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Heating system based on heat recovery from sewage

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Abstract

Buildings consume 40% of the total global energy and contribute to over 30% of all CO_2 emissions. Space heating forms a significant part of energy consumption in buildings. A possible solution is to recover waste heat from sewage and to upgrade its exergy using a heat pump. Polymers reduce cost and energy required for manufacturing the heat exchangers. The impact of sewage flow and temperature, heat exchanger dimensions and thermal enhancement of polymers on heat recovery is studied using a Matlab model. The model integrates a sewage heat exchanger with a heat pump and optimizes heat recovery from sewage. A heat pump is used to obtain hot water at 55°C for space heating. Heat recovered from sewage and overall COP are quantified. In case of HPDE with graphite filler, increase in filler content from 0% to 30% increases thermal conductivity from 0.46 to 1.89 $Wm^{-1}K^{-1}$ increasing the heat recovery with 34%. The heat transfer coefficient becomes twice as large when polymer with no filler is enhanced with 30% filler content. Large heat exchange area and variability of sewage level limit the recovered heat.

Keywords: enhanced polymer; sewage heat recovery; heat pump; building heating.

1. Introduction

Buildings consume about 40 % of the total global energy and contribute to over 30 % of all CO_2 emissions [17]. Space heating and cooling and domestic hot water supply form the largest part of the energy consumed in residential buildings [2]. Use of fossil fuels to cope with heating and air-conditioning demands of buildings leads to a series of critical problems such as pollution, climate change and energy shortage [9]. Next to this, the Dutch government has set goals to phase out the use of natural gas and wants to be free from natural gas in 2050. The city of Rotterdam has set a sub target for 2030: 49% CO_2 reduction. Thus, it is vital to develop sustainable technology that can assist in reducing this energy consumption.

A possible route to reduce the energy consumption from buildings is to recover heat from sewage (waste) water. Water that has been affected in quality due to anthropogenic influence is called waste water. According to Hepbasli et al. [5] more than 15% of the thermal energy supplied to buildings is lost through the sewer system. Waste water can be used as a heat source for heat pumps to fulfill the heating and cooling requirements of buildings. These streams are suitable heat sources because, as reported by Frijns et al. [3], in the Netherlands, these flows reach to 1928 Mm^3 per year so that by cooling the flow with 5 K 40.4 PJ heat can be extracted from the flow. Additionally its temperature is higher than ambient in the winter and lower in the summer and daily temperature changes are small.

Currently, mainly in Europe, about 500 Waste Water Source Heat Pumps (WWSHP) are estimated to be in operation with thermal rating in the range of 10 - 20,000 kW. Installation of WWSHP systems can be either in the sewer system or after the waste water treatment plant (WWTP).

Nomenclature

Roman symbols	*Greek symbols*	req	Required

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A	Area	m^2	α	Heat transfer coef.	$Wm^{-2}K^{-1}$	s	Tube surface
c_p	Specific heat	$kJkg^{-1}K^{-1}$	Δ	Difference		sub	Submerged
d	Diameter	m	λ	Thermal conductivity	$Wm^{-1}K^{-1}$	sw	Secondary water
l	Length	m	μ	Dynamic viscosity	Pa s	t	Tube
LMTD	Log. Mean ΔT	K	ρ	Density	kgm^{-3}	tot	Total
$\dot{m}$	Mass flow rate	Kgs^{-1}				ww	Waste water
N	Number	-	*Subscripts*				
P	Perimeter	m	act	Actual	*Abbreviations*		
Q	Energy	kWh	c	Cross sectional	HDPE	High density polyethylene	
$\dot{Q}$	Heat flow	kW	ch	Sewage channel	LDPE	Low density polyethylene	
r	Radius	m	comp	Compressor	MEG	Mono-ethylene glycol	
T	Temperature	ºC or K	cond	Condenser	PC	Polycarbonate	
U	Overall heat transfer coef.	$Wm^{-2}K^{-1}$	elec	Electrical	PPS	Polyphenylene sulphide	
v	Velocity	ms^{-1}	hyd	Hydraulic	PS	Polystyrene	
W	Work	kJ	in	Inlet	WWHEX	Waste water heat exchanger	
$\dot{W}$	Power	kW	o	Outer diameter	WWSHP	Waste water source heat pump	
YTS	Yield strength	MPa	out	Outlet	WWTP	Waste water treatment plant	

Although recovering heat after WWTP would eliminate the risk of bio-film growth in the heat exchanger, the maximal temperature of waste water is usually at the initial stages of the sewer system. Moreover, heat recovery location in the sewer is closer to the consumers than waste water treatment plants [16].

A WWSHP consists of three components (i) Waste Water Heat Exchanger - Heat is recovered from waste water (ii) Heat pump - The heat recovered is upgraded to be used in the heating system of buildings (iii) Distribution system of heating and cooling in buildings.

Waste water can lead to the fouling of the waste water heat exchanger. Fouling occurs when fluid degrades near heat transfer surface or solids deposit on surface. Sometimes, microorganisms create bio-film matrices on heat exchange surface which will also result in reduced heat transfer performance of the heat exchanger [2]. Liu et al. [9] have reported that the convective heat transfer and fouling resistances on the sewage side of the waste water heat exchanger accounted for 80% of the total thermal resistance of their system.

In this paper, sustainable and economic system design is considered to recover waste heat from sewage for heating / cooling of buildings to reduce their carbon footprint. The "Doelen" case in Rotterdam is considered to illustrate the benefits of heat recovery in terms of renewable energy, economics and sustainability of installing such systems in sewers. The Doelen is a concert venue and convention center in Rotterdam, Netherlands. The heat recovered from sewage will contribute to the heating requirements of 'Doelen'. Furthermore, polymer sewage heat exchangers are considered for heat recovery due to their advantages such as low cost, lesser weight, lower fouling and higher corrosion resistance. It is estimated that the energy required to produce a unit mass of polymers is two times lower than of common metals, which makes polymer heat exchangers environmentally friendly [1].

