Experimental investigation on water quality standard of Yangtze River water source heat pump
Zenghu Qin, Mingwei Tong and Lin Kun

ABSTRACT

Due to the surface water in the upper reaches of Yangtze River in China containing large amounts of silt and algae, high content of microorganisms and suspended solids, the water in Yangtze River cannot be used for cooling a heat pump directly. In this paper, the possibility of using Yangtze River, which goes through Chongqing, a city in southwest China, as a heat source–sink was investigated. Water temperature and quality of the Yangtze River in the Chongqing area were analyzed and the performance of water source heat pump units in different sediment concentrations, turbidity and algae material conditions were tested experimentally, and the water quality standards, in particular surface water conditions, in the Yangtze River region that adapt to energy-efficient heat pumps were also proposed. The experimental results show that the coefficient of performance heat pump falls by 3.73% to the greatest extent, and the fouling resistance of cooling water in the heat exchanger increases up to 25.6% in different water conditions. When the sediment concentration and the turbidity in the river water are no more than 100 g/m³ and 50 NTU respectively, the performance of the heat pump is better, which can be used as a suitable river water quality standard for river water source heat pumps.

Key words | coefficient of performance, fouling resistance, heat capacity, water quality, Yangtze River water heat pump

INTRODUCTION

Water source heat pump systems, which are now considered to be a viable alternative to conventional cooling and heating systems, have a wide utilizing prospect and value. Heat sources and sinks commonly used are river water, lake water, seawater, groundwater, wastewater and effluent. They have different thermal characteristics, which directly affect the technical and economic performance of heat pumps.

In Turkey, an experimental investigation of Seyhan River and Dam Lake as a heat source–sink for heat pumps was carried out (Buyukalaca et al. 2003). Nam and Ooka developed the dual-source hybrid heat pump system using groundwater and air. In spring and autumn, based on the temperature comparison between the groundwater and the ambient temperature, the groundwater heat pump system is not more efficient than an air source heat pump, and the developed hybrid system showed an improvement of 2–7% compared with a water cooling system, and 4–18% compared with an air source heat pump (Nam & Ooka 2010). Yong Cho and Rin Yun investigated the heating and cooling performance of a heat pump utilizing the heat energy of raw water supplied to a water treatment facility. The raw water source provides a favorable heat source compared with an ambient air source except for in spring; the average coefficient of performance (COP) of the system in the heating season is 3.3, and the average COP for the cooling season is 7.2 (Cho & Yun 2011). Chen et al. investigated an underground water source heat pump system installed in a tall apartment building in Beijing, China. By analyzing this system for 2 years, operation methods and a controlling algorithm for the system were developed (Chen et al. 2005). Yu et al. studied a ground source heat pump for an archives building in Shanghai, whose rooms were kept at a constant temperature and relative humidity. It is notable that some of the rejected heat is used to heat the air in the air handling units in this study. The COP of the system in spring and autumn is lower than that in summer and winter by 42 and 14%, respectively. However, the

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operating cost of a ground source heat pump was reduced by 55.8% compared with an air source heat pump (Yu et al. 2011). Nam et al. investigated the performance of a groundwater source heat pump and this system depends on the temperature and depth of the water and its efficiency is much higher than that of the air source heat pump (Nam et al. 2016). Koo et al. studied the heating performance of a GSHP system in a field test. The average seasonal heating COP of the heat pump was 5.1 at a part load of 46.9%, while the seasonal system COP including the power consumption for the pump and the fans was found to be 4.2 (Koo et al. 2007). Buonomano Annamaria et al. presented a purposely designed code for the performance analysis of the Water Loop Heat Pump (WLHP) systems. Hourly, daily and seasonal energy system consumptions, operating economic costs and environmental impact assessments are dealt with (Annamaria et al. 2012).

The water source heat pump system has been paid more and more attention as the energy consumption of an air conditioning system increases and has been widely utilized in the USA, Europe, etc. (Henderson et al. 2000). More than 50 years ago, it was first introduced into China. Water temperature is relatively stable and lower than ambient air temperature, thus making for high energy efficiency of the water source heat pump. However, the application of water source heat pumps is restricted by local water conditions and regulations. A river water source heat pump is being widely used in China, especially in large areas of the Yangtze River basin. Because of the abundance of surface water resources in these areas, the promotion of the river water source heat pump has great prospects. However, barriers still exist considering the river water contains large amounts of sediment and suspended solids in the upper reaches of the Yangtze River area.

