STUDIES ON THE EFFECTIVENESS OF RIVER WATER SOURCE HEAT PUMPS AND ENERGY EFFICIENCY IN WINTER

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Abstract: The applicability of river water source heat pump systems should be considered for designing and operating. And compared with gas boilers, its energy efficiency is limited by some conditions. Based on the common forms of river water source heat pump systems, the functions of the main parts in systems is analyzed, including the heat pump, the water pump, the water-treating equipment and the heat-exchanger. The key factors that influence the effectiveness of the river water source heat pump system are studied. Taking a real project as example, the energy efficiency of the water source heat pump system is analyzed, combined with the actual operating conditions and the requirements of regulations. The conditions and the effectiveness of saving energy of the system are proposed based on results of several scenarios. It shows that the COP of the river water source heat pump system is not less than 3.0 when the COP of the heat pump is above 5.0 and the transportation energy consumption is less than 39%, which means the river water source heat pump system is more efficient than the conventional systems.

Key Words: river water, heat pump, adaptability, energy efficiency analysis

1 INTRODUCTION

A water source heat pump system consists of several subsystems, such as water source, heat pump, water transportation systems, and end users, which energy consumption is contributed from each part. In terms of water source, the heat pump has great advantages on energy efficiency and environmental protection, while the whole system might not be good as expected because of the cost and energy consumption for source water. In general, the source water, the water pumping installations, the pipe network and the water treatment equipments constitute the water source subsystem which additional investment and operating costs compromise advantages of water source heat pump. So the application of water source systems is limited by conditions, economics and energy efficiency comparing with the conventional heating system using boilers. The forms of water transportation, arrangement and operation of pumps play key roles on the water transportation energy consumption, which influences the energy-saving effect of river water source heat pump. The greater proportion of energy consumption for water transportation takes, the lower the system energy efficiency is. To a certain extent, water source heat pump systems might not energy efficient. Therefore, the applicability and effectiveness of river water source heat pump systems should be considered for designing and operating according to the real conditions besides the basic requirements of water temperature, water quality and water volume. Based on the river water conditions in Chongqing, the key factors that influence the

energy efficiency of the river water source heat pump system will be analyzed and the application limitations will be studied.

2 ENERGY CONSUMPTION OF COMPONENTS IN THE RIVER WATER SOURCE HEAT PUMP SYSTEM

2.1 Forms of River Water Source Heat Pump Systems

The thermal energy stored in water can be applied directly and indirectly in water source heat pump systems. Direct use of water means that the source water directly enter the heat pump for heat exchange after a series of water treatment equipment, while indirect way means that the source water flow through the heat exchange equipment to achieve heat exchanging. Schematic diagrams of two forms are shown in Figure 1 and Figure 2. The system energy consumption and performance are different for these two forms. In order to calculate the energy efficiency of WSHP systems, each main component is analyzed as follows.

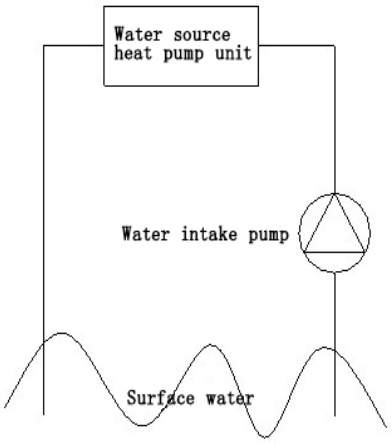


Figure1: Form of Water Used Directly

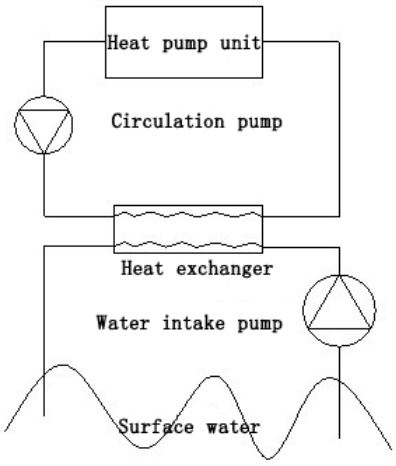


Figure 2: Form of Water Used Indirectly

2.2 Energy Consumption of the Heat Pump

The energy consumption of heat pumps is a major part of energy consumption of WSHP systems, thus, the system energy efficiency is directly affected by the performance of heat pumps. Table 1 lists main component specification and characteristics of some types of WSHP manufactured in China which can be regarded as representatives averagely. The correction factor of COP changing with variable water flow rate is shown in Table 2.

