A field study of a wastewater source heat pump for domestic hot water heating

Shen Chao¹, Jiang Yiqiang¹, Yao Yang¹, Deng Shiming² and Wang Xinlei³

Abstract
An experimental heat pump utilizing wastewater discharged from the common bathroom in a SPA center as a heat source was built. In this article, the field measured operating performance of the wastewater source heat pump is reported. An analysis based on the collected field data under various operating conditions is included. It was shown that the temperature of wastewater greatly affected the evaporating temperature and the coefficient of performance of the wastewater source heat pump. Circulating wastewater from the bottom to the top of the wastewater storage tank could weaken even out the vertical wastewater temperature distribution inside the wastewater storage tank and improve the coefficient of performance and compressor suction pressure of the wastewater source heat pump accordingly. The daily averaged coefficient of performance of the wastewater source heat pump was monitored for over an entire month. It was shown that the measured coefficient of performance gradually reduced, suggesting the need for regular cleaning of the heat exchangers used in a wastewater source heat pump system. In addition, the recorded maximum transporting capacity of the wastewater pipe reduced by 16.9% over the 1 month operation and by 20.1% after ~5 months due to the bio-fouling build-up. Finally, an analysis comparing the economics of operating a wastewater source heat pump system with that of operating conventional water heating systems is presented.

Practical application: The use of heat pump to recover heat from wastewater is significant to energy conservation and environmental protection. A number of researches and projects on wastewater source heat pumps using urban sewage or treated sewage as a heat source have been carried out. However, field measured results on a heat pump, which recovered heat from waste bath water, was not previously reported. As the quality of waste bath water was different from that of sewage in terms of temperature, amount, and the degree of cleanliness, the experiences on designing and operating urban

¹Department of Building Thermal Energy Engineering, Harbin Institute of Technology, Harbin, China
²Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR, China
³Department of Agricultural and Biological Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Corresponding author:
Jiang Yiqiang, Department of Building Thermal Energy Engineering, Harbin Institute of Technology, Harbin 150090, China.
Email: jyq7245@sina.com
sewage source heat pumps previously obtained could not be used as a full reference for designing a waste bath water source heat pump. In this article, field experiment work of designing and operating a heat pump which used waste bath water as a heat source for hot water heating is presented, and the results can be used as a key reference for designing and operating waste bath water source heat pump systems in the future.

**Keywords**
Heat recovery, bath water, hot water heating, coefficient of performance, wastewater source heat pump

**Introduction**

Problems regarding energy shortage and environmental pollution caused by excessive energy consumption require an efficient and economical use of present available energy resources. Therefore, alternative energy sources or improved energy utilization methods should be more actively developed. Waste heat recovery from wastewater is of considerable significance to energy conservation and environmental protection. A heat recovery system which recovered heat from the wastewater discharged from dishwashers was developed by Paepe et al. It has been proven that the system is economically beneficial. A heat pump recovering heat from the treated sewage in a sewage treatment plant was simulated by Yao et al., and it showed a good performance on energy conservation. Waste bath water discharged from large-scale public bathing facilities (in schools, barracks, and bath center) was also an available heat source, which has the following unique characteristics:

1. Waste bath water is relatively clean and adequate in quantity with a high temperature (at up to 30°C).  
2. The opening schedule for a bathing facility is normally specified throughout a year. Therefore, the amount of the available waste heat and the required heat for water heating by the facility can be determined, so that a suitable hot water heating system may be designed correspondingly.

Several studies on recovering heat from waste bath water using heat pumps have been reported in earlier literature. Some of these include economic evaluation of heat recovery, simulation of heat pumps to recover heat from spring water obtained from hotels, and even from clean water rather than wastewater. These earlier studies demonstrated that recovering heat from waste bath water through heat pump to heat hot water could bring about low energy consumption, reduced pollution, and low operating cost, as compared to conventional water heating methods.

