid 3 metres deep and is surrounded by anthropogenic soil, which is quite damp. The model exchangers are made from steel, copper, and stainless steel. Conductive materials were selected for the filling such as concrete, bentonite, and equivalent air. The heat transfer speed is given by the temperature difference and the concrete and soil conductivity. The temperature differences are small, therefore the temperature gradient is small and the heat transfer speed is low. Various boundary calculation conditions were selected based on the period being simulated. At the upper edge of the model, the Dirichlet boundary condition was selected. To determine the soil boundary conditions, a model of a sewage pipeline was made using a $10 \times 10 \text{ cm}$ gross grid. Only the upper boundary condition and the real pipeline temperatures were entered. The subsequent simulation determined the temperatures which were used as further boundary conditions. They are the boundary conditions delimiting the model. In the $3 \times 3 \text{ mm}$ calculation grid, there are Newton boundary conditions. Both the wastewater and the sewage heat exchanger pipeline are approximated as Newton boundary conditions, which represent the temperatures measured or the mean temperatures calculated.

**Figure 1.** Boundary conditions**Figure 2.** Condition of pipeline

To optimize the sewage heat exchanger, it was simulated using various types of material combined with various types of pipeline and filling. The sewage heat exchanger was modelled from steel, stainless steel, and copper. In terms of heat transfer, copper is the most suitable material. However, it is the least suitable due to the aggressiveness of wastewater and the subsequent corrosion. Equivalent air, concrete, and bentonite were used as the fillings.

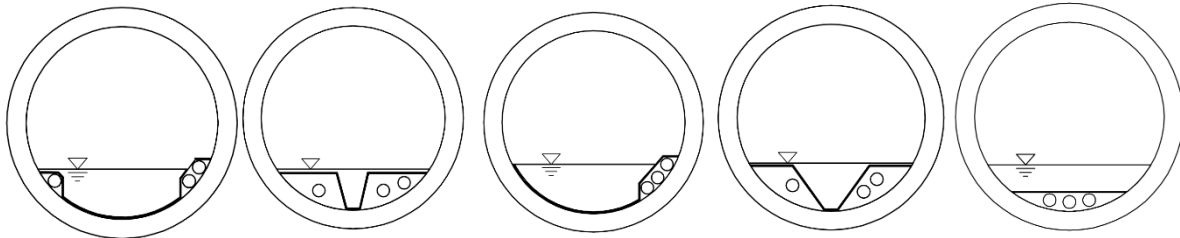


Figure 3. Types of sewage heat exchangers (type 1 from the left)

The goal of the modelling using the CalA software was not only proposing the optimal shape of a sewage heat exchanger for a specific sewage pipeline. The goal was also to find out the optimal number of sewage heat exchangers necessary to cover the need of energy in an office building under certain climatic conditions which are very changeable.

3. Results

The simulation of sewage heat exchangers was carried out using various types of material under various boundary conditions. Several types of sewage heat exchanger were created from stainless metal, steel, and copper. The pipeline was modelled from polyethylene, steel, stainless steel, and copper. The flow speed presumed for all the types of pipeline (for the cold water supply to the exchanger and hot water recovery from the exchanger) was 1.5 m.s^{-1} and the pipe diameter was 76 mm.

3.1. Optimal number of sewage heat exchangers

The simulation was carried out under the selected boundary conditions given for the average annual temperature, for the average winter temperature, and for the mean temperature calculated from temperatures at the inlet and outlet of the sewage heat exchanger. Minimal, average, and maximal flow rates were simulated. The volume weight, specific thermal capacity, and thermal conductivity were presumed based on the material. The results of the simulations show various temperature distributions based on the combination of the materials and boundary conditions.