CHARACTERISTICS OF YANGTZE RIVER AND THE CITY OF CHONGQING

Chongqing, the largest industrial and economic center in southwestern China, is one of the four municipalities in China with a population of over thirty million. Yangtze River and Jialing River from Chongqing passed relatively abundant of surface water for water source heat pump technology in the development of the Chongqing natural conditions, and the flow rate of water in Yangtze River also varies. However, the average annual flow is 10,950 m³/s in Chongqing. Developing Yangtze River water source heat pump technology has been included in the ‘Eleventh Five-Year Plan’ in China. If the government, businesses and residents promote the development of the water source heat pump together, the water source heat pump in Chongqing will be promising. Therefore, rationally using these surface water resources and developing an energy efficient heat pump system for building energy efficiency have profound and lasting significance.

However, the application of surface water source heat pumps is rare, some are still in the development and feasibility study stage in Chongqing area, besides, the general situation of Yangtze River water as the cooling and heating source lacks better understanding and analysis.

The change of river temperature over time determines the grade and continuous stability as the cooling and heating source and the water quality plays a decisive role in the selection of the form of heat pump system and the heat pump performance. Thus, the transactional distribution and temporal changes of Yangtze River water temperature have been tested and analyzed by the author since July 2007 in order to understand the general situation of Yangtze River water in Chongqing. Meanwhile, the water quality is also analyzed.

The test results showed that Yangtze River water maintains a constant temperature across its transaction, the monthly mean water temperature is 23–25°C in summer and 13–15°C in winter, the temperature of the river water at bottom is 21°C and 15°C in summer and winter respectively. Because daily variations of water temperature do not exceed 0.7°C, water temperature is more relatively stable and lower than ambient air temperature, thus providing high energy efficiency of the water source heat pump. In accordance with (GB/T19409–2003), it provides heat pump cooling and heating water temperature requirements (10–25°C), and Yangtze River water is a high quality cooling and heating source.

Water quality standards are developed worldwide by national and international agencies for pollution control decision-making (Babaei Semiromi et al. 2011). Additionally, water quality of the Yangtze River was studied by determining the levels of various physico-chemical parameters (Amoako et al. 2010). Comparison of water quality of the Yangtze River with recommended water quality of the water source heat pump unit is shown in Table 1, which is referred to (GB50366–2005). If an industrial area was built at a river edge, the river water would be polluted (Banerjee & Srivastava 2009). The Yangtze River is far from the industrial area, so the river has not been serious
polluted. In general, river water meets the requirements of the chemical criteria, but it cannot meet the sediment concentration and turbidity criteria. This situation means that excessive amounts of sand and particles are present in the condensing water and would cause abnormal wear on pipe, valve components and unit equipment.

In the current study, the operation of a river water source heat pump using the Yangtze River water in different conditions of sediment concentration and turbidity as heat source and sink was investigated experimentally, and by testing the changing trends of unit performance in different conditions of sand content and turbidity, a suitable water quality standard was put forward which adapts to the conditions of the upper reaches of the Yangtze River water source heat pump.

### EXPERIMENTAL SET-UP

A simplified system is shown schematically in Figure 1. The system is located nearby the Yangtze River in Chongqing Jialing Refrigeration & Air Conditioning Equipments Co.,

Table 1 | Comparison of water quality of Yangtze River with recommended water quality of water source heat pump unit

<table>
<thead>
<tr>
<th>Description</th>
<th>Water quality of Yangtze River</th>
<th>Allowable content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment concentration (kg/m³)</td>
<td>0.02–2</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Particle diameter (mm)</td>
<td>0.01–1.2</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>&lt;250</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Cl– ion (mg/L)</td>
<td>&lt;10</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Cl (ppm)</td>
<td>&lt;0.1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>pH</td>
<td>6.42–8.21</td>
<td>6.5–8.5</td>
</tr>
<tr>
<td>H₂S (mg/L)</td>
<td>&lt;0.2</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Suspended solids (g/m³)</td>
<td>&lt;1.2</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Mineral salts (g/L)</td>
<td>&lt;1.2</td>
<td>&lt;3</td>
</tr>
</tbody>
</table>
Ltd which researches water source heat pump technology specifically. The test system mainly consists of a screw type compression heat pump, circulation water pumps, electromagnetic flow meters, auxiliary heat pumps, electrical heaters, temperature controllers, sensors for various measurements and a data collection system.