Table 1: Performance parameters of some WSHP units

Type			460M-4F	480M-4F	520M-4F	560M-4F	620M-4F
R22	Rated cooling capacity	kW	1558	1669	1779	1912	2159
	Rated heating capacity	kW	1561.6	1671.9	1782.3	1915.5	2163.3
Compressor	Cooling power	kW	236.0	252.8	269.6	286.4	319.6
	Heating power	kW	312.0	334.2	356.4	378.6	422.5
Cooling water flow rate	Cooling conditions	m^3/h	308.6	330.5	352.3	378.1	426.3
	Heating	m^3/h	268.6	287.6	306.6	329.5	372.1

	conditions						
Chilled water flow rate	Cooling conditions	m^3/h	268.1	287.0	305.9	328.8	371.3
	Heating conditions	m^3/h	214.9	230.1	245.2	264.3	299.4
Rated conditions	cooling: inlet water temperature of evaporator is 12°C, outlet water temperature is 7°C; inlet water temperature of condenser is 25°C, outlet water temperature is 30°C. Heating: inlet water temperature of evaporator is 10°C, outlet water temperature is 5°C; inlet water temperature of condenser is 40°C, outlet water temperature is 45°C.						

Table 2：Correction factor of COP changing with variable water flow rate

Cooling water		**Chilled water**		**Cooling capacity**	**Power**	**COP**
Inlet temp.	**Flow coefficient***	**Outlet temp.**	**Flow coefficient**			
chilled water flow is constant, while cooling water flow is variable						
25	0.5	7	1	0.951	1.055	0.901
25	0.6	7	1	0.966	1.038	0.931
25	0.7	7	1	0.977	1.025	0.953
25	0.8	7	1	0.991	1.015	0.976
25	0.9	7	1	0.994	1.007	0.987
25	1	7	1	1	1	1

* Flow coefficient = actual flow rate / rated flow rate

It can be seen that the COP of WSHP for cooling in rated conditions is above 6.6 and the COP for heating is above 5.0, and the COP will change with the cooling water flow rate decreasing. Therefore, the performance and energy efficiency of WSHP under both design conditions and operating conditions should be considered.

2.3 Energy Consumption of Pump

Compared with conventional systems, the river water source heat pump system adds a cycle for source water transportation and distribution, which influences the energy-saving effect of WSHP systems. As the main energy consumed equipment, the circulating pump is important for system energy efficiency. Pump power is calculated as Eq. (1).

$$N = \gamma \bullet G \bullet H / \eta \tag{1}$$

G = pump flow rate, m^3/h;
H = pump head, m; H = height + resistance of water treatment equipment + resistance of heat exchanger + resistance of heat pump + resistance of pipe and valves;
η = pump efficiency.

In variable speed conditions, the relationship among flow rate, head, and power of pump is described as Eq. (2) obeying the similarity law (Fu 2006).

$$N_0 / N_1 = (H_O / H_1)^2 = (G_0 / G_1)^3 = (n_0 / n_1)^3 \tag{2}$$

The subscript "0" stands for rated value of pump, "1" for actual value of pump.
n = pump speed, r/min.

2.4 Water Treatment

2.4.1 The quality of river water in Chongqing

The application of WSHP has a great energy-saving potential in Chongqing of China since there is abundant water resource there. According to the hydrological data from hydrological stations of Beibei, Cuntan and Zhutuo located on Yangtze River and Jialing River, the monthly average values of sediment concentration of river water in Yangtze River and Jialing River in 2006 have been shown in Figure 3.

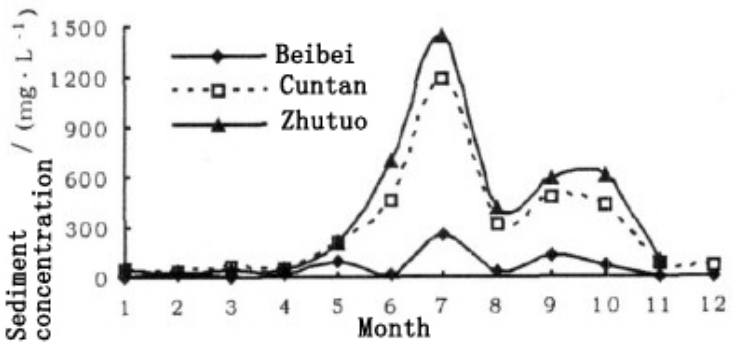


Figure 3: The Monthly Average Values of Sediment Concentration of The Yangtze River and Jialing River In 2006

According to sediment data of Yangtze River from Yangtze River Hydrological Bureau, the sediment concentration and the median particle size in Yangtze River have been making a substantial decline since 2005 compared with the average value of many years. The situation of water quality in Yangtze River in Chongqing is shown as Table 3.