Although waste heat recovery from wastewater is significant, however users have to be confronted with the fouling problem. Heat transfer tubes exposed to the wastewater suffer the well-known phenomenon of fouling, consisting of the formation of a film that covers the surfaces in contact with the wastewater. Three types of fouling are usually considered: biological, corrosion, and precipitation. The annual cost of fouling and corrosion for the US industry was $3–10 billion. This report emphasizes the need to develop appropriate fouling mitigation strategies. The mechanism of fouling build-up is complex. Operating time, the geometric structure, and surface material of the heat exchanger, as well as hydrodynamic flow conditions, play an important role in reducing the fouling rate. The tube bundle with unequal cylinders could achieve a significant (~30%) reduction in particle deposition rate. In addition, it has also been demonstrated that titanium tubes are more prone to be fouled than...
brass tubes. In the lower range of fluid velocities (<0.5 m/s), the deposition process was controlled by mass transfer. As the fluid velocity increases, the maximum asymptotic limit of the thermal resistance decreased correspondingly. An electronic anti-fouling technology on fouling mitigation in a heat exchanger was studied and proven effective as well.

However, these studies were either based on simulation or carried out using clean water instead of actual waste bath water. So the work on actual field or experimental studies for wastewater source heat pumps (WWSHPs) remains to be investigated. Therefore, an experimental heat pump system using waste bath water discharged from the common bathroom in a SPA center as a heat source to heat hot water was studied. The field measured performances of the WWSHP under different operating conditions are presented and analyzed in this article.

**Measured characteristics of waste bath water discharged**

The SPA center was located inside a five-star hotel in the city of Shenzhen in southern China. Fifty one out of all 100 guest rest rooms were VIP rooms with private bathroom and the other 49 were non-VIP rooms without private bathroom. The guests staying in these non-VIP rooms would have to use the common bathroom. In general, as reported by the SPA center management, 60% of guests would stay in non-VIP rooms, and hence use the common bathroom.

The measured temperature of the wastewater discharged from common bathroom was relatively stable, as shown in Figure 1. As seen, from 15:00 pm on 15 July to 04:00 am on 16 July 2010, the temperature of waste bath water discharged from the common bathroom in the SPA center varied between 33.6°C and 31.4°C, with an average of 32.5°C. On the other hand, Table 1 presents the accumulated amount over a 2h measuring interval for a week in July 2010. Since the collected waste bath water was only from the common bathroom, the amount shown in Table 1 was actually smaller than the total amount of waste bath water discharged from the entire SPA center. As shown in Table 1, the amount of wastewater discharged at the weekend was less than that on weekdays. On weekdays, the discharged amount normally peaked at 20:00 pm to 00:00 am, while at the weekend, it peaked in the afternoon.

![Figure 1. Measured wastewater temperature discharged from the common bathroom on 15 and 16 July 2010.](image-url)
Table 1. Wastewater amount discharged from the common bathroom (m$^3$).

<table>
<thead>
<tr>
<th>Time</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
<th>Mean</th>
<th>Business</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:00–12:00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Closed</td>
</tr>
<tr>
<td>12:00–14:00</td>
<td>0.50</td>
<td>0.61</td>
<td>0.44</td>
<td>0.75</td>
<td>0.55</td>
<td>0.83</td>
<td>0.73</td>
<td>0.63</td>
<td>Open</td>
</tr>
<tr>
<td>14:00–16:00</td>
<td>2.11</td>
<td>1.78</td>
<td>1.61</td>
<td>1.95</td>
<td>1.50</td>
<td>2.75</td>
<td>2.84</td>
<td>2.07</td>
<td>Open</td>
</tr>
<tr>
<td>16:00–18:00</td>
<td>3.95</td>
<td>4.29</td>
<td>4.46</td>
<td>4.12</td>
<td>3.67</td>
<td>3.95</td>
<td>4.13</td>
<td>4.08</td>
<td>Open</td>
</tr>
<tr>
<td>18:00–20:00</td>
<td>3.65</td>
<td>3.78</td>
<td>4.01</td>
<td>3.95</td>
<td>4.18</td>
<td>3.60</td>
<td>3.18</td>
<td>3.76</td>
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</tr>
<tr>
<td>20:00–22:00</td>
<td>5.55</td>
<td>5.87</td>
<td>6.27</td>
<td>6.04</td>
<td>5.68</td>
<td>3.17</td>
<td>3.65</td>
<td>5.17</td>
<td>Open</td>
</tr>
<tr>
<td>22:00–0:00</td>
<td>5.96</td>
<td>5.66</td>
<td>6.04</td>
<td>5.80</td>
<td>5.74</td>
<td>2.90</td>
<td>3.14</td>
<td>5.03</td>
<td>Open</td>
</tr>
<tr>
<td>00:00–02:00</td>
<td>1.92</td>
<td>1.59</td>
<td>1.81</td>
<td>1.47</td>
<td>1.64</td>
<td>0.94</td>
<td>1.14</td>
<td>1.50</td>
<td>Open</td>
</tr>
<tr>
<td>02:00–04:00</td>
<td>0.55</td>
<td>0.66</td>
<td>0.48</td>
<td>0.53</td>
<td>0.66</td>
<td>0.42</td>
<td>0.33</td>
<td>0.52</td>
<td>Open</td>
</tr>
</tbody>
</table>