The system is still some distance away from the Yangtze River. Therefore, it was unfeasible to use river water directly in the experiments. Instead of using the river water directly, two water tanks were used in the system to model the river water. Each of the water tanks has a capacity of 4,000 L and provides cooling water and chilled water, respectively. In order to keep the temperatures of the water returning to water tanks at a fixed desired value, a source of cold water chiller and two heat exchangers were also used. Chilled water and cooling water will make heat exchange in the heat exchanger H1. And then, in order to maintain the stability of the temperature set values, the cooling water flowing through the heat exchanger H1 will make heat exchange with the source of cold water in the heat exchanger H2. Two electrical heaters (one for the cooling water and the other for the chilled water) are both controlled by PT100 temperature controllers, to make the fine adjustment of water temperature. The temperature set values were adjusted daily so that the temperature of water returning to the system was constant and equal to that of the Yangtze River.

The test system has two different water fluid loops: cooling water loop and chilled water loop, which were used for the transportation of energy to the evaporator and condenser. Flow meters and temperature controllers are located in the entrance of the evaporator and condenser to measure the flow rate and the temperature of chilled water and cooling water, respectively. Chilled water pump rated flow is about 45 m³/h, while cooling water pump rated flow is about 50 m³/h. During the test, the computer control system controls the electric valves in the valves FM1–FM8 to change the frequency of the water pump, automatically, so that the flow rates and the temperatures of inlet and outlet are controlled at a fixed desired value.

The stirrer is set in the cooling tank; stirring the water to prevent the deposition of sediment in the tank. The sediment concentration of simulated river water is set by sediment sampler: removing a certain volume of simulated river water, filtering out the sand by 200 mesh, placing it inside the drying oven and weighting the quality of the sand, and then, the sediment can be calculated. The turbidity of simulated river water is measured by dedicated turbidity meter.

Energy efficiency of the water source heat pump unit is used in the experiment, which could adapt to the upper reaches of the Yangtze River region. The unit model is SRBLG500, which has a nominal cooling (heating) capacity of 500 (575) kW, cooling (heating) power input is 81 (113) kW. It has passed detection by Hefei General Machinery & Electrical Products Inspection Institute. The COP of the unit can achieve 6.10 in clean water conditions.

The performance of the unit is not very sensitive to sediment and other water quality indicators predictably, therefore, indicators of sediment and turbidity were tested over a wide range, and the measured water quality indicators are listed in Table 2. During the heat pump performance test experiments, maintaining the cooling water inlet/outlet temperature at 25/30 °C and the chilled water inlet/outlet temperature at 12/7 °C, the unit was continuously operated respectively for 10 days (10 hours a day, 24 days of continuous operation) in each water quality condition, and various performances of the unit were tested simultaneously. Moreover, after each set of tests was conducted, the unit heat exchanger was cleaned.

COP values of the heat pump unit in different river water quality conditions were determined. The heating and cooling performances of the heat pump were calculated respectively from the following equations (Buyukalaca et al. 2005):

$$\text{COP}_c = \frac{Q_c}{W_i} = \frac{m_{cw}c_{cw}(T_{cw,ci} - T_{cw,co})}{W_{com} + W_p}$$  \hspace{1cm} (1)

$$\text{COP}_h = \frac{Q_c}{W_i} = \frac{m_{cw}c_{cw}(T_{cw,co} - T_{cw,ci})}{W_{com} + W_p}$$  \hspace{1cm} (2)

where $Q_c$ and $Q_e$ are the amount of the heat subtracted from the condenser and added to the evaporator by the transport river water, respectively. $W_i$ is the total power consumption of the system, which includes the power consumption of the

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment concentration (g/m³)</td>
<td>100.3</td>
<td>100.7</td>
<td>201.5</td>
<td>403.1</td>
<td>700.2</td>
<td>1,000.2</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>20.6</td>
<td>51.8</td>
<td>52.5</td>
<td>103.1</td>
<td>252.2</td>
<td>501.1</td>
</tr>
</tbody>
</table>
compressor ($W_{com}$) and the power consumption of the river water pumps ($W_p$), and $m_{tw}$ and $c_{tw}$ show the river water flow rate and specific heat of the transport river water, respectively. $T_{tw,ci}$, $T_{tw,co}$, $T_{tw,ei}$, $T_{tw,eo}$ are the temperatures of the transport river water at the condenser inlet and outlet and at the evaporator inlet and outlet respectively.