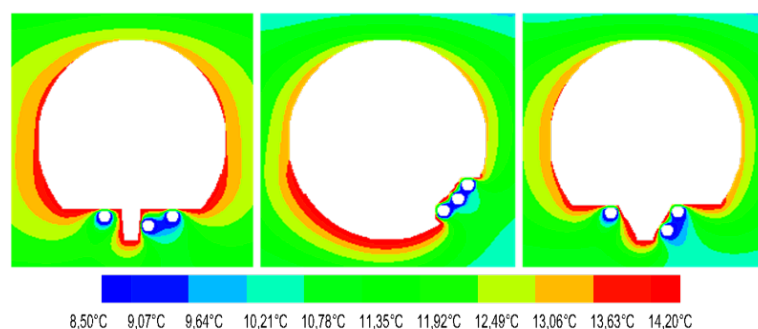


Figure 4. Examples of temperature distributions

From all the combinations of the type 1 exchanger materials, the exchanger capacity per 1 meter length was determined.

It is clear from the graph 1 that the most suitable heat exchanger for a wastewater treatment plant is the type 1 exchanger. This sewage heat exchanger reaches the capacity of around 2.2 kW per 1 meter

length for the average annual temperature for all the selected materials. For the average winter temperature, the capacity of the type 1 sewage heat exchanger is just above $1\text{ kW}\cdot\text{m}^{-1}$. Very good results were also obtained for the type 5, version 2 heat exchanger, whose capacity per one meter length is around 1.7 kW for the average annual values and for the average winter temperatures, it is $0.8\text{ kW}\cdot\text{m}^{-1}$.

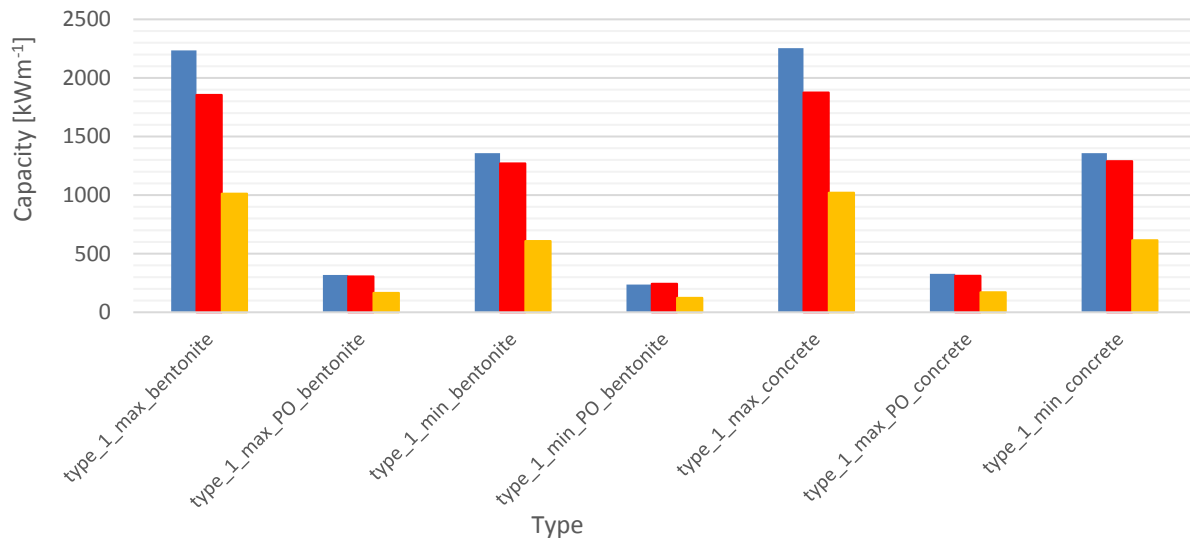


Figure 5. Comparison of the type 1 heat exchanger capacities (average annual temperature – blue, average winter temperature – yellow, mean temperature – red)