The wastewater collected was only from the common bathroom with 13 shower headers.

**Description of the experimental WWSHP and testing conditions**

**Experimental WWSHP**

The experimental WWSHP is shown schematically in Figure 2. It consisted of four sub-systems: wastewater collection, heat pump cycle, hot water heating, and data acquisition and control (DAC).

First, the wastewater collection sub-system consisted of a wastewater storage tank (WST) measured at $0.9 \times 0.7 \times 1.2 \text{ m}^3$, wastewater pipes, a filter, a solenoid valve, $V_1$, and a wastewater pump. Waste bath water discharged from the common bathroom passed through the filter before entering the WST.

Second, the heat pump sub-system included a tube-coil evaporator, a plate condenser, a thermal expansion valve, two parallel-connected compressors, and all other necessary control and safety accessories. The tube-coil evaporator, which was made of 16 numbers of S-shaped 8 mm copper tubes, was placed inside the WST. Leaving the expansion valve, Refrigerant-134a entered a 10 mm diameter copper header which distributed the refrigerant to the 16 tubes. After absorbing heat from the wastewater, the refrigerant flowed out of the evaporator and was sucked into the compressors. The detailed specifications of the heat pump are given in Table 2.

Third, the hot water sub-system consisted of a hot water storage tank (HWST), a hot water pump, hot water supply pipes, and a solenoid valve, $V_2$. The HWST had a storage capacity of $0.21 \text{ m}^3$ with a maximum working pressure of 3 MPa.

Finally, the DAC sub-system included a PC and a data logger, so that operating parameters could be monitored, recorded, and displayed. The water pumps, compressors, and solenoid valves could be controlled using the DAC sub-system.

**The control of the WWSHP**

As a prerequisite, the wastewater temperature, $T_6$, determined whether the WWSHP could be started or not. When $T_6$ was higher than $T_{set-ww}$, the WWSHP system could be started, otherwise it was stopped, to prevent the temperature of wastewater inside the WST was too low that it would freeze.

Solenoid valve, $V_1$, was controlled based on the higher water level controller ($L_1$). When the water level inside the WST was below $L_1$, $V_1$ remained open; otherwise $V_1$ was closed, to insure that no wastewater overflowed from the
WST. The wastewater pump was controlled based on the lower water level controller (L2). When the wastewater level inside the WST was above L2, the pump was operated; otherwise it was stopped, to insure that the evaporator immersed in the wastewater totally.

The compressors, hot water pump and the solenoid valve, V2, were controlled based on hot water temperature, T2. When T2 reached Tset-hw1, both compressors and hot water pump were stopped. At the same time, V2 was opened to draw-off hot water from the HWST. When T2
reduced to $T_{set-hw2}$, both compressors and hot water pump were started, and $V_2$ was closed. All these designs insured that the temperature of hot water ($T_2$) inside the HWST was controlled between $T_{set-hw1}$ and $T_{set-hw2}$.