Cooling/chilled water temperatures, the inlet and outlet temperatures of the condenser and evaporator were measured by T-type thermocouples with an uncertainty of $\pm0.2^\circ$C. To eliminate the errors involved in absolute temperature measurement, an ice bath was employed as the reference junction for all the thermocouples used. Water flow rate and power consumption were measured respectively by electromagnetic flow meters with an uncertainty of $\pm0.5\%$ of actual flow rate and by digital power meters with an uncertainty of $\pm0.5\%$ of reading. Supply voltage and electric current were also measured with an uncertainty of $\pm0.5\%$ of reading. The uncertainty associated with COP was calculated such that the maximum uncertainty in COP was found to be 6.35% in different river water quality conditions.

**RESULTS AND DISCUSSION**

Because the sediment deposition rate in heating conditions is faster than in cooling conditions, the water quality standard that tested out in cooling conditions in summer was also suitable for the heating conditions in winter. Therefore, heating in winter was not considered in this study. The experiments were performed from January to June 2010 to acquire practical data about system operation.

**The impact for unit performance due to the change in water quality**

For different water quality conditions, experiments were carried out mainly considering two main indicators of sediment concentration and turbidity. However, sediment concentration has some impact on turbidity, but the rule of impact can not be verified in this test. Besides, the study of two indicators impacting on unit performance is rare at home and abroad, therefore, we followed different combinations of sediment concentration and turbidity experiments. In order to indicate these different combinations of sediment concentration and turbidity more clearly and concisely, the logarithm of the product of two indicators values to describe their combined effect was used: if $A$ is the value of sediment concentration, $B$ is the turbidity value, log ($A*B$) is the combined effect of two indicators, and $A> B$. An energy efficient water source heat pump unit was used in the experiment, it was designed for the upper reaches of Yangtze River water quality conditions. Various performance parameters of the unit were tested in different quality conditions of cooling water.

Figure 2 shows the variation of the unit COP value in different conditions of sand content and turbidity. It is clearly shown that COP value will decrease rapidly when log ($A*B$) is greater than 4. This proves that it is very unfavorable for heat pump unit operation in these types of water quality conditions. The COP of the unit has its highest value when log ($A*B$) is approximately 3.7. Therefore, it is favorable for the operation of the heat pump in water quality conditions of the sediment concentration $\leq100$ g/m$^3$ and turbidity $\leq50$ NTU. Obviously, COP value of the unit maximum decreased by 3.73% from the experimental results, so the sediment concentration and turbidity have no significant impact on the experimental unit performance, and the energy efficient water source heat pump unit has a lower requirement for river water quality conditions.

**The impact for specific heat $c_{tw}$ of the cooling water due to the change in water quality**

The amount of the heat subtracted from the condenser was calculated from the following equation:

$$Q_c = m_{tw}c_{tw}(T_{tw,co} - T_{tw,ci})$$

(3)

Temperatures of the cooling water at the condenser inlet and outlet have nothing to do with the water quality, so it can be measured accurately. The flow rate of the cooling water can be calculated by measuring the volume flow and density of cooling water. Changes in water quality will cause a slight change in the density of cooling water. However, solids content just occupies a small proportion in the cooling water, so the density of cooling water is

![Figure 2](https://iwaponline.com/wst/article-pdf/66/5/1103/443261/1103.pdf) | Change of the unit COP value at different conditions of sediment concentration and turbidity.
regarded as being constant. With clean water as the criterion, variation of specific heat of the cooling water can be drawn according to the results.

Figure 3 presents the specific heat values of cooling water in different quality conditions, which is calculated by Equation (3). It is seen from Figure 3 that, if the specific heat of clean water is 4.18 kJ/(kg K), the specific heat value maximum increased by 0.6% in different quality conditions of cooling water. Therefore, changes in physical properties of the cooling water can be neglected in heat transfer calculations of the water source heat pump.