The objective of this study is to develop technology that provides a strong basis for scaling up sewage waste heat recovery systems for large urban areas. The scope includes designing, modeling and validation of the most suitable polymer heat exchangers for heat recovery from sewage systems.

2. State-of-the-art

2.1. Sewage heat recovery potential

About 70% of the total drinking water produced in the Netherlands is used for domestic purposes [6, 15] and contributes most to the temperature of the sewage flow. Roest et al. [12] report that drinking water enter the sewage at around 27 ºC and the water from bathing and showers at 38 to 40 ºC. Tap water and water from the dish washer and washing machine enter the sewage at approximately 40 ºC. According to Hofman et al. [6] these flows correspond to 40 % of the total energy losses from modern Dutch dwellings. The temperature of the effluent leaving the WWTP was found to be roughly 15 ºC. Cooling the total effluent flow (1928 Mm^3/year, [3]) with 5 K ΔT from 15 ºC to 10 ºC delivers 40.4 PJ low temperature energy available as heat source for heat pumps. With a COP of 4 these heat pumps could deliver 53.9 PJ of heat at 55 ºC at national level and 1.6 PJ for a town with 500,000 inhabitants. This is sufficient to cover 12% of the heating requirements of the built environment (448 PJ in 2015).

2.2. Possible sewage heat recovery locations

Heat recovery from sewage can be done in three locations of the sewage network [2]. Heat can be recovered at the source of sewage (buildings), or in the sewage line or after the treatment of sewage.

Waste water temperature affects the water treatment process. Nitrification, one of the steps of water treatment, is a temperature dependent process. Growth of nitrifying bacteria is impeded at lower waste water temperatures [16].

Looking at the pros and cons of each location, recovering heat from the sewage network is more advantageous since waste water flow is higher and continuous in comparison to the decentralized domestic sewage system. The problem with recovering heat after treatment is that the WWTPs are located far away from residential buildings, implying additional investment on pipelines and insulation.

2.3. Waste Water Heat Exchangers

Liu et al. [9] report the COP of a WWSHP system designed for the (partial) heating supply of a residential building with 10,000 occupants in Dalian, China. The system can be used for heating and cooling. Heat recovery is of the indirect type so that the waste water exchanges heat with a secondary flow in a heat exchanger, after which it is sent back to the municipal sewage pipeline. This system uses a shell and tube heat exchanger.

Spriet and Hendrick [14] developed a simulation to evaluate the potential of heat recovery from waste water. The model has been validated using experimental data of an installation located in Myrtes (Brussels), Belgium. The sewage heat exchanger is installed in the sewer while the heat pump is placed in a machine room. The recovered heat is used for heating of a conditioned space. The waste water heat exchanger is of the multi-row tube type. HDPE tubes are connected in series in multiple tube rows. A solution of glycol in water (MEG 33 %) is used as the heat transfer medium inside the tubes to recover heat from waste water.

Among the two WWSHP systems described, the first one used a metallic shell and tube heat exchanger for heat recovery from waste water. The use of shell and tube was only possible because the sewage was cleaned off of the fouling elements using complex anti-clogging equipment. The anti-clogging system requires regular maintenance and adds to the overall cost of the system. Thus, considering the overall system complexity, space requirements and the cost of metallic heat exchangers, the system used in Myrtes was selected for further investigation in this study. Experimental data and simulation results of the Myrtes site can then be used for validation purposes.

2.4. Polymer materials

Different polymers have been compared based on the values of three of the most important features : thermal conductivity, λ, yield strength (YTS) and cost of raw materials. The four polymers with the highest thermal conductivity are listed in Table 1. PS is included because it is commonly used in heat exchangers.

The fillers used in polymer composites are particles, fibers, flakes and laminas. Chen et al. [1] provide a list of some composites with their matrix material, filler material, filler volume and the resulting thermal conductivity values. For instance, the thermal conductivity of PS (0.14 $Wm^{-1}K^{-1}$) rises to 0.25 $Wm^{-1}K^{-1}$ when 10 % graphite is added as filler to the material and to 0.90 $Wm^{-1}K^{-1}$ when 30% graphite is added.

Table 1. Commonly used polymers with highest thermal conductivity. Please consult the list of abbreviations in the nomenclature for the polymer specifications. The thermal conductivity of copper, a frequently used material in heat exchangers, is 401 $Wm^{-1}K^{-1}$ and copper costs around 5.54 €/kg.

Polymer	λ_t [$Wm^{-1}K^{-1}$]	YTS [MPa]	Cost [€kg^{-1}]
HDPE	0.46	25.9	0.54
LDPE	0.30	10.8	0.57
PPS	0.30	68.9	1.10
PC	0.20	62.0	1.10
PS	0.14	43.9	0.90

The advantage of having high YTS is that the thickness required to withstand pressure can be lower. Low thickness leads to higher *U*-values. When compared to metals, the benefit of low cost of polymers far outweighs that of high thermal conductivity of metals. Among the remaining options, HDPE shows the highest λ value and a relatively high YTS. For this reason, HDPE has been selected for application in the sewage heat exchanger.

3. System model

3.1. Local characteristics of sewage network

The model concerns a specific sewage channel in the center of Rotterdam. The data required for modeling of the sewage heat recovery system such as sewage channel dimensions, sewage temperature and sewage flow has been provided by the Municipality of Rotterdam.

