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Monitoring and optimization of an existing heat pump system using waste water as the heat source

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Abstract

Aiming at expanding the applicability of systems for recovering the thermal energy potential of waste water in urban areas, this paper is analyzing the performance of the existing heat pump installation (Amstetten, Austria) which is using waste water as the heat source. The implemented system consists of the water-to-water heat pump with a thermal capacity of 230 kW, which is based on R134a as refrigerant in an enhanced vapor injection (EVI) configuration. A mixing type control loop, operating with a three way valve, regulates the inlet temperature of the heat source. The heat sink is connected to a thermal heat storage. Presented in this paper is the selection of the monitoring results gathered during the system operation over entire year, and the seasonal performance factor of this system under real operating conditions. The dynamic system simulations have been carried out, in order to assess the energy performance system improvements.

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Keywords: Non-residential heat pumps; Enhanced vapor injection (EVI); Waste heat recovery; Monitoring; Dynamic system simulation;

Introduction

Despite numerous studies which indicated a large energy potential of recovering waste heat in urban areas, this potential is still not widely used due to operation uncertainties. The project Abwasserenergie [1] investigated the possibility of using wastewater heat for some promising applications: sludge drying at a wastewater treatment plant, heating of surrounding objects after the wastewater treatment plant, and heat recovery from the wastewater channel. In that respect, the studies on the technological feasibility, CO2 reduction and energy efficiency have been done.

As for the wastewater heat recovery from the channel before the water treatment plant, the existing heat pump system of Stadtwerke Amstetten was examined in detail, aiming at the solutions for increasing the energy efficiency: first by scrutinizing the monitoring data, and then by optimization calculations. Namely, in October 2012 started the operation of the heat recovery system built in Amstetten, Austria (Fig. 1 left). To that purpose, the heat pump was installed, the inner-channel heat exchanger was introduced (Fig. 1 right), the piping between channel and heat pump was built, and for the heating system (including the building management system, BMS) the power plant was converted to low temperature heating system. To test its performance, this system was equipped with temperature and pressure measurement points located before and after the wastewater channel and

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heat storage, as well as the condenser and evaporator within the heat pump, and the monitoring campaign was carried out for two years.

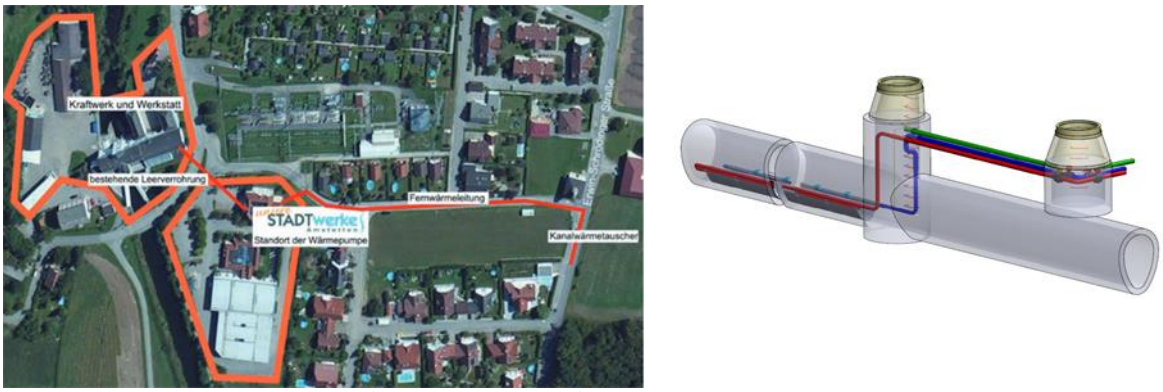


Figure 1: Map of the Amstetten plant (left), and inner-channel heat exchanger (right).