The operation of the WWSHP

After being chilled by the immersed evaporator within the WST, waste bath water was discharged by wastewater pump from the bottom. On the water heating side, when the WWSHP was running, low-temperature water from the bottom of the HWST flowed into the condenser where it was heated, afterward, it returned into the HWST from the top. Owing to the cyclic heating, the water temperature inside the HWST increased gradually. When hot water on top of the HWST was drawn off, tap water flowed into the HWST from the bottom due to the pressure of tap water.

The performance of the WWSHP was evaluated by its coefficient of performance (COP), as follows

$$ COP = \frac{Q_h}{W_{tot}} = \frac{\dot{V}_w \rho_w c_w (T_{w,co} - T_{w,ci})}{\varphi \cdot \dot{I}_{tot} \cdot U_{tot}} \quad (1) $$

Measurement uncertainty for the operating parameters was estimated at $\pm 0.1^\circ C$ for temperature, $\pm 2\%$ for water flow rate, $\pm 0.25\%$ for pressure, and $\pm 0.2\%$ for both current and voltage. The maximum uncertainty associated with the calculated COP was evaluated at $5.6\%$.

Testing conditions

To investigate the performance of the WWSHP, a series of field tests were carried out with different operating parameters including wastewater draw-off patterns from the WST, hot water supply temperatures, and flow patterns of wastewater inside the WST, etc. In addition, the COP of the WWSHP was monitored for an entire month. The whole procedure was repeated for five times to check the validity of the experiment considering the outdoor air temperature variation to almost constant throughout the year. These different testing conditions are summarized in Table 3.

Results and discussions

Measured operating performance of the WWSHP under the two different wastewater draw-off patterns from the WST

At the high–low hot water supply temperature setting of 45–48$^\circ C$, the operating performance
of the WWSHP was tested under two different wastewater draw-off patterns from the WST: no draw-off and consecutive draw-off. For each pattern, three heating processes were included. In the first heating process, hot water in the HWST was heated up from 27°C to 48°C. Afterward, the WWSHP was stopped, and high-temperature hot water in the HWST was drawn off from the top, with low-temperature tap water flowing into the HWST. When \( T_2 \) dropped to 45°C, the second heating process was started, where hot water (\( T_2 \)) in the HWST was heated up again from 45°C to 48°C. After this process, a hot water drawing off process and the third hot water heating process (from 45°C to 48°C) were carried out sequentially.

The measured operational parameters of the WWSHP under the two wastewater draw-off patterns are shown in Figures 3 and 4, respectively. As shown in Figure 3, at the first pattern where the wastewater pump was switched off so that no wastewater was drawn off from the WST, the wastewater temperature at the top point of the WST (\( T_4 \)) dropped slightly from 33.2°C to 31.3°C. However, the wastewater temperature at the bottom point of the WST (\( T_6 \)) experienced a vertical water temperature distribution was presented inside the WST when the wastewater was static. This may cause a poor performance of the WWSHP (proven in Figure 6, ‘Measured operating performance of the WWSHP under different flow patterns of wastewater inside the WST’) as compared to the performance that obtained with circulating water inside the WST. Results also suggested that the WWSHP was able to extract a large amount of heat from the waste bath water. On the other hand, the refrigerant temperature at evaporator inlet was positively proportional to the wastewater temperature, with an average of 17.9°C, 16.6°C, and 14.8°C, respectively, during the three heating processes. It can be further seen that a higher averaged COP was obtained at a higher wastewater temperature. The recorded average COPs of the WWSHP were 3.38, 3.01, and 2.87, with the maximum being 3.80, 3.25, and 3.13, for the three heating processes, respectively.

Figure 4 shows the measured operating performance of the WWSHP at the consecutive wastewater draw-off pattern, where high-temperature wastewater from the common bathroom flowed into the WST and the low-temperature wastewater was drawn off from the WST consecutively at a flow rate of \( 3.3 \times 10^{-4} \) m³/s. No significant changes in the wastewater temperatures at both the top and bottom points inside the WST may be observed. During each heating process, with the rising of hot water temperature in the HWST, the refrigerant temperature at the evaporator inlet went up gradually. The results showed that the measured average refrigerant temperatures at the