Table 3: Water Quality of the Yangtze River in Chongqing (**mg/L**)

Test items	PH	Mineral degree	Cl^-	SO_4^{2-}	CaO	Fe^{2+}	H_2S
Measurements	6.42—8.21	<1200	<10	<110	<82	<0.2	<0.2

Figure 3 and Table 3 show that the average monthly sediment concentration of the Yangtze River and the Jialing River are 8-1440mg/L in summer and 2-89mg/L in winter. According to the water quality requirements (Xiang et al. 2009) regulated by the standard of "Heating, Ventilation and Air Conditioning design specification (HVAC) (GB50019-2003)", the river water quality in Chongqing can meet regulatory requirements except the sediment concentration. Therefore, sediment clean is a key point of water treatment when using the Yangtze River water as heat source/sink.

2.4.2 The basic form of water treatment

The choice of water treatment equipment not only determines the quality of water that enters the heat exchanger but also affects the pump head. At present, the water cyclone degriter and the integrated water processor are combined for water treatment of river WSHP systems mostly in Chongqing. Its functions are cleaning sediment and dirt, removing rust and algae, sterilization, and filtering. The water treatment equipment which is lower resistance and more efficient should be selected according to specific water quality conditions.

2.5 Heat Exchange Equipment

For the indirect application of river water, water flows through heat exchangers to exchange heat instead of entering heat pumps directly, using medium water to extract cold or heat from water (Ma and Lu 2007). Two types of heat exchange equipment can be applied for river water source heat pump systems. One type is coil heat transfer submerged directly in water.

However, this kind coil heat exchanger is less utilized now since the material selection, technology for protecting against corrosion and fouling are still need to be further studied besides it affects sailing safety. Plate heat exchangers are widely used in indirect river water source heat pump systems as compact heat exchange equipment. The performance of plate heat exchangers can be specified by heat exchange capacity, temperature difference and resistance.

2.5.1 Heat exchange capacity

The heat exchange capacity of plate heat exchanger is defined as the following Eq. (3) (Feng 1994);

$$Q = KA\Delta T_m \tag{3}$$

K = heat transfer coefficient, W / (m^2.^{o}C);
A = heat transfer area, m^2;
$\triangle T_m$ = temperature difference, ^{o}C.

2.5.2 Heat transfer temperature difference (ΔT_m)

The heat transfer temperature difference affects the heat exchange capacity. The average temperature difference of plate heat exchanger ($\triangle T_m$) can be calculated as logarithmic mean temperature difference in countercurrent situation. It is calculated as Eq. (4);

$$\Delta T_{\mathrm{m}} = (\Delta t_{\max} - \Delta t_{\min}) / \ln(\Delta t_{\max} / \Delta t_{\min}) \tag{4}$$

$\Delta t_{\max}$ = the largest value of end of the temperature difference in countercurrent situation, ^{o}C;

$\Delta t_{\min}$ = the smallest value of end of the temperature difference in countercurrent situation, ^{o}C.

2.5.3 Resistance (ΔP)

Liquid pressures drop in plate heat exchanger (ΔP) mainly due to the friction and some structural parts. According to the similarity theory, resistance characteristics can be expressed as the relationship of Euler Criterion Equation (Cai 2008).

$$Eu = C \bullet \mathrm{Re}^n \tag{5}$$

Eu stands for Euler numbers, and the pressure can be calculated by Eq. (6);

$$Eu = \Delta P / (\rho \bullet u^2) \tag{6}$$

$\triangle$P = pressure drop from the inlet to the outlet, Pa;
ρ = fluid density, kg/m^3;
u = fluid velocity, m/s;
C = constant.

The Eq. (7) can be deduced from Eq. (5) to linearization by logarithmic transformation.

$$\log Eu = \log C + n \log \mathrm{Re} \tag{7}$$

From Eq. (7), the constant C and constant n can be calculated through fitting a series of numbers of Re and Eu. And then, the pressure drop of the plate heat exchanger can be obtained by formula (6).