1. Description of the plant

The implemented heat recovery system consists of a water-water heat pump with a thermal output of 230 kW, operating with the refrigerant R134a, and equipped with the intermediate injection system (EVI) for increasing the energy efficiency of the refrigeration cycle. The heat pump provides the thermal energy through the low-temperature heating network and the heat storage buffer of 1.5m³ volume. The energy source for the heat pump is realized through an inner-channel heat exchanger placed within the Amstetten GAV wastewater collectors (Fig. 1, left), approximately 210 meters away from the heat pump

The system operation has three different modes: heating, direct heating and cooling. The hydraulic scheme of the Amstetten plant, shown in Fig. 2, reveals the necessary hydraulic connections for the different operating modes. In the heating mode, the system uses the heat from the wastewater as a heat source, whereby in the transitional period it can be used directly (without heat pump operation) for the heat supply of the building. On the other hand, in the cooling mode, the sewer is used as a heat sink. Due to the high wastewater temperatures direct cooling (without heat pump operation) is not possible, and the heat pump is required for the cooling operation. Namely, specific for Amstetten is the discharge of a high temperature wastewater from the paper industry, achieving the sewage temperatures up to 27°C at the inlet of inner-channel heat exchanger. In order to keep the temperatures at the heat pump inlet within their operating limits, the mixing loop was constructed to limit the maximum water inlet temperature in the heat pump evaporator at 20°C. In order to ensure undisturbed operation, the existing gas boilers have been retained as a backup system and for the absolute peak loads. The system operation showed, however, that 99% of the heat loads are provided by the heat pump system. The wastewater energy recovery plant was controlled and monitored by the central control unit, and for this purpose the existing control unit of Stadtwerke Amstetten was adapted and extended accordingly.

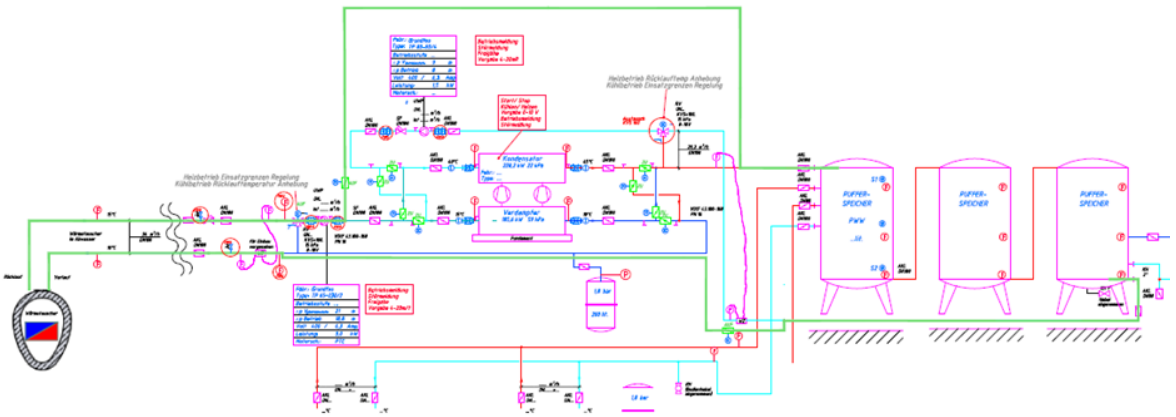


Figure 2: Hydraulic scheme of the heat recovery system in Amstetten plant.

2. Monitoring results

For the monitoring of the energy recovery system under consideration, the temperature and pressure measurement points are located at the characteristic positions within the heat pump (inlets and outlets of condenser and evaporator), as well as in the system hydraulics (before and after the wastewater channel and heat storage). With the total of 27 measurement points and data recording frequency of one minute, the heat pump system in Amstetten offered a closer look at the operation of the wastewater heat recovery system. For a detailed analysis of the operating performance and the optimization of the heat pump system, a monitoring plan was prepared based on the energy flow analysis, mass flow analysis and pressure loss calculation. The detailed examination of the system was performed from the data measured between October 2014 and September 2016.

The energy efficiency of the heat pump system evaluated is expressed in terms of the seasonal performance factor for which the system boundaries are defined following the developments within the EU project SEPEMO [2]: for the calculations of the performance factor in the present paper, the heat on the condenser and the required electric power from the heat pump are taken into account (corresponding to SPF1, as defined in SEPEMO). Starting from the evaluation of the available building control data, the initial optimization measures have been recognized already on the system hydraulics level. The first monitoring results showed that the heat recovery plant delivered 316MWh of heat to the heating system, and 10% of the required heat (in particular for the months of October 2014 and September 2015) could be provided by the direct heating operation mode (Fig. 3 left). 61MWh of electricity was needed for the operation of the plant, whereby 88% of the electrical energy are the needs for the heat pump operation and the remaining 12% are for the pumping within the system (Fig. 3 middle).