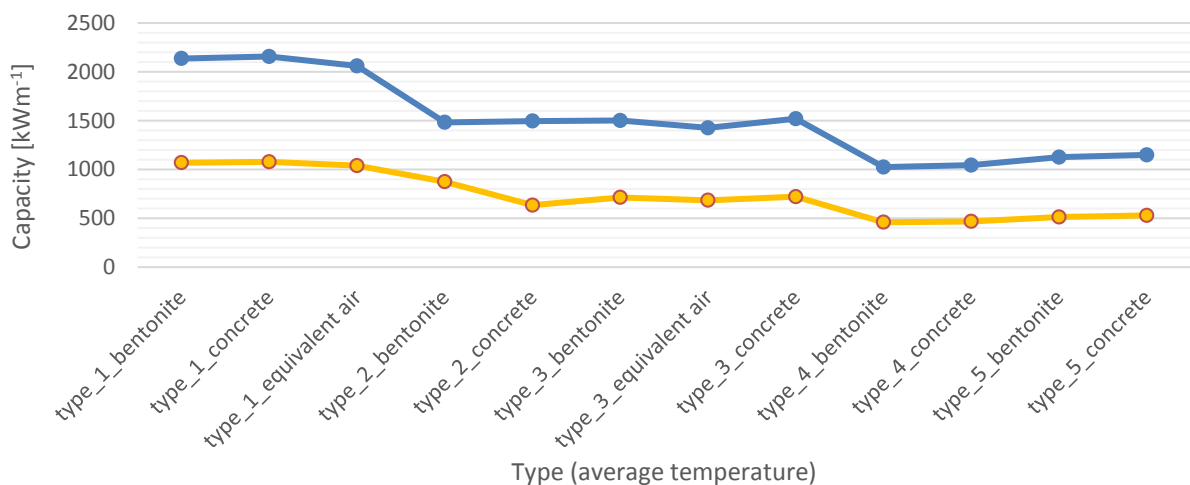


Figure 6. Comparison of the flow rates of all the sewage heat exchanger types (average annual temperature – blue, average winter temperature – yellow)

Heat exchanger 1 has an optimal shape not only in terms of heat transfer but also for the sewer hydraulics. The heat exchanger hardly affects the flow area of the sewer pipes. The shape of this sewage heat exchanger is inspired by the heat exchanger shape used in reality.

The source of heat for heating and hot water heating selected for an office building is the water/water IVAR.HP WW DIPLOMAT O-G3 13 heat pump. The heat pump was designed using the HPC2 computational programme by Thermia. When designing the heat pump, the conditions in a sewage system and the CalA programme simulations results were taken into account. Thanks to the simulation

results, the temperature on the primary side of the heat pump (which means the sewage heat exchanger) could be determined exactly.

3.2. Economic assessment

To verify the suitability of the use of sewage heat exchangers from the economic point of view, a case study was conducted. It aims to verify not only one specific office building which is close to a wastewater treatment plant. There are a large number of such buildings in the Czech Republic and thus the case study may also serve as a model solution for other wastewater treatment plants.

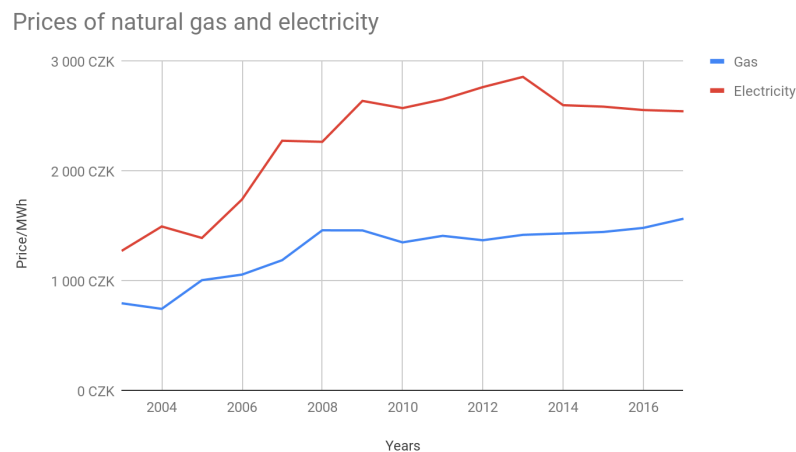


Figure 7. Development of natural gas and electricity prices in the Czech Republic based on offers made by distributors from 2003 to 2017

The year-on-year increase in energy prices was considered for the operating costs. It was derived from the development of energy prices in the Czech Republic between 2003 and 2017. The price of gas increases by 3.27% a year on average and electricity prices go up by 2.99% a year on average. The year-on-year increase in energies was determined based on offers made by energy suppliers for the building type in question.