3 ENERGY EFFICIENCY OF THE RIVER WSHP

3.1 The Main Factors Influencing The System Energy Efficiency

As the schematic diagram shown in Figure 4, the energy consumption of the river water source heat pump system is mainly made up of heat pump units, primary and secondary pumps, and pumps in the user side, which can be expressed as Eq.(8);

$$N = N_1 + N_2 + N_3 + N_4 \tag{8}$$

N = system energy consumption, kWh;
N_1 = energy consumption of the heat pump, kWh;
N_2 = energy consumption of the primary water pump, kWh;
N_3 = energy consumption of the secondary water pump, kWh;
N_4 = energy consumption of the pump in the user side, kWh.

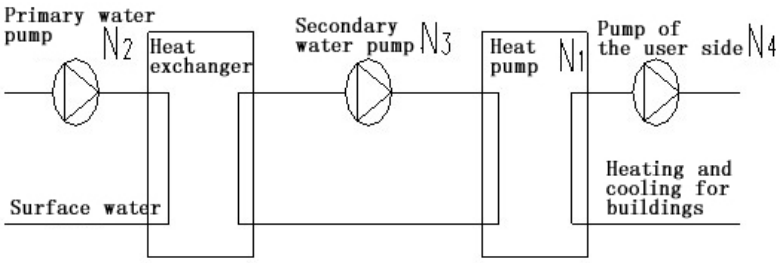


Figure 4: Water - Water Heat Pump Schematic

The system COP can be expressed as following Eq. (9);

$$COP = Q / N = Q / (N_1 + N_2 + N_3 + N_4) \tag{9}$$

Q = cooling or heating capacity of system, kWh;
N = energy consumption of system, kWh.

It shows that the main factors affecting the system COP are the heat capacity (Q) provided by the system and the energy consumption of the related equipments (N). The heat capacity is cooling or heating load of the room, the influence factors on which are mainly composed of the envelope, outdoor climate conditions, indoor people and furniture. N_1 is related to the temperature both in the river water side and the user side. The greater the temperature difference is, the greater the power consumption for generating the unit heat. N_2 is mainly determined by the water flow rate and pumping height, the resistance of water treatment equipment and heat exchanger. N_3 is relevant to the heat pump, the heat exchanger and the medium water flow rate. And N_4 mainly depends on the circulating water flow rate in the user side, the heat pump and the terminal equipment.

3.2 Analysis of System Energy Efficiency

3.2.1 Energy consumption of the river water side

Taking the same type of WSHP as specified on Table 1 and Table 2 for analysis. The relationship between the temperature difference of cooling water and the correction factor of WSHP power φ is listed in Table 4.

Table 4: Cooling water temperature difference and correction factor of WSHP power

Flow coefficient of the cooling water	0.5	0.6	0.7	0.8	0.9	1
Cooling water temperature difference Δt (°C)	10	8.35	7.15	6.25	5.55	5
Correction factor of WSHP power φ	1.055	1.038	1.025	1.015	1.007	1

From data in Table 4, the relationship between the temperature difference of cooling water (Δt) and the correction factor of WSHP power (φ) can be fitted and expressed as Eq. (10).

$$\varphi = -0.0002\Delta t^2 + 0.0142\Delta t + 0.9343 \tag{10}$$

From the Eq. (10), it can be seen that the WSHP power increases as the temperature difference of cooling water increases, but the variation extent is much small. For example, the WSHP power increases only by 5% or so when the temperature difference of cooling water is twice of the rated temperature.

In general, the energy consumption of pump in source water circulation is one major part of the energy consumption in plant, which is mainly determined by the water flow rate (Q) and the pump head (H). When the heat supplied is constant, energy consumption of pumps can be reduced by reducing the pump flow rate, which will increase the temperature difference. According to the similarity theory and the formula $Q = G \bullet C_p \bullet \Delta t$, the relationship between temperature difference and pump power can be expressed as the following Eq. (11).

$$N_0 / N_1 = (\Delta t_1 / \Delta t_0)^3 \tag{11}$$

It shows that the rate of power changing is much greater than that of the temperature difference changing. Therefore, a reasonable design temperature difference of river water plays an important role in improving the system energy efficiency.

3.2.2 Energy consumption of the user side

In the annual report on energy efficiency development for buildings in China, a research on the principle of pump energy consumption and water temperature difference is presented (ORNL 2009). The result is listed in Table 5.