In most of the heat pump operating hours the condenser outlet temperatures were ranging between 34°C and 42°C, whereas the most frequent evaporator inlet temperatures were in the range between 16°C and 20°C (Fig. 3 bottom). From the distribution of the evaporator inlet temperatures and the inner-channel heat exchanger outlet temperatures, it can be seen that during the heat pump operation the evaporator inlet temperature was limited by a mixing loop (installed to prevent excessive temperatures at the heat pump inlet). Further optimization potential was recognized by these higher heat source temperatures, especially for the direct mode of heat pump operation.

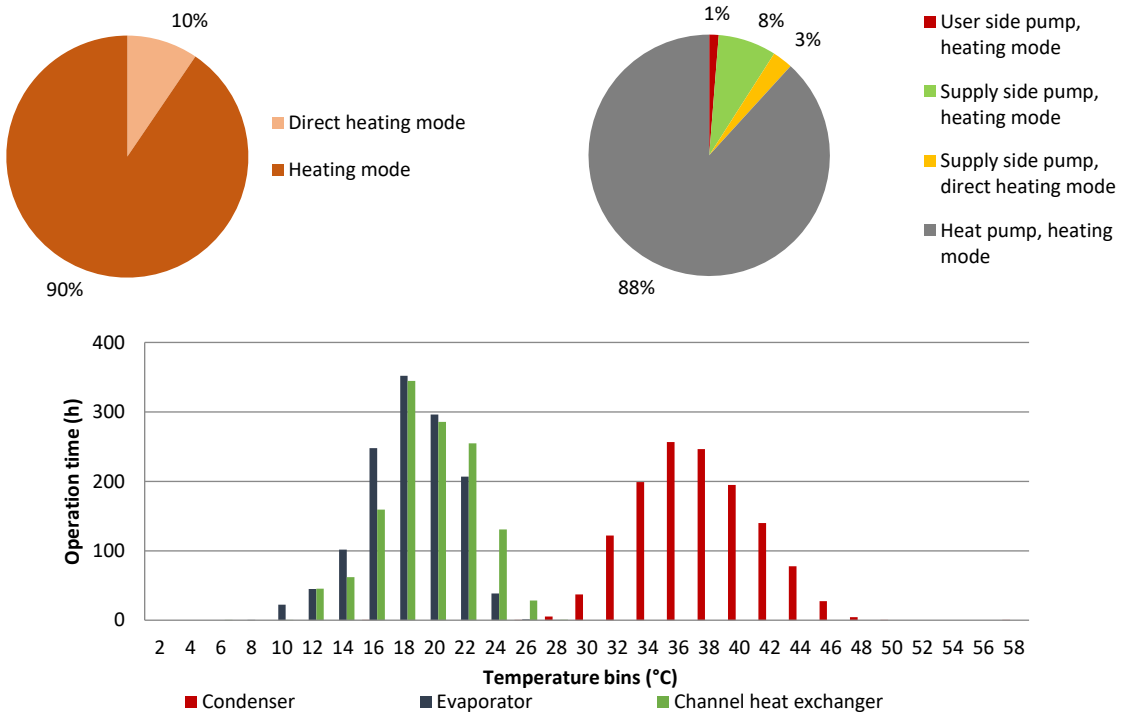


Figure 3: Shares in the heating mode (top left), share of electrical energy consumers (top right), distribution of temperatures in the heat supply and heat consumption side (bottom).

Further optimization measures are identified by looking at the transient behavior of the heat pump. Defining the ON/OFF cycle of the heat pump through the evaporator inlet/outlet temperatures and the low pressure, certain settling process at the beginning of the ON/OFF cycle is observed, in which unstable operating conditions are identified. Namely, the analysis of the monitoring data shows that the average ON/OFF cycle lasts between 15 and 36 minutes (depending on the month), whereas the unstable phase at the start of the ON/OFF cycles lasts 8 to 10 minutes. In total, this unstable operation of the heat pump cycle amounts to 30% in the winter months, and

