

SIMULATION AND OPERATION OPTIMIZATION OF THE BEIJING OLYMPIC VILLAGE DHC SYSTEM USING MUNICIPAL RECLAIMED WATER SOURCE HEAT PUMP

*Cheng Zan, PH.D Candidate, Lin Shi, Professor, and Tao Han
Key laboratory for Thermal Science and Power Engineering of Ministry of Education,
Tsinghua University, Beijing, China*

Abstract: Based on the promise of “Green Olympics” for 2008 Beijing Olympic Games, the municipal reclaimed water source heat-pump system (MRWSHP) is introduced into Beijing Olympic Village District Heating & Cooling (DHC). However, the energy efficiency and economic performance of the large-scale MRWSHP are still the uncertain indexes because of some complex factors, such as the change of municipal reclaimed water temperature, the fouling in the heat exchanger, etc. This paper conducts a detailed investigation of the operation performance and energy-saving potential of the Olympic Village DHC system. Firstly, the calculation models and simulation program were presented. Secondly, the performances of heat pump system were simulated hourly during air conditioning and heating period. Finally, the operation optimization for heat pump system was discussed. The simulation results proved the high efficiency of the Olympic Village DHC system. Moreover, the system performance could be effectively improved by fouling mitigation and adjustment of heat supply water temperature.

Key Words: *municipal reclaimed water, heat pump, simulation, operation optimization, district heating & cooling, Beijing Olympic Village*

1 INTRODUCTION

With the aim of achieving “Green Olympics”, the municipal reclaimed water source heat-pump system (MRWSHP) is introduced into 2008 Beijing Olympic Village District Heating & Cooling (DHC). This project is the largest-scale application of municipal reclaimed water source heat pumps to a DHC system so far in China. Moreover, the Olympic Village DHC system is unique in that it is the first DHC system in China using large-scale plate heat exchanger for high-efficiency recovery of waste energy from the reclaimed water.

As shown in Fig.1, the Olympic Village DHC system is divided into three units: 1) heat pump system; 2) energy transport system; 3) heating/air conditioning terminal devices. In winter, the low-grade waste thermal energy contained in the reclaimed water is recovered by plate heat exchangers (PHE), and then the moderately-high grade thermal energy generated by centrifugal heat pump (CHP) is supplied for residential heating. In summer, the municipal reclaimed water served as cooling medium absorbs heat rejected by the condenser of heat-pump system.

The contribution on environmental protection, as the outstanding advantage of the MRWSHP, has been acknowledged by Chinese government and energy consumers. However, the economical efficiency and energy efficiency of Olympic Village DHC system are still the uncertain indexes because of some variable factors, such as the rate of heating/cooling load, the hot/cold water outlet temperature, the reclaimed water temperature, and the heat transfer coefficient of the PHE. All of the above factors play important roles in

seasonal performance of the heat pump system. Therefore, a detailed appraisal is needed for the operation performance of the Olympic Village DHC system.

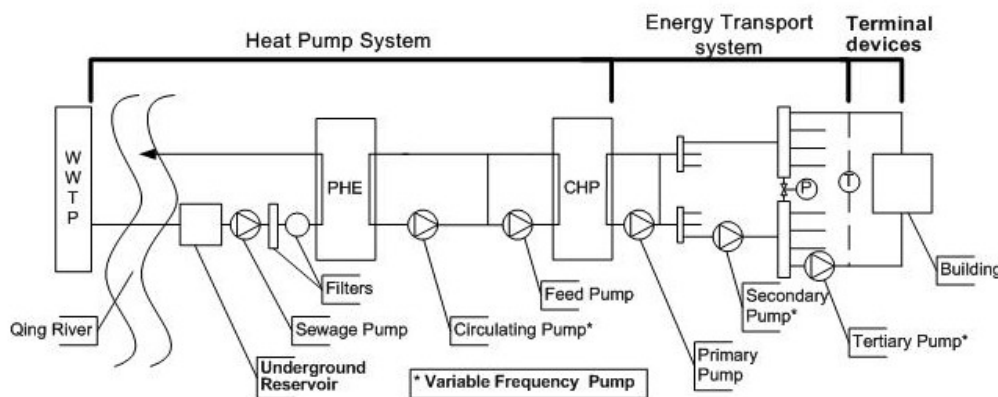


Figure 1: The flowchart of Olympic Village DHC system

In the following sections of this paper we set out firstly, the calculation models of the heat pump system in Olympic Village DHC, including plate heat exchanger, centrifugal heat pump, heating and cooling loads, municipal reclaimed water temperature, and the composite fouling in the PHE. Based on these models, a simulation program for the heat pump system is