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter/operation</th>
<th>Range/state</th>
<th>Results shown in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term test</td>
<td>Draw-off patterns of wastewater</td>
<td>Draw-off consecutively at 3.3 \times 10^{-4} \text{m}^3/\text{s}; no drawn off</td>
<td>Figures 3 and 4</td>
</tr>
<tr>
<td></td>
<td>Flow patterns of wastewater inside the WST</td>
<td>Static, circulation; both without wastewater draw-off</td>
<td>Figures 5 and 6</td>
</tr>
<tr>
<td>Long-term test</td>
<td>COP</td>
<td>Hot water temperature setting: 45–50°C; wastewater was drawn off from the WST consecutively at 3.3 \times 10^{-4} \text{m}^3/\text{s}</td>
<td>Figure 7</td>
</tr>
</tbody>
</table>

WST: wastewater storage tank; COP: coefficient of performance.
evaporator inlet for the three heating processes were 20.6°C, 22.4°C, and 22.0°C, respectively, and the measured average COPs of the WWSHP were 3.57, 3.37, and 3.37, corresponding to the three water heating processes.

Measured operating performance of the WWSHP under different flow patterns of wastewater inside the WST

Under the condition that no wastewater from the common bathroom was supplied to, and no wastewater was drawn off from the WST, tests at two different wastewater flow patterns inside the WST were performed: one with wastewater being circulated (4.5 × 10⁻⁴ m³/s) and the other with wastewater being static inside the WST. The high–low hot water temperature setting for both of these two tests were 50–55°C. The test results are shown in Figures 5 and 6, respectively. As shown in Figure 5, after the three heating processes which are explained in ‘Measured operating performance of the WWSHP under the two different wastewater draw-off patterns from the WST’ section, $T_4$ dropped from 31.6°C to 20.9°C and $T_6$ decreased from 30.6°C to 19.2°C when the WWSHP ran with wastewater inside the WST being circulated. However, when the wastewater inside the WST was static (shown in Figure 5), $T_4$ slightly dropped by 1.2°C and $T_6$ greatly decreased from 30.5°C to 13.9°C. All these results suggested that the uneven vertical temperature distribution, which appeared when the
wastewater inside the WST was static, could be alleviated when the WWSHP ran with wastewater being circulated.

Furthermore, the measured results shown in Figure 6 suggested that both the COP and the compressor suction pressure were higher when the WWSHP ran with wastewater being circulated than that with wastewater being static. The improvements in both COP and the suction pressure were more obvious when the WWSHP ran with a lower wastewater temperature. When the wastewater inside the WST was circulated, the averaged COP of the WWSHP was improved by 7.1% and the averaged increase in compressor suction pressure was 0.021 MPa, compared to the data recorded when the wastewater was static. From the results, it can be suggested that the design – ‘wastewater was circulated in the WST’ was more recommendable owing to its good performance. Two possible reasons can explain why circulating water increased the COP. One is that circulating water can promote the down-move of the high-temperature wastewater on the top to the bottom of the WST, where the evaporator is installed to extract the heat. The increased temperature of heat source around evaporator ($T_6$, as shown in Figure 5) can improve the COP. The other is that circulating water increased the flow rate of wastewater inside the WST from 0 to $9.26 \times 10^{-4} \text{m}^3/\text{s}$ (flow rate, $4.5 \times 10^{-4} \text{m}^3/\text{s}$; area, 0.486 $\text{m}^2$), i.e. it improved the free convection heat transfer coefficient of 904 $\text{W}/(\text{m}^2\text{K})$ (when wastewater was static) to a forced convection heat transfer of 1001 $\text{W}/(\text{m}^2\text{K})$ (when wastewater was circulated) through calculation. Therefore, the total COP was increased by circulating wastewater.

**Figure 4.** Measured operating parameters of the WWSHP during three water heating processes (wastewater being supplied to and drawn off from the WST consecutively).