The dimensions of the sewage channel considered for the installation of waste water heat exchanger are as shown in Fig. 1. The sewage channel is located in the center of Rotterdam near the 'Doelen'. The sewage channel is approximately oval shaped with the flow passage area spanning 1.5 m in width and 1.44 m in height.

Number of tubes of heat exchanger actually submerged in sewage flow, hydraulic diameter of the channel, flow cross-sectional area and sewage flow velocity are all dependent on the sewage level. These parameters are dynamically evaluated for each sewage level. The angle between the horizontal and l_2 is 30°. When the sewage level is higher than l_4, the flow area is divided into a trapezium with sides l_1; l_2; l_5; l_3 and a rectangle with area l_5 x l_6. In that case, the length of the sides l_6=l_7 is calculated as the difference in sewage level and l_4. For sewage level lower than l_4, the flow area is just a trapezium and length of sides l_6=l_7 is 0. From a measurement in 2018, the highest sewage level that can be attained is 0.5 m. Thus, the maximum possible value for l_4 + l_6 is 0.5 m. Dimensions of the sewage channel calculated for the sewage level of 0.5 m are provided in Table 2.

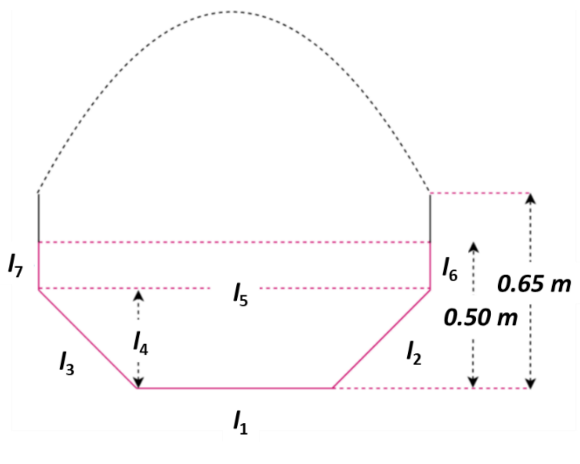

Fig. 1. Schematic of the cross section of the sewage channel.

Table 2. Dimensions of the sewage channel for a sewage level of 0.5 m.

l_1 [m]	l_2 [m]	l_3 [m]	l_4 [m]	l_5 [m]	l_6 [m]	l_7 [m]	$P_{tot,ch}$[m]	P_{ch}[m]	$d_{hyd,ch}$[m]	$r_{hyd,ch}$[m]	$A_{c,ch}$[m^2]
0.50	0.58	0.58	0.29	1.50	0.21	0.21	3.58	2.08	0.68	0.17	0.61

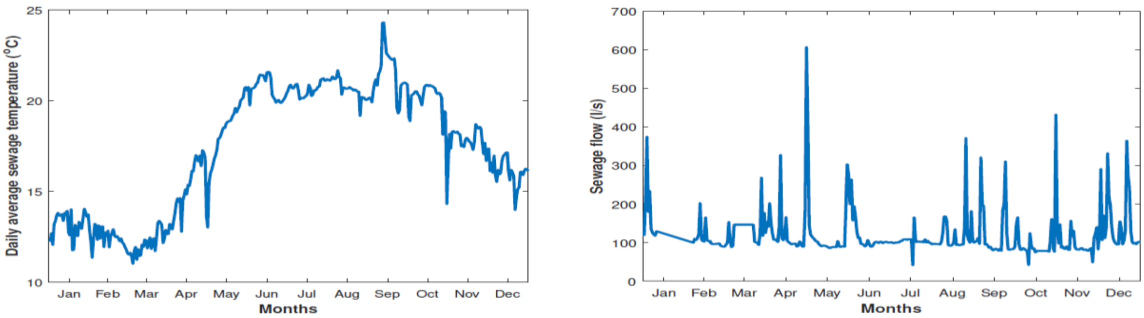

Fig. 2. Daily averaged temperature (left) and volumetric flow rate (right) of the sewage flow in 2018.

Sewage temperature values were available in intervals of 5 minutes for each day of the year 2018. Since the daily variation of sewage temperature was not significant, daily average was calculated for each day of the year and was considered to be the sewage temperature for that day. Variation of daily average sewage temperatures throughout the year is plotted in Fig. 2 (left). Sewage temperature was found to vary between a maximum of 24.3 ºC to a minimum of 11 ºC. It can be seen that sewage temperatures are higher in the summer (June, July and August) and lower in the winter.

The volume flow rate is given in Fig. 2 (right) and, in 2018, varied between a maximum of 606.8 l/s to a minimum of 41.5 l/s. Sewage flow velocity and level were calculated based on flow data and channel dimensions. From the known data that the highest sewage level in 2018 was 0.5 m, sewage levels for all other flow rates were interpolated linearly with sewage flow. The sewage level variation is plotted in Fig. 3 (left). Velocity of sewage flow was estimated from sewage flow rate, sewage level and the corresponding channel dimensions. Flow area is dependent on the sewage level and sewage level is dependent on flow. Fig. 3 (right) shows the variation of sewage velocity along the year. It can be observed that on the day of the highest sewage level, flow velocity is the lowest. Sewage velocity varied between a minimum of 1 m/s to a maximum of 2.17 m/s. The corresponding Reynolds number varied between 15000 and 76000, indicating turbulent flow.