The impact for fouling resistances \( R_f \) of cooling water due to the change in water quality

Because the surface water in the upper reaches of the Yangtze River contain large amounts of sediment and algae, high content of microorganisms and suspended solids, heat exchangers are easy to scale, therefore, the unit should be considered for the impact of fouling resistance of cooling water in long-term operation. If the fouling resistance cannot be experimentally tested, the actual operation of the unit would be adversely affected. Fouling resistance of cooling water in condenser selection was lower in Guangzhou Metro station chillers for the air conditioning system, which would cause many problems such as lower unit cooling capacity and high energy consumption (Ma 2002).

\( Q^c_c \) is the amount of the heat subtracted from the condenser when the cooling water uses clean water and it can be calculated by the following equation:

\[
Q^c_c = m_{tw}c_{tw}(T_{tw,co} - T_{tw,ci})
\]  

where \( T_{tw,co} \) is the temperature of the cooling water at the condenser outlet when the clean water is used as cooling water. The fouling resistance for clean water may use the recommended value in the design manual. Analysis shows that density and specific heat of cooling water are able to use the physical property values of clean water.

The fouling resistance of cooling water in condenser \( R_f \) can be calculated by the following equations:

\[
K = \frac{Q_c}{A\Delta T_{tw}} \tag{5}
\]

\[
K^* = \frac{Q^c_c}{A\Delta T_{tw}} \tag{6}
\]

\[
\Delta T_{tw} = \frac{T_{tw,co} - T_{tw,ci}}{\ln\frac{T_{tw,s} - T_{tw,ci}}{T_{tw,s} - T_{tw,co}}} \tag{7}
\]

\[
\Delta T^*_w = \frac{T^*_w,co - T^*_w,ci}{\ln\frac{T^*_w,s - T^*_w,ci}{T^*_w,s - T^*_w,co}} \tag{8}
\]

\[
R_f = \frac{1}{K} - \frac{1}{K^*} \tag{9}
\]

\[
R_f = \frac{A}{m_{tw}c_{tw}} \left( \frac{\Delta T_{tw}}{T_{tw,co} - T_{tw,ci}} - \frac{\Delta T^*_w}{T^*_w,co - T^*_w,ci} \right) \tag{10}
\]

where \( K \) is heat transfer coefficient for the condenser; \( A \) is heat transfer area for the condenser; \( \Delta T_{tw} \) is the logarithmic mean temperature difference and \( T_{tw,s} \) is condensing temperature. Among them, all the items with * indicate the corresponding items when it uses clean water as the cooling water.

Figure 4 is drawn to show the variation of fouling resistance of cooling water in different conditions of

![Figure 3](https://iwaponline.com/wst/article-pdf/66/5/1103/443261/1103.pdf)  

Change of specific heat of cooling water \( c_{tw} \) at different conditions of sediment concentration and turbidity.

![Figure 4](https://iwaponline.com/wst/article-pdf/66/5/1103/443261/1103.pdf)  

Change of fouling resistance of cooling water \( R_f \) at different conditions of sediment concentration and turbidity.
sediment concentration and turbidity according to the results. Fouling resistance is $1.72 \times 10^{-4} \text{ m}^2/\text{W}$ when clean water is used as the cooling water. With clean water as the criterion, the fouling resistance value maximum increased by 25.6% in different quality conditions of cooling water. It is clear from Figure 4 that fouling resistance value becomes relatively stable in $1.77 \times 10^{-4} \text{ m}^2/\text{W}$ when log $(A*B)$ is greater than 4, and fouling resistance value is about $1.969 \times 10^{-4} \text{ m}^2/\text{W}$ when log $(A*B)$ is approximately 3.7, which increases by 14.7%.

CONCLUSION

The investigation of the key technical problems before using Yangtze River water directly as cooling water of a heat pump unit has been introduced. The experiment of testing the water quality standard has been carried out in particular surface water conditions in the Yangtze River region. The experimental results show that when the sediment concentration is less than or equal to 100 g/m$^3$ and the turbidity is 50 NTU or less in the river water, the performance of the heat pump is better, which can be used as a suitable river water quality standard for river water source heat pumps, and the fouling resistance value is about $1.969 \times 10^{-4} \text{ m}^2/\text{W}$ in these water quality conditions which just increases by 14.7% with clean water as the criterion.

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