WWSHP: wastewater source heat pump; WST: wastewater storage tank.
Effect of water quality of waste bath water on the operating performance of the WWSHP system

Bio-fouling build-up. According to field test, a soft bio-fouling layer on the internal surface of wastewater pump and wastewater transfer pipes was found at a thickness of greater than 1 mm. Owing to the increase in flow resistance along the pipe line caused by the bio-fouling build-up, the maximum transporting capacity of the wastewater discharge pipe, at $5.3 \times 10^{-4}$ m$^3$/s without bio-fouling, went down by 16.9% to a value of $4.4 \times 10^{-4}$ m$^3$/s after the 1 month bio-fouling build-up. At the end of the ~fifth month, the maximum transporting capacity dropped by 20.1% although without a cleaning during the ~5 months. This result suggested that in the first month the maximum transporting capacity of wastewater pipe dropped seriously, but in the following months it decreased slowly. Therefore, an appropriate oversize design and a periodical cleaning on the wastewater transfer pipe were also recommended to keep an effective transfer capacity.

The effect of bio-fouling on the system performance was also reflected by the measured data. Figure 7 shows the variations of the recorded daily average COP of the WWSHP for 1 month, under the following testing conditions: $T_{set-hw1} = 50^\circ C$; $T_{set-hw2} = 45^\circ C$; wastewater was drawn off from the WST consecutively at a flow...
Figure 6. Measured COP and suction pressure of the WWSHP under the two wastewater flow patterns inside the WST. WWSHP: wastewater source heat pump; WST: wastewater storage tank; and COP: coefficient of performance.

Figure 7. Recorded daily average COP of the WWSHP for 1 month. WWSHP: wastewater source heat pump; COP: coefficient of performance.
Since waste bath water was not clean and may contain suspended substances, which deposited on the heat transfer surface in the form of precipitation and biological growth. Therefore, the heat transfer may be affected accordingly by the bio-fouling on the heat transfer surface. As illustrated in Figure 7, in the first 5 days, the daily averaged COP had no an obvious variation. However, in the following 20 days, the COP declined rapidly from 3.39 to 2.89. After the 25th day, the COP changed slightly from 2.89 to 2.87. This trend is also confirmed by Melo and Pinheiro\textsuperscript{13} using bio-fouling thermal resistance and Bryers and Characklis\textsuperscript{16} using the accumulated mass of the bio-fouling. It can be concluded that the bio-fouling gradually decreases the COP of the WWSHP. Hence, it became necessary to clean the heat transfer surface regularly when using waste bath water as a heat source for WWSHP.

Table 4. Initial cost of different systems (RMB = Chinese Yuan).

<table>
<thead>
<tr>
<th>System</th>
<th>Initial cost (thousand RMB)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) HWST</td>
<td>44.0</td>
<td>55 m$^3$, the boiler only works in the valley period of electricity, with a lowest electricity price</td>
</tr>
<tr>
<td>(2) Boiler, auxiliaries, and installation cost</td>
<td>80.0</td>
<td>The capacity of the boiler is 0.21 MW</td>
</tr>
<tr>
<td>Total</td>
<td>124.0</td>
<td></td>
</tr>
<tr>
<td>Gas boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) HWST</td>
<td>32.0</td>
<td>40 m$^3$, assuming 20 working hours per day for the boiler</td>
</tr>
<tr>
<td>(2) Boiler, auxiliaries, and installation cost</td>
<td>35.0</td>
<td>The capacity of the boiler is 0.07 MW</td>
</tr>
<tr>
<td>Total</td>
<td>67.0</td>
<td></td>
</tr>
<tr>
<td>Oil boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) HWST</td>
<td>32.0</td>
<td>40 m$^3$, assuming 20 working hours per day for the boiler</td>
</tr>
<tr>
<td>(2) Boiler, auxiliaries, and installation cost</td>
<td>35.0</td>
<td>The capacity of the boiler is 0.07 MW</td>
</tr>
<tr>
<td>Total</td>
<td>67.0</td>
<td></td>
</tr>
<tr>
<td>Coal boiler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) HWST</td>
<td>32.0</td>
<td>40 m$^3$, assuming 20 working hours per day for the boiler</td>
</tr>
<tr>
<td>(2) Boiler, auxiliaries, and installation cost</td>
<td>30.0</td>
<td>The capacity of the boiler is 0.07 MW</td>
</tr>
<tr>
<td>Total</td>
<td>62.0</td>
<td></td>
</tr>
<tr>
<td>Heat recovery system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) HWST</td>
<td>32.0</td>
<td>40 m$^3$, working time is consistent with the open time of the SPA center</td>
</tr>
<tr>
<td>(2) Heat pump</td>
<td>130.0</td>
<td>Including WST integrated with immersed heat exchanger and controls</td>
</tr>
<tr>
<td>(3) Pumps and filter and auxiliaries</td>
<td>15.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>177.0</td>
<td></td>
</tr>
</tbody>
</table>