The mass flow rate of sewage can be obtained from its velocity using eq. (1).

$$\dot{m}_{ww} = \rho_{ww} \cdot A_{c,ch} \cdot v_{ww} \tag{1}$$

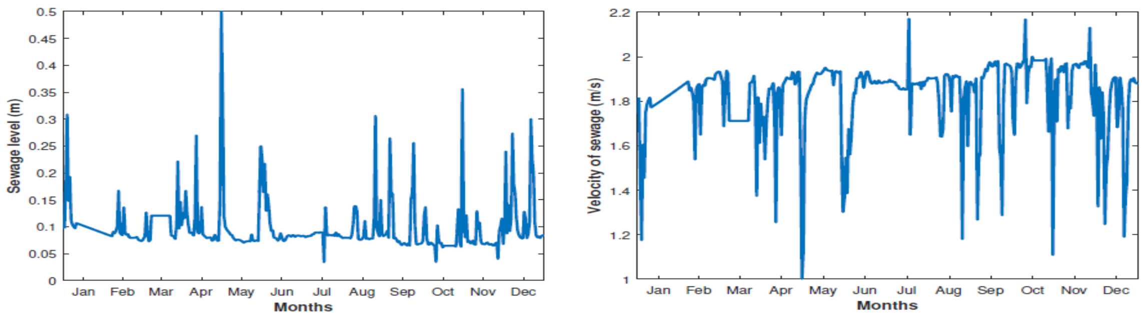

Fig. 3. Daily averaged sewage level (left) and velocity (right) of the sewage flow in 2018.

3.2. Waste water source heat pump (WWSHP) system

The waste water source heat pump systems considered in this work are schematically illustrated in Fig. 4. In the winter, heat is recovered from the sewage and in the summer rejected to the sewage. For this reason a reversible heat pump is used. Polymer waste water heat exchangers (WWHEX) are used to transfer heat with the sewage. Four heat exchangers are installed in parallel inside the sewage channel as illustrated in Fig.4.

Secondary water (a solution of glycol in water) is used as an intermediate fluid between the heat pump and the WWHEXs.

During the winter secondary water transfers the heat recovered from the sewage to the refrigerant in the evaporator of the heat pump. In the evaporator, the hot secondary water is cooled to a temperature 2 K higher than the evaporation temperature. The heat required by 'Doelen' is supplied by the condenser of the heat pump. The condensation temperature is set at 55 ºC. The water used for heating in the 'Doelen' is heated from 25 ºC to about 53 ºC in the condenser and then supplied to the heating network of the 'Doelen'. In the summer, the heat pump is operated in reverse. Chilled water from the cooling network of 'Doelen' is cooled from 14 ºC to 10 ºC in the evaporator of the heat pump which operates at 8 ºC. The condensation temperature of the heat pump is varied such that the secondary water inlet temperature to the waste water heat exchanger is higher than the sewage temperature.

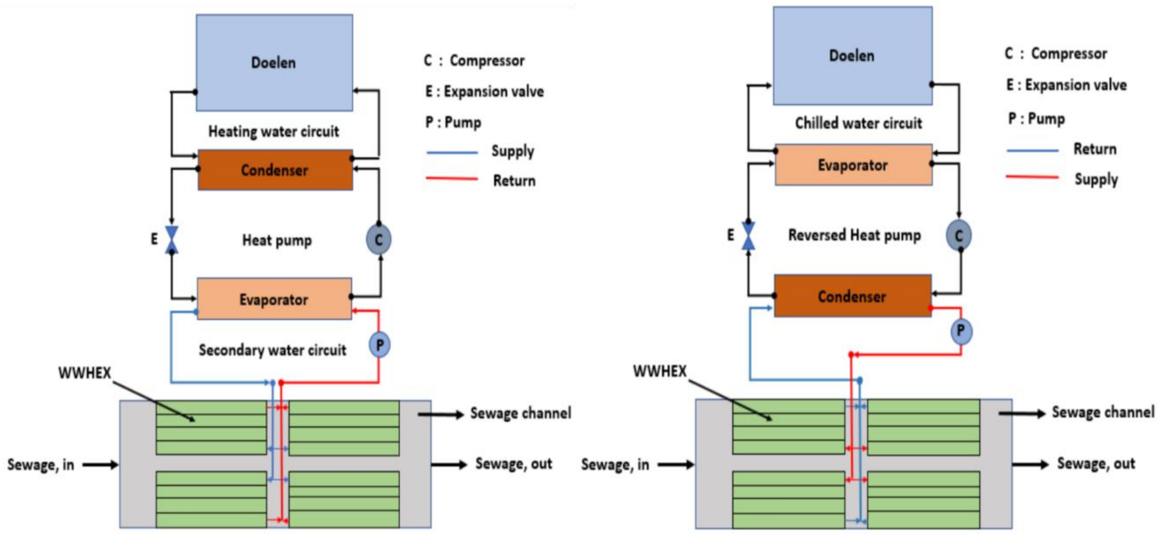

Fig. 4. WWSHP system as connected during the winter season (left) and summer season (right).

Winter and summer situations are simulated separately due to the differences in operation. For each combination of tube length and diameter of the waste water heat exchanger, the winter model is simulated on a daily basis for nine months of winter. In the heat recovery system, the sewage and heat pump condensation temperature are the only known values while all other temperatures are unknown. Based on the sewage temperature, the secondary water outlet temperature ($T_{sw,out}$) is set. The secondary water inlet temperature ($T_{sw,in}$) is varied from 0 ºC to a temperature 2 K lower than $T_{sw,out}$. The evaporation temperature of the heat pump is set 2 K lower than $T_{sw,in}$. For each of the 9 months, a primary inner loop was run for the number of days of that month while a secondary inner loop ran over all combinations of temperatures until the increase in *COP* of the system was less than 5% (convergence criterion). Once the combination of temperatures with the optimized *COP* is found, the secondary inner loop is terminated and the calculations for the next day start. After the winter model has been simulated for 9 months, the total heat recovered, heat supplied, required pump and compressor power and seasonal *COP* are calculated. After that, the same calculations were repeated for the next combination of tube dimensions. At the end, all the seasonal performance parameters are compared to find the most optimal heat exchanger tube dimensions.