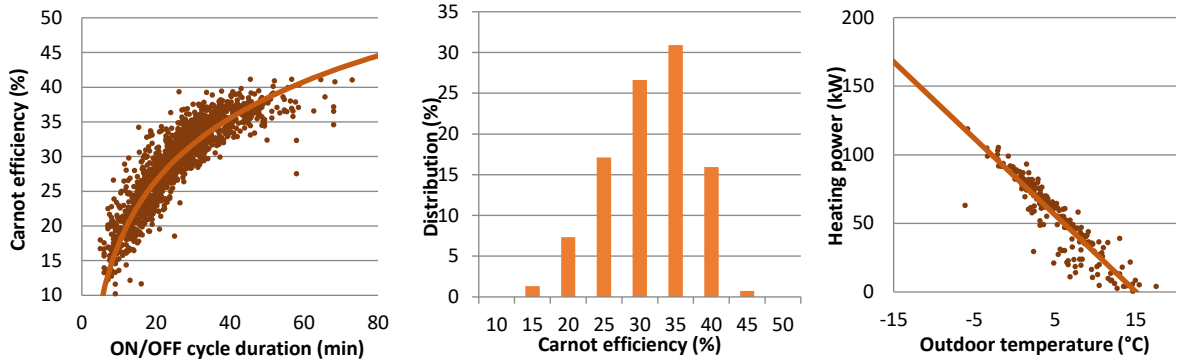


Figure 4: Carnot grade depending on the ON/OFF cycle time (left), distribution of the Carnot performance level (middle), heating load based on the outdoor temperature (right).

60% in the transitional part of the year. Clearly, such transient behavior of the heat pump affects also the system efficiency: during 60% of the operating hours the Carnot coefficient of the heat pump reached 30 to 35% (Fig. 4 middle), which is far below the expected Carnot performance level of 40% to 45% [3]. The monitoring data established a direct correlation between the ON/OFF cycle duration and the Carnot efficiency: having longer duration times of stabile operation, the heat pump can reach the Carnot coefficient values of up to 42% (Fig. 4, left), which is a clear indication of another optimization potential for increasing the overall plant efficiency.

3. Simulation and optimization

In order to test several feasible optimization solutions, the system simulations have been performed using programming language Modelica, within the simulation environment Dymola [4]. For these simulations the heat pump components (heat exchanger, compressor, expansion valve, control parts) were represented using the commercial TIL library (TLK-Thermo GmbH), which has a special focus on the refrigeration applications. As shown in Fig. 5, the simulation model of the system consists of the heat pump side (Fig. 5, left) and the user side (Fig. 5, right). The heat pump side includes the refrigerant cycle (Fig. 5, light green), and the system hydraulics to connect it with heat sink and source (Fig. 5, dark green). The user side includes the representation of the building and the storage tank (Fig. 5, dark blue), together with the heat pump operation control based on predefined heat load specified as a function of the outdoor temperature (Fig. 5, light blue).