WST: wastewater storage tank; HWST: hot water storage tank.
### Table 5. Operating costs of different water heating systems per year (RMB = Chinese Yuan).

<table>
<thead>
<tr>
<th>System</th>
<th>Energy consumption</th>
<th>Unit price&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Operating cost (thousand RMB)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric boiler</td>
<td>424,860 kWh</td>
<td>Electricity price in the normal (valley) period: 0.84(0.44) RMB/kWh</td>
<td>356.882 (186.938)</td>
<td>5% heat loss was allowed</td>
</tr>
<tr>
<td>Gas boiler</td>
<td>51,100 m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Gas: 4.9 RMB/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>250.390</td>
<td>5% heat loss was allowed; the efficiency of the boiler: 85%; and caloric value of gas: 8400 kcal/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Oil boiler</td>
<td>42,924 kg</td>
<td>Oil: 8.85 RMB/kg</td>
<td>379.877</td>
<td>5% heat loss was allowed; the efficiency of the boiler: 85%; and caloric value of oil: 10,000 kcal/kg</td>
</tr>
<tr>
<td>Coal boiler</td>
<td>151,318 kg</td>
<td>Coal: 0.9 RMB/kg</td>
<td>136.185</td>
<td>5% heat loss was allowed; the efficiency of the small size boiler: 45%; 10 kg coal are consumed by the daily process of starting and stopping; and caloric value of coal: 5500 kcal/kg</td>
</tr>
<tr>
<td>Heat recovery system</td>
<td>126,417 kWh</td>
<td>Electricity price in the normal period: 0.84 RMB/kWh</td>
<td>106.190</td>
<td>The averaged COP of the WWSHP system was 3.2</td>
</tr>
</tbody>
</table>

COP: coefficient of performance; WWSHP: wastewater source heat pump.

<sup>a</sup>Energy cost quoted in Shenzhen, China, where the SPA center studied is located.

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**Figure 8.** Comparison of projected operating cost for estimated 15 years of service (initial cost + operating cost × 15 years).
Others. During field test, the staple fiber from bath towel, toothpick, and human hair were found in the collected bath water. They either blocked the common filter or intertwined the impeller of the water pump, so as to cause the failure of the filter or the stop of the pump. These clearly suggested that a special filter should be used for waste bath water to prevent it from being blocked and to intercept these contained objects.

Economic analysis

The WWSHP water heating system was compared with several conventional water heating methods including electric boilers, gas boilers, oil boilers, and coal boilers, in terms of initial and operating cost.

Initial cost

Table 4 presents the initial cost estimates of the different systems being evaluated in this study. At the same amount of hot water provided, the ranking of the initial cost is: coal boiler < gas or oil boiler < electric boiler < heat recovery system. Among these systems, the electric boiler must work during the valley period at night to reduce the operating cost, which makes the electric boiler and water storage tank capacity higher and the initial cost (124,000 RMB) higher than the other boiler systems. The initial cost of the heat recovery system was slightly higher than the cost of conventional boilers (about 177,000 RMB).

Operating cost

In carrying out the comparison, since the maintenance costs for different water heating methods were comparable, only the operating cost was, therefore, considered. The field operating parameters in this SPA center were: the supply hot water temperature was at 46°C; the tap water temperature was at 27°C; the average hot water consumption in this SPA center was 50 m³/day. The COP for WWSHP was assumed at 3.2, which was the averaged value of the data recorded in the first 25 days of the long-term test (after the 25th day, the COP dropped to a lowest value, when the bio-fouling was suggested to be cleaned). A 5% heat loss was also allowed for each water heating method. The calculated results are given in Table 5.