The same set of optimized tube dimensions are used for the summer model since the waste water heat exchanger installation is the same in the summer. In the summer, the secondary water rejects heat to the sewage, thus its temperature is set higher than the sewage temperature. The increase in secondary water temperature ($T_{sw,in} + \Delta T$) at the inlet of waste water heat exchanger over $T_{ww,in}$ is varied from 10 K to 50 K to study the effect on system performance. Thus, the summer model was simulated for different secondary water inlet ($T_{sw,in}$) temperatures. For each $T_{sw,in} + \Delta T$, a primary inner loop iterated over the summer months. A secondary inner loop iterated over all the days of the summer where the condensation temperature was set to be equal to $T_{sw,in}$ + 2 K and the secondary water outlet temperature ($T_{sw,out}$) is set 2 K higher than the daily average sewage temperature. Similar to the winter model, all the seasonal values of the system performance indicators are calculated to find the most optimum value for $T_{sw,in}$.

3.3. Waste water heat exchanger

The WWHEX has sewage on the hot side and secondary water on the cold side in the winter and vice-versa in the summer. Multi-row polymer tube heat exchanger is selected as the WWHEX type. The polymer tubes are arranged in series. To reduce the pressure drop, the total secondary water flow required is distributed among 4 parallel heat exchangers which have tubes arranged in series. All the tube rows are installed against the surface of the sewage channel, so that the sewage flows directly over the polymer tubes. From initial analysis, it was concluded that, due to low thermal conductivity of the polymer tubes, a large number of tubes is required. For this reason the tubes are closely packed. Fig. 5 illustrates the cross sectional view of an indicative tube arrangement to assist the understanding of modeling of the heat exchanger. All the dimensions in the diagram are in mm. Fig. 5 indicates the tube arrangement for a sewage level of 0.5 m and depicts two heat exchangers placed symmetrically. In each heat exchanger, the tubes are connected in series. One heat exchanger is on the RHS and another on the LHS. A small separation between the two can be seen on the bottom side. Two more heat exchangers are placed along the channel adjacent to these two heat exchangers. A common header was used to carry the total secondary water flow, which was split into the 4 heat exchangers.

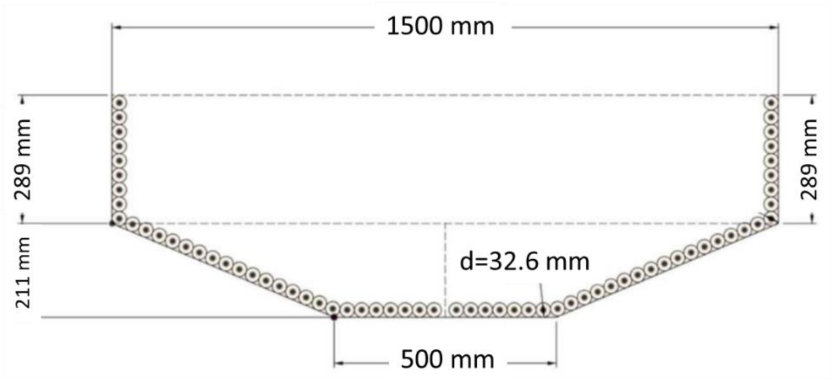

Fig. 5. Cross section of the sewage channel showing the arrangement of the polymer tubes along the surface of the channel. Fig. 3 shows that the liquid level is generally lower so that preferably only the trapezium part of the channel should be covered with tubes.

3.4. Design duty for WWHEX

The WWHEX has been designed to exchange (recover/reject) 180 kW from the sewage. It should recover 180 kW during the day with the lowest temperature in the winter and to reject 180 kW to the sewage during the hottest day in the summer. The months of September to May are the months requiring heating (winter). The rest of the months, June to August are the months requiring cooling (summer). The required heat duty of the waste water heat exchanger was considered to scale linearly with the ambient temperature. Thus, 180 kW should be recovered from sewage during the day with the lowest outside temperature while no heat should be recovered ($\dot{Q}_{ww} = 0$ kW) when the ambient temperature is above 20 ºC in the winter. In the summer, 180 kW should be rejected to the sewage on the hottest day and cooling is not required on those days when ambient temperature is lower than 20 ºC. Heat recovered from the sewage was considered to be equal to the capacity of the evaporator in the winter and the heat rejected to sewage to be equal to condenser capacity in the summer. Fig. 6 (left) depicts the variation of ambient temperature in 2018 and the required heat exchange with sewage in the winter and Fig. 6 (right) indicates the heat to be rejected to the sewage in the summer. A horizontal line marking 20 ºC is shown in both plots. It can be seen that in the winter when the ambient temperature crosses the 20 ºC line, the heat duty goes to zero and in the summer, the heat duty goes to zero when the ambient temperature is below the 20 ºC.

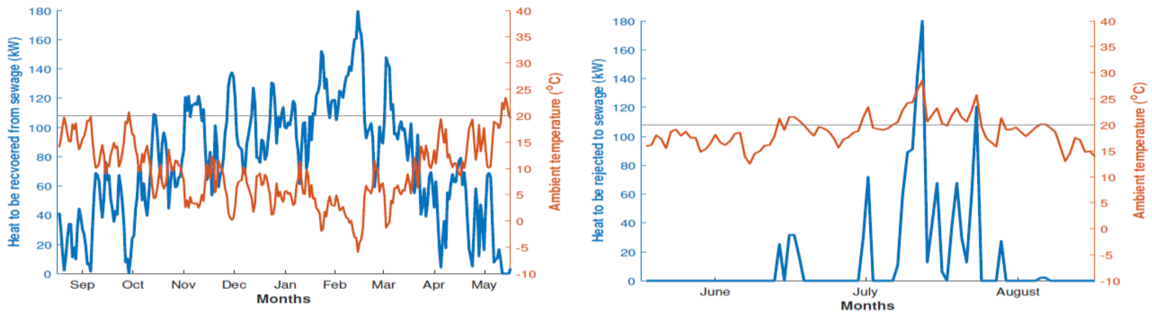

Fig. 6. Heat to be extracted from the sewage in the winter season (left) and rejected to the sewage in the summer season (right).