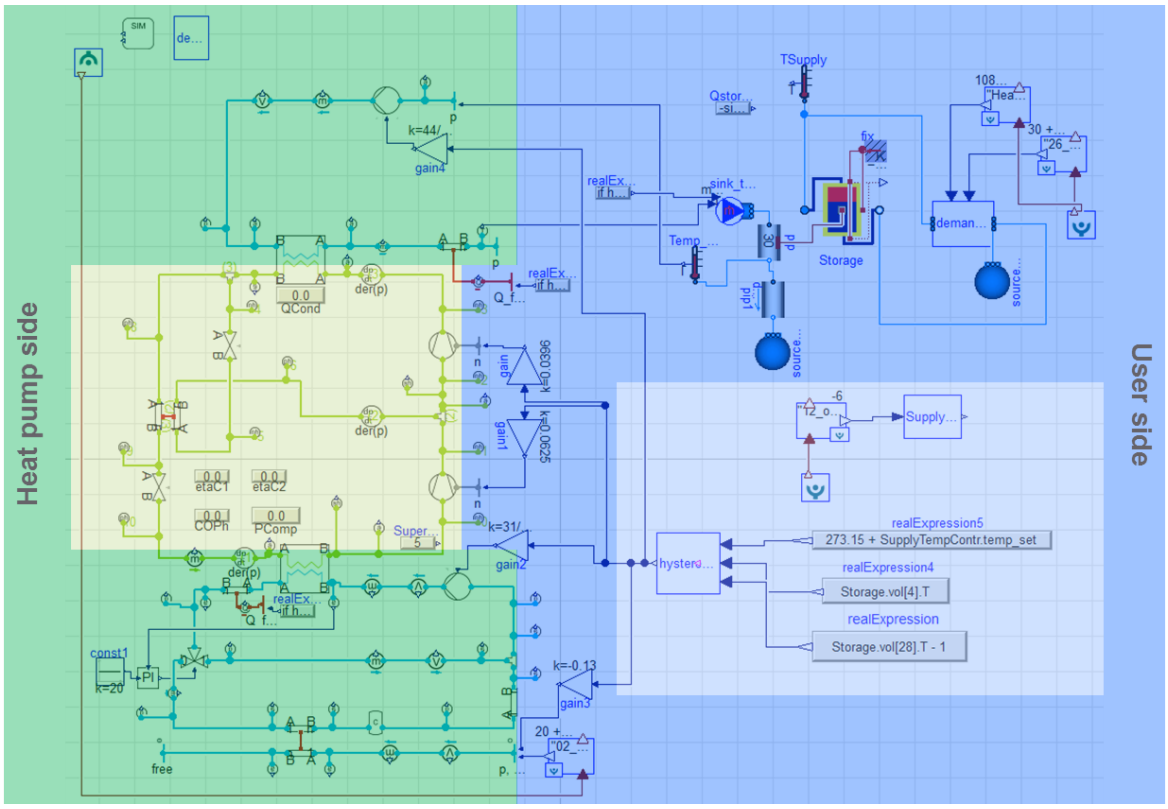


Figure 5: Scheme of the simulation system, consisting of the heat pump side (left: refrigerant cycle in light green, and connecting hydraulics in dark green), and the user side (right: building and storage tank in dark blue, and control system in light blue).

A preliminary design step in a steady state manner was used for the dimensioning of the heat pump components to match the monitoring results at design conditions. Typically, the heat exchanger is defined from the mean temperature difference and the expected operation time, the secondary flow parameters are obtained from desired heating load and outlet temperature, whereas the EVI intermediate design parameter is defined as the geometric mean between the condensation and evaporation pressure [5]. With the proper parametrized heat pump components, the dynamic model was deployed to investigate the transient behavior of the system.

The dynamic simulations have been performed for short-term operation (one-day simulation) and long-term operation (yearly simulation) of the system, in order to identify the trends in the energy performance of the system, and to assess its energy optimization potential. Namely, the monitoring data pointed out that the problem with short cycle durations can be related to the heat pump over-sizing: the designed heat load of heat pump was 230kW at the outside temperature of -16°C, but the monitoring data showed required heat load of 160kW. Another optimization measure identified by monitoring is on the level of the hydraulic layout: on the one hand there is a significant improvement with the adaptation of the system allowing for direct-heating operation, and on the other the serial storage integration allows for better temperature stratification and hence better energy performance. Finally, it is expected that longer ON/OFF cycle times contribute to better heat pump efficiency, and in that view the benefit of applying the mixing valve was put in the focus of investigation.

3.1 One-day simulation

The first dynamic simulation sequence was performed for a single day, with the system boundary conditions (the outdoor and building return temperatures, as well as the temperature in the sewer channel) taken from the monitoring data for the selected reference day. The resulting simulation data for the heating mode were validated using the monitoring data, as reported in the Table 1.

Table 1. Validation of the one-day simulation model

Parameter	Unit	Monit.	Simul.	Parameter	Unit	Monit	Simul

Evaporator, inlet	[°C]	18,8	18,4	Building supply temp.	[°C]	40,8	39,4
Evaporator, outlet	[°C]	12,2	13,6	Building return temp.	[°C]	30,3	30,1
Condenser, inlet	[°C]	37,3	37,3	Thermal power	[kW]	237,1	219,5
Condenser, outlet	[°C]	41,6	41,6	Electric power	[kW]	51,5	42,4
Sewer channel, outlet	[°C]	19,0	18,9	Carnot efficiency	[%]	35,6	35,8
Heat storage, below	[°C]	32,5	33,5	Performance factor	[-]	4,91	4,84
Heat storage, middle	[°C]	40,0	38,3	ON cycle duration	[min]	47,4	39,6
Heat storage, above	[°C]	41,1	39,8	OFF cycle duration	[min]	50,4	45,3
Operating time	[h]	11,9	11,8	ON/OFF switching frequency	[-]	15,0	17,0

Thus developed model of the system allowed for the parametric study of its performance, with respect to the selected characteristics of the system. Aiming at the optimization of the overall efficiency, the variation regarding the following two characteristic, as compared to the baseline scenario (REF), has been performed: the size of the heat storage tank (SG), and the deployment of the heat capacity controlled heat pump (LR). The results, shown in Table 2, are indicating the largest increase of efficiency for the heat capacity controlled scenario: 16% increase of the total operation time in the reference day, as compared to the baseline scenario. On the other hand, the results are showing that 50% larger storage tank implies an increase of the ON duration time of about 16 minutes compared to the baseline scenario, and a reduction of 5 ON/OFF cycle for the reference day.