As observed from Table 5, the ranking of the operating cost from low to high for different heating methods was as follows: WWSHP, coal boiler, gas boiler, electric boiler, and oil boiler.

By taking the 15 years of service into consideration, the projected operating cost (initial cost + operating cost × 15 years) of all the systems are shown in Figure 8. The rank of all the systems is as follows: heat recovery system < coal boiler < electric boiler < gas boiler < oil boiler (the operating cost of electric boiler was calculated with the low electricity price in valley period). The overall operating cost of the heat recovery system was only 1,769,900 RMB, which was 30.7% of oil boiler (saving 3,995,300 RMB), and 84% of coal boiler (saving 334,900 RMB). The second lowest cost was the coal boiler, which had an operating cost of 2,104,800 RMB, but it produced serious pollution.

Therefore, the use of waste heat recovery system – WWSHP for water heating was more financially advantageous than the use of other conventional water heating methods, due to its low initial cost, low overall operating cost, and significant energy saving performance.

Conclusions

An experimental heat pump system using wastewater discharged from a common bathroom as heat source was built. A field study on its operating performance has been carried out and is reported in this article. A number of conclusions can be drawn as follows:

1. A significantly uneven vertical wastewater temperature distribution was presented when the WWSHP ran with wastewater inside the WST being static, leading to a
low COP. Circulating wastewater inside the WST could help improve the operating performance of the WWSHP significantly.

2. The variation of daily averaged COP over 1 month suggested that an effective and regular cleaning on the heat transfer surface of the wastewater heat exchanger was necessary, which may insure that the WWSHP would efficiently recover heat from waste bath water with an acceptable COP.

3. As a result of bio-fouling build-up, the maximum transporting capacity of the wastewater discharge pipe was reduced by 16.9% after 1 month operation, and by 20.1% after ~5 months. Thus, an appropriate oversize design and a periodical cleaning on the wastewater transfer pipe were also recommended to keep a designed flow rate. In addition, a special filter should be deployed to remove objects found in waste bath water such as staple fiber and human hair.

4. Using this environment-friendly heat recovery system was also more financially advantageous, than using other conventional water heating methods.

Acknowledgments
The authors acknowledge the financial supports from the National Key Technology R&D Program in the 11th Five-Year Plan of China (No. 2006BAJ01A06), and The Hong Kong Polytechnic University, and University of Illinois at Urbana-Champaign, USA.

References

Appendix

Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$c_w$</td>
<td>specific heat of water (J/(kg K))</td>
</tr>
<tr>
<td>$I_{tot}$</td>
<td>total current of the system, for compressors and pumps (A)</td>
</tr>
<tr>
<td>$Q_h$</td>
<td>water heating capacity in the condenser (W)</td>
</tr>
<tr>
<td>$T_{set-hw1}$</td>
<td>higher hot water temperature setting inside HWST (°C)</td>
</tr>
<tr>
<td>$T_{set-hw2}$</td>
<td>lower hot water temperature setting inside HWST (°C)</td>
</tr>
</tbody>
</table>
$T_{\text{set-ww}}$ lower wastewater temperature setting inside WST (°C)

$T_{w,ci}$ water temperature at condenser inlet (°C)

$T_{w,co}$ water temperature at condenser outlet (°C)

$T_1$ hot water temperature at HWST outlet (°C)

$T_2$ hot water temperature at the middle point inside HWST (°C)

$T_3$ hot water temperature at HWST inlet (°C)

$T_4$ wastewater temperature at the top point inside WST (°C)

$T_5$ wastewater temperature at the middle point inside WST (°C)

$T_6$ wastewater temperature at the bottom point inside WST (°C)

$\dot{U}_{\text{tot}}$ total voltage of the system (V)

$\dot{V}_w$ mass flow rate of water passing through the condenser (m$^3$/s)

$\dot{W}_{\text{tot}}$ total power input to the WWSHP ($\dot{W}_{\text{tot}} = \dot{W}_{\text{pump}} + \dot{W}_{\text{comp}}$) (W)

$\rho_w$ density of water (kg/m$^3$)

$\varphi$ power factor, 0.98