Due to the large sewage flow, reduction in sewage temperature was negligible after heat extraction. Thus, the physical properties of sewage at inlet and outlet of waste water heat exchangers were considered to be the same. Due to the fact that exact data indicating the quantitative and qualitative analysis of the sediments in the sewage of Rotterdam was not available, properties of water were considered for sewage water calculations. Measurements by the Municipality indicated that the sediments were low in the sewage channel considered. Properties of water have been evaluated as a function of the sewage temperature.

Flow of sewage in the sewage channel was approximated to flow through tubes. Hydraulic diameter of the channel based on the sewage level was considered to be the diameter of the channel for Nusselt number calculation. Thus, the convective heat transfer coefficient on the sewage side (α_{ww}) was calculated based on sewage flow velocity (v_{ww}) and hydraulic diameter of the channel ($d_{hyd,ch}$). Properties of sewage such as λ_{ww}, μ_{ww}, ρ_{ww} and $c_{p,ww}$ required for the calculation of (α_{ww}) were calculated at the sewage temperature.

The secondary fluid was a mixture of water and mono-ethylene glycol with a concentration leading to a freezing point of -20 °C. The properties of this mixture have been obtained from Melinder [10]. The mass flow of secondary water has been obtained with eq. (2) where the heat duty is obtained from Fig. 6 and ΔT_{sw} is the temperature change of the secondary water as it passes the heat exchanger.

$$\dot{m}_{sw} = \frac{\dot{Q}_{ww}}{c_{p,sw} \cdot \Delta T_{sw}} \tag{2}$$

The velocity of the secondary water through the heat exchanger tubes follows from the cross section of the flow, the density and the number of heat exchangers in parallel (4). The convective heat transfer coefficient on the secondary water side α_{sw} was calculated using the same correlations as for the sewage side [11]. A fouling resistance of 0.00067 m^2KW^{-1} [9] has been assumed on the sewage side and of 0.0002 m^2KW^{-1} [13] on the secondary water side. These extra resistances have been included in the calculation of the overall heat transfer coefficient based on the external area of the tubes, U_o.

Based on the value of U_o, LMTD and the heat duty per heat exchanger, the external surface area of the tubes ($A_{tot,t}$) required per heat exchanger was obtained from eq (3).

$$A_{tot,t} = \frac{\dot{Q}_{ww,req,1}}{U_o \cdot LMTD} \tag{3}$$

This allowed for the calculation of the required number of tubes. The number of tubes must be even to ensure that the return line can be connected from the same side as that of the supply line. The number of tubes required per heat exchanger was compared with the total number of tubes that were submerged in sewage at any given time ($N_{t,sub}$) to see if it was feasible. $N_{t,sub}$ depends on sewage level with corresponding wetted perimeter, tube diameter and tube pitch. The actual heat recovered from the sewage per heat exchanger is then obtained from eq. (4).

$$\dot{Q}_{ww,act,1} = U_o \cdot \frac{N_{t,sub}}{2} \cdot A_{s,t} \cdot LMTD \tag{4}$$

With $A_{s,t}$ the surface area of a single tube. The pressure drop on the secondary flow side was obtained from the number of tubes and connecting elbows, length of the tubes, connecting header and mass flow through the heat exchanger. This pressure drop allowed for calculation of the power consumption of the pump. For the heating period, the instantaneous COP was then obtained from eq. (5).

$$COP = \frac{\dot{Q}_{cond}}{\dot{W}_{sw,pump} + \dot{W}_{comp}} \tag{5}$$

The working fluid of the heat pump was propane (R290). In the winter season the condensation temperature of the cycle was maintained at 55 ºC. The temperature of the refrigerant at the outlet of the compressor was then around 64 ºC. In the condenser, the refrigerant was cooled from 64 ºC to a sub-cooled temperature of 30 ºC. Water from the 'Doelen' heating system was heated from 25 ºC to 53 ºC with a pinch of 5 K in the condenser. The secondary water temperature $T_{sw,in}$ at the outlet of the evaporator was the limiting factor for the evaporation temperature. The evaporation temperature of the heat pump was set 2 K lower than $T_{sw,in}$ to prevent temperature cross-over. $\dot{Q}_{cond}$ and $\dot{W}_{comp}$ were obtained from the heat pump model making use of Refprop [8] for the propane properties.

4. Model results

4.1. Validation

The data reported by Spriet and Hendrick [14] collected in Myrtes has been used for validation purposes. This test plant makes use of 30 HPDE tubes of 6 m long with internal diameter of 32 mm and a wall thickness of 2.13 mm. The recovered heat is upgraded making use of a R410A heat pump. During the experiments, the sewage flow varied between 5 and 60 m^3/h and its temperature from 6 to 18 ºC. The secondary water (MEG) was pumped over 230 m. Table 3 compares the reported experimental data with the results of the model proposed in this work.

Table 3. Comparison of the experimental data of the Myrtes plant and the proposed model.