Table 5: Energy consumption of pump with various water temperature difference

Water temperature difference(°C)	2	4	6	8
Energy consumption of pump for1kW heat (kW)	0.1	0.05	0.035	0.025

The functional relationship between the energy consumption of pump in the user side (N4) and temperature difference of supply water and return water (ΔT) can be fitted as follows;

$$N_4 = 0.0025\Delta T^2 - 0.037\Delta T + 0.1625 \quad (12)$$

In general, the water temperature difference of the user side in WSHP systems is 5°C. It can be calculated by Eq. (12) that the pump energy consumption is 0.0425kW for transporting 1kW heat.

4 ANALASIS ON A REAL PROJECT

4.1 The System Instruction

A project of river water source heat pump air conditioning system with a cooling load of 16497.5kW for summer and a heating load of 6489.9kW for winter is located in Chongqing, China. In winter, design temperature of water supply and return are 45°C and 40°C, while design temperature difference of water is 5°C. The main components specification and characteristics of the system is shown in Table 6.

Table 6: Basic parameters equipment

Equipment	Basic parameters
Water source heat pump	Rated heating capacity: 2163.3kW,Heating power: 422.5kW Heating condition: Condenser inlet/outlet water temperature, 40/45°C Evaporator inlet/outlet water temperature, 10/5°C
Pump in the river water side*	Rated flow: 365 m^3/h, Rated head: 49m, Efficiency: 78%
Pump in the user side	Rated flow: 450 m^3/h, Rated head: 25 m, Efficiency: 80%

* Form of water used directly

4.2 Comparison of System Energy Efficiency

4.2.1 Design conditions

Under the design condition with full-load, the energy consumption of the WSHP, the circulation pump in the river water side, and the circulation pumps in the user side are 1267.5kW, 320 kW, and 260 kW respectively. It is calculated by Eq. (8) and Eq. (9) that the system COP is 3.5, which is equivalent to coal consumption of 98.5gce/kWh (heat).

4.2.2 Operation conditions

Under the operation condition with full-load, the energy consumption of equipments in the WSHP air conditioning system and the system energy efficiency is calculated and listed in Table 7.

Table 7: Energy efficiency ratio (EER) of system in operation condition

operation condition	Scenario	Energy consumption of WSHP （kW）	Energy consumption of pump in the river water side （kW）	Energy consumption of pump in the user side （kW）	System COP	Equivalent coal consumption （gce/kWh）
Temperature difference of water side is constant. Temperature difference of user side is various.	I: 4°C for the user side; 5°C for the water side	1267.5	320	507.8	3.09	111.6
	II: 3°C for the user side; 5°C for the waterside	1267.5	320	1203	2.3	150
Temperature difference of water side is various. Temperature difference of user side is constant.	III: 6°C for the user side; 5°C for the waterside	1283.5	185	260	3.75	91.9
	IV: 7°C for the user side; 5°C for the water side	1298.2	116.6	260	3.87	89.1
	V: 8°C for the user side; 5°C for water side	1312	78	260	4.18	82.5

It can be concluded from Table 7 as following: (1) When the WSHP COP is greater than 5.0, and the percentage of energy consumption for river water transportation is less than 39% of the total system energy consumption in plant, the system heating COP is more than 3.0 ,which is higher than that of conventional boiler. (2) Increase of temperature difference of river water application can improve energy efficiency of system, and the higher the water temperature difference is, the greater the system COP will be. However, the river water temperature generally is 12°C in Chongqing in winter, and the temperature difference for river water application is not more than 8°C considering normal operating conditions for WSHP. (3) The hot water temperature difference in the user side should not be less than 4°C, otherwise, the energy-saving effect will not be obvious in this project.

5 CONCLUSIONS

(1)Water source heat pump is an energy-saving and renewable energy application technology, which people have been paid more and more attention on in recent years. However, certain conditions for the effect of energy efficiency should be emphasised and the situation and performance of the heat source/sink should be considered.

(2) The characteristic parameters of various components are coupling in river water source heat pump system. Water temperature and operation temperature difference directly affect system energy efficiency and applicability. The temperature difference in water side should be increased as high as possible when WSHP can operate normally and safely.

(3) Energy consumption of water side plays an important role in energy consumption of water source heat pump systems compared with conventional systems. Therefore, to reduce energy consumption of river water transportation is a key factor to improve system energy efficiency. Taking a real project for analysis, it shows that COP of the heat pump unit is greater than 5.0, the percentage of transportation energy consumption is less than 39% of the total system energy consumption in plant, the system heating COP is more than 3.0, which is higher than that of conventional boiler.

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