Table 2. Optimization results for the one-day simulation

Parameter	**Unit**	**Baseline (REF)**	**Heat storage size (SG)**			**Heat capacity control (LR)**
			-50 %	**+50 %**	**+100 %**	**75 – 100 %**
Performance factor	[-]	4,84	4,59	4,88	4,98	5,17
Carnot efficiency	[%]	35,8	33,9	36,4	37,0	38,0
Thermal power	[kW]	219,5	219,7	218,6	219,9	201,6
Electric power	[kW]	42,4	42,3	42,7	42,5	36,5
ON cycle duration	[min]	43,8	24,3	59,8	71,1	50,7
OFF cycle duration	[min]	41,0	20,1	60,7	81,3	41,8
ON/OFF switching frequency	[-]	17,0	32,0	12,0	9,0	16,0

3.2. Yearly simulation

For the purpose of yearly dynamic simulations, slight modifications of the system modeling approach have been introduced. Namely, this concerns mainly the deployed time scale for resolving the operation of the heat pump itself, aiming at suitable accommodating of the characteristics of interest for the long-term simulation period. The validation of the model with monitoring data for one year is shown in Table 1. The monitored input data are the sewer channel inlet temperature, outdoor temperature and building return temperature.

Table 1: Validation of the yearly simulation model

Parameter	**Unit**	**Monit**	**Simul**	**Parameter**	**Unit**	**Monit**	**Simul**
Condenser, inlet	[°C]	32,2	32,0	Thermal power	[kW]	218,3	180,5
Condenser, outlet	[°C]	36,6	36,1	Electric power	[kW]	40,9	40,5
Evaporator, inlet	[°C]	17,7	17,4	Carnot efficiency	[%]	40,4	31,0
Evaporator, outlet	[°C]	12,7	12,8	Performance factor	[-]	5,33	5,14
Sewer channel, outlet	[°C]	22,2	19,1	Operating time	[h]	1490	1240
Heat storage, below	[°C]	25,6	25,6	ON cycle duration	[min]	27,4	17,1
Heat storage, middle	[°C]	27,9	33,3	OFF cycle duration	[min]	156,7	103,4
Heat storage, top	[°C]	31,0	37,1	ON/OFF switching frequency	[-]	2785	4699
Building supply temp	[°C]	30,6	37,4	Heat Energy	[kWh]	325190	258194

Building return temp	[°C]	23,8	26,0	Electric energy	[kWh]	61005	50263

For the long-term operation optimization of the system energy performance, two different strategies have been considered: the pre-running of the circulation pump on the heat source side, and the effectiveness of the mixing loop. Regarding the pre-running of the circulation pump on the heat source side of the heat pump (evaporator side), the idea was to switch it on 4 minutes before the heat pump compressor starts to run. This would allow the temperature at the evaporator inlet to reach higher values, given the fact that the piping system which connects the sewage channel and the evaporator is about 200m long. The starting point for the investigation of the mixing loop effectiveness was to analyze the behavior when no limitation for the evaporator inlet temperature are imposed (in the current setting 20°C is the maximum allowed inlet temperature, set point of the mixing valve). The main results of these two optimization simulation runs are summarized in Table 2.