Parameter	Myrtes plant data	Present model
Heat recovered from sewage [kW]	2.5 – 5.5	1.2 – 5.5
Heat delivered by heat pump [kW]	3.2 – 7.0	2.7 – 7.4
COP	3.7 – 5.0	3.9

In general the model predicts reasonably well the peak values recovered and delivered by the system. The lower values of the recovered heat and delivered heat are lower in the present model. The reason for this deviation is that the sewage design of Rotterdam was assumed to apply for Myrtes since its real geometry was not reported by the Spriet and Hendrick [14].

4.2. Tube dimensions of waste water heat exchanger

The winter model was run for 6 combinations of tube lengths and diameters. Standard HDPE tube lengths of 12 m and 30 m and tube inner diameters of 17 mm, 29 mm and 58 mm were selected for these simulations. The lowest COP value was observed for the combination of l_t = 30 m and $d_{i,t}$ = 17 mm while the highest COP was observed for $d_{i,t}$ = 58 mm options. Smaller tube diameters resulted in more heat recovery due to higher secondary water velocity (hence higher U_o). The highest amount of heat recovered from the sewage was for l_t = 30 m and $d_{i,t}$ = 17 mm. The lowest amount of heat recovered was for the l_t = 12 m and $d_{i,t}$ = 58 mm combination. Table 4 provides the seasonal values of COP, heat recovered from sewage, total electrical energy required to run the pump and the compressor along with a cost comparison. The cost column includes the cost of the waste water heat exchanger and the cost of electricity. The cost of heat exchanger is based on the weight of material used in the heat exchanger and the specific price of the material. It is assumed equal to three times the material cost. The cost of electricity was considered to be 50.7 €/MWh [4]. The system performance was quantified as the amount of heat delivered to 'Doelen', Q_{cond}, per unit cost (kWh/€).

Table 4. Optimization of tube dimensions for the waste water heat exchanger.

Dimensions		Q_{cond}	Q_{ww}	W_{elec}	N_t	Cost [€]			kWh/€	*COP*
l_t [m]	$d_{i,t}$ [mm]	[MWh]	[MWh]	[MWh]		WWHEX	W_{elec}	Total		
	17	236	181	66	200	396	3346	3742	63	3.6
12	29	131	103	30	128	415	1521	1936	**68**	**4.5**
	58	43	34	9	64	403	456	859	50	4.6
	17	535	405	331	200	989	16782	17771	30	1.6
30	29	486	374	126	128	1037	6388	7425	**65**	**3.9**
	58	188	148	41	64	1007	2079	3085	61	4.6

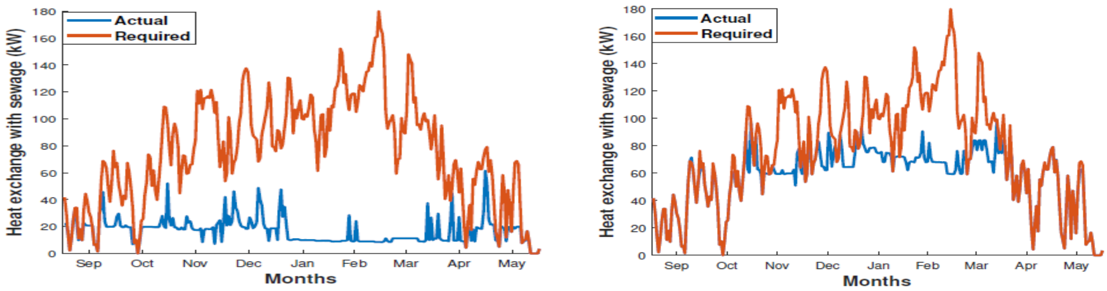

Fig. 7. Difference between the required (red) and recovered (blue) heat from the sewage for the 29 mm tube. Left for tubes of 12 m; right for tubes with 30 m.

The best two options were $d_{i,t}$ = 29 mm, l_t = 12 m and $d_{i,t}$ = 29 mm, l_t = 30 m. The 12 m option delivered 68 kWh/€, while the 30 m option delivered 65 kWh/€ which is only 4.6% lower. Thus, to make a choice between l_t = 12 m and l_t = 30 m, a comparison between the actual heat recovered and the required heat exchange with the sewage was compared as shown in Fig. 7. The heat recovered in the case of l_t = 12 m option was much lower than what was necessary (Fig. 7 left), while it was much better in the case of l_t = 30 m (Fig. 7 right). Thus, making use of just one heat exchanger with l_t = 12 m was not sufficient to recover the required amount of heat. Thus, l_t = 30 m and $d_{i,t}$ = 29 mm were chosen as the optimized tube dimensions.

Based on the time dependent sewage temperature values, secondary water inlet and outlet temperatures were determined. Based on secondary water inlet (to waste water heat exchanger) temperature, the heat pump evaporation temperature was determined (2 K lower). Condensation and evaporation temperature of the heat pump, sewage inlet and outlet temperatures and secondary water temperatures for the winter season are plotted in Fig. 8 left. The optimum COP of the system was obtained when the temperature of the secondary water increased by 10 K. Fig. 8 right shows how the COP of the system changes during the heating season.

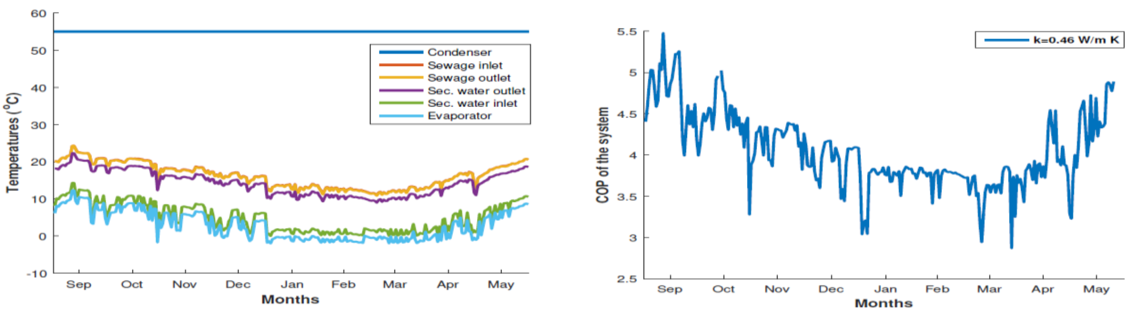

Fig. 8. Change of the operating temperatures during the heating season (left). Notice that in and outlet of sewage are the same. Right: the change of system COP during the heating season.