Table 2. Example of economic assessment of the installation of a heat pump based on the prediction of annual cost of heating for each variant.

	var. 1 gas boiler	var. 2 electric boiler	var. 3 heat pump
Initial costs/years	200, 000 CZK	45, 000 CZK	440, 000 CZK
1	51, 190 CZK	81, 557 CZK	22, 845 CZK
2	52, 864 CZK	83, 987 CZK	23, 526 CZK
14	77, 777 CZK	119, 467 CZK	33, 464 CZK
15	80, 320 CZK	123, 027 CZK	34, 461 CZK
Sum of operating costs over 15 years	971, 148 CZK	1, 514, 646 CZK	424, 270 CZK
Savings over 15 years when using a heat pump	546, 878 CZK	1, 090, 375 CZK	-

The usable area of the office building is 235 m². The envelope of this building was partly modernized, which led to a reduction in its energy intensity. For heating and water heating, it is necessary to supply the building with 31, 420 kWh/a including the loss through heat sharing (hot water heating system). The

subject is assessing the installation of a water-water heat pump with an additional installation of a heat exchanger in a sewer with a total length of 20m. Considering the constant temperature in the sewer, the heating factor is considered to be 4.79 (COP) over the whole year (based on the data supplied by the manufacturer). The cost of the acquisition and assembly of the heat pump, the installation of the sewage heat exchanger and the connection to the existing heating system was determined to be 440,000 CZK incl. VAT based on the offers made by the implementation companies. The expected life of the equipment is 15 years. The cost of service and inspection of the equipment is also included. For comparison, other commonly available heating systems are considered. They include heating through a gas condensing boiler (variant 1) and an electric boiler (variant 2).

3.2.1. Payback method. It is the basic economic indicator giving the return on investment (Payback Period = Initial Investment / Cash Inflow per Period). In both cases, the return on investment takes into account the impact of the year-on-year increase in energy prices. The return on investment does not exceed the lifespan of the investment. The investment may be recommended.

Table 3. Payback method

Variant	Payback
heat pump vs. gas boiler	6.6 y
heat pump vs. electric boiler	5.4 y

3.2.2. Net present value. Another economic indicator expressing an investment discounted to the present value. For the calculation, a discount rate of 5% was applied. It was derived from the economic situation in the Czech Republic and the situation in the bank market.

Table 4. Net present value

Variant	Net present value
heat pump vs. gas boiler	126, 800 CZK
heat pump vs. electric boiler	339, 683 CZK

3.2.3. Internal Rate of Return. Rate of Return (IRR) is metric used in capital budgeting to estimate the profitability of potential investments. A common interest rate for companies in the Czech Republic is 5%. It can be considered minimal for the purpose of IRR assessment. For both the variants, investment in a heat pump with a sewage heat exchanger is advantageous.

Table 5. Internal Rate of Return

Variant	IRR
heat pump vs. gas boiler	11 %
heat pump vs. electric boiler	15 %

4. Conclusion

Using a heat pump as an ecological source may contribute to the reduction of greenhouse gases. However, we can also save money thanks to a high heating factor. The most important aspect for the installation of a sewage heat exchanger is the wastewater temperature and its flow rate. It is not possible to consider only some numbers. The sewer must meet the required conditions throughout the entire year. If the water flow rate decreased, uncontrollable cooling of wastewater could occur, which would have a negative impact not only on the heat pump operation but also on the biological processes taking place

at the wastewater treatment plant. Around 200 sewage heat exchangers were modelled and then simulated from various materials and under various boundary conditions using the CalA software.

The type 1 heat exchanger had the best results. This sewage heat exchanger reaches a capacity of around 2.2 kW per 1 meter length for the average annual temperature for all the selected materials. For the average winter temperature, the capacity of the type 1 sewage heat exchanger is just above 1kW.m¹. Based on the assessment of each variant, an investment in a heat pump as the main source of heating in an office building can certainly be recommended. A positive result can be seen in all the return on investment methods. The assessed solution does not turn out to be borderline for any of the evaluated parameters and its positive impact could be expected even if the initial price got higher or if the efficiency got lower.

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