Table 2: Optimization results for the yearly simulation

Parameter	**Unit**	**Baseline (REF)**	**Sink Pump Pre-Running**	**No Mixing Valve**
Performance factor	[-]	5.14	5.26	6.16
Carnot efficiency	[%]	30.9	30.9	38.9
Thermal power	[kW]	180.5	185.9	209.1
Electric power	[kW]	40.5	40.6	40.3
ON cycle duration	[min]	17	18	14
OFF cycle duration	[min]	103	112	102
ON/OFF switching frequency	[-]	4699	4374	4872
Heat energy	[kWh]	258194	258179	258246
Electric energy	[kWh]	55411	55088	46281

Having implemented the pre-running of the circular pump, the results are showing that with a comparable performance factor (slightly increased by 2%), about 323kWh of total electric energy is saved, as compared to the baseline case. This comes as the result of compressor energy savings of 1142kWh, and the circular pump energy increase of 837kWh. For the case when the mixing valve is not in use (thus, higher temperatures are occurring at the heat pump evaporator inlet), the performance factor is increased by 20% in comparison to the baseline scenario. The total energy thus saved amounts to 9.1MWh, which is due to the higher temperatures at evaporator inlet occurring in the autumn and spring period. The results summarized in Table 3 are showing the case without the mixing valve operating during the representative day: the performance factor is improved of about 41%, and the total energy savings of about 40kWh are achieved, as compared to the reference configuration.

Table 3: The operation of the system without mixing valve during the representative day

Parameter	**Unit**	**Ref**	**No Mix Valve**	**Parameter**	**Unit**	**Ref**	**No Mix Valve**
Condenser, inlet	[°C]	29.3	29.6	Thermal power	[kW]	206.0	290.9
Condenser, outlet	[°C]	33.4	35.3	Electric power	[kW]	37.7	37.6
Evaporator, inlet	[°C]	18.9	21.3	Carnot efficiency	[%]	25.7	35.1
Evaporator, outlet	[°C]	14.1	14.0	Performance factor	[-]	5.43	7.7
Sewer channel, outlet	[°C]	24.2	24.1	Operating time	[h]	3.5	2.5
Heat storage, below	[°C]	23.5	23.7	ON cycle duration	[min]	13.0	9.4
Heat storage, middle	[°C]	30.5	31.2	OFF cycle duration	[min]	79.7	85.4
Heat storage, top	[°C]	35.2	36.2	ON/OFF switching frequency	[-]	16.0	16.0
Building supply temp	[°C]	35.6	36.5	Heat Energy	[kWh]	710.7	727.1
Building return temp	[°C]	23.7	23.8	Electric energy	[kWh]	130.8	94.6

4. Conclusions

This paper presented the results on the application of a heat pump for recovering the thermal energy of waste water in urban areas. To this purpose the existing heat pump installation using waste water as a heat source (Amstetten, Austria) was in the focus of the investigation. The man characteristics of the implemented water-to-water heat pump system are the following: the heat pump with the thermal capacity of 230kW is based on R134a as refrigerant, it equipped with EVI vapor injection, it includes a mixing loop in the heat source circle (for the regulation of the heat pump inlet temperature), and a thermal storage in the heat sink circle (for the regulation of the supply thermal energy).

From the obtained monitoring results, gathered during the system operation over an entire year, the performance of this system under real operating conditions was analyzed. Already from the monitoring results several system optimization measures were drawn (hydraulic layout of the system). In addition to the system monitoring, the dynamic system simulations have been carried out for a selected representative day, in order to be able to test the system behavior and explore the optimization potential with respect to the energy performance of the system. The performed parametric study showed that longer ON/OFF cycle times (targeted control of pumps operation) can significantly contribute to increased energy efficiency of the system.

The one-day simulation results are showing the largest increase of efficiency for a heat pump capacity controlled scenario of 7%. Furthermore, there is 16% increase of the total operation time in a representative day, as compared to the baseline scenario from the monitoring results. On the other hand, these results are showing that a 50% larger heat storage tank implies an increase of the ON duration time of the heat pump for about 16 minutes compared to the baseline scenario, and a reduction of 5 ON/OFF cycle for the representative day. The less ON/OFF heat pump cycles, means less operating time during start-up and shut-down at low efficiencies. As a result, the overall performance factor of the heat pump system can be increased.

The analysis of the long-term performance of the system showed that, although originally intended to improve the safety of the heat pump operation, the mixing loop is actually not contributing to the effective operation of the system. On the other hand, its exclusion leads to 20% increase of the performance factor, together with certain energy savings (due to higher inlet temperatures), as compared to the baseline scenario. Regarding the idea to switch on the circulation pump 4 minutes before the heat pump compressor starts to run, the positive side is the compressor energy savings, while the negative side is the energy increase for the circular pump itself. Nevertheless, the simulation results are showing that there is 323kWh of net electric energy is saved, together with a comparable performance factor of thus modified system.

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