4.3. Effect of using enhanced polymers

Table 5 shows a comparison of WWSHP system performance in the winter and summer. Increase in thermal conductivity of the polymer tubes from 0.46 to 1.89 $Wm^{-1}K^{-1}$ enhances heat recovery in the winter much more than in the summer. The electrical energy consumption was higher in the winter due to longer period of operation (9 months) and more heat recovery. Seasonal COP value of summer was higher than winter for both the cases (of thermal conductivity). The increased U_o in both the cases was almost two times the initial value.

Table 5. Optimization of tube dimensions for the waste water heat exchanger.

Season	λ_t [Wm^{-1}K^{-1}]	U_o [Wm^{-2}K^{-1}]	Q_{cond} [MWh]	Q_{evap} [MWh]	W_{elec} [MWh]	Cost [€]			kWh/€	COP
						WWHEX	W_{elec}	Total		
Heating	0.46	149	486	374	126	1037	6388	7425	65.5	3.9
Cooling		143	26	23	3		152	1189	19.3	7.3
Heating	1.89	296	650	495	211		10698	11735	55.4	3.1
Cooling		290	30	27	4		203	1240	21.8	6.9

5. Conclusions

The feasibility of using locally the sewage network to deliver heat to buildings in the center of Rotterdam has been investigated. Polymer heat exchangers to be submerged along the sides and bottom of the sewage channel have been proposed in combination with a heat pump delivering heat at 55 ºC. The following has been concluded:

- Using HDPE tubes 8.1 MWh/m$_{sewage}$ heat at 55 ºC can be delivered yearly. The system yearly averaged COP is then 3.9. To deliver 1 PJ of heat 34.3 km of sewage need to be equipped with such heat exchangers.
- Using thermally enhanced HDPE tubes 10.8 MWh/m$_{sewage}$ heat at 55 ºC can be delivered yearly. The system yearly averaged COP is then 3.1. To deliver 1 PJ of heat 25.7 km of sewage need to be equipped with such heat exchangers.
- The heat exchangers can be designed to deliver local heating requirements during the whole heating season.

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References

[1] Chen X, Su Y, Reay D, Riffat S. Recent research developments in polymer heat exchangers - A review. Renewable and Sustainable Energy Reviews; 2016; **60**:1367–1386.
[2] Culha O, Gunerhan H, Biyik E, Ekren O, Hepbasli A. Heat exchanger applications in waste water source heat pumps for buildings: A key review. Energy and Buildings; 2015; **104**: 215–232.
[3] Frijns J, Hofman J, Nederlof M. The potential of (waste)water as energy carrier. Energy Conversion and Management; 2013; **65**:357–363.
[4] Greunsven J, Derks M. Tennet - Annual Market Update. page 3, 2018.
[5] Hepbasli A, Biyik E, Ekren O, Gunerhan H, Araz, M. A key review of waste water source heat pump (WWSHP) systems. Energy Conversion and Management; 2014; **88**:700–722.
[6] Hofman J, Hofman-Caris R, Nederlof M, Frijns nJ, van Loosdrecht M. Water and energy as inseparable twins for sustainable solutions. Water science and technology; 2011; **63**:88–92.
[7] Hussain ARJ, Alahyari AA, Eastman SA, Thibaud-Erkey C, Johnston S, Sobkowicz MJ. Review of polymers for heat exchanger applications: Factors concerning thermal conductivity. Applied Thermal Engineering; 2017; **113**:1118–1127.
[8] Lemmon, E. W., Huber, M. L. and McLinden, M. O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg. 2013.
[9] Liu Z, Ma L, Zhang J. Application of a heat pump system using untreated urban sewage as a heat source. Applied Thermal Engineering; 2013; **62**:747–757.
[10] Melinder A. Properties of secondary working fluids for indirect systems. International Institute of Refrigeration, 2010.
[11] Mills AF. Basic heat and mass transfer. Prentice Hall, New Jersey, 1999, p. 269-280.

[12]Roest K, Hofman J, van Loosdrecht M. De Nederlandse watercyclus kan energie opleveren. H_2O; 2010: **47**(25/26):47–51.
[13]Sinnott RK, Towler G. Chemical Engineering Design. Elsevier. Butterworth-Heinemann, 5th edition, 2009. Chapter 12 – Heat transfer equipment, p. 815-978.
[14]Spriet J, Hendrick P. Waste water as a heat source for individual residence heating: A technoeconomic feasibility study in the Brussels capital region. Journal of Sustainable Development of Energy, Water and Environment Systems; 2017; **5**:289–308.
[15]van der Hoek JP, de Fooij H, Struker A. Wastewater as a resource: Strategies to recover resources from Amsterdam's waste water. Resources, Conservation and Recycling; 2016; **113**:53–64.
[16]Wanner O, Panagiotidis V, Clavadetscher P, Siegrist H. Effect of heat recovery from raw waste water on nitrification and nitrogen removal in activated sludge plants. Water Research; 2005; **39**(19):4725–4734.
[17]Yang L, Yan H, Lam JC. Thermal comfort and building energy consumption implications - A review. Applied Energy; 2014; **115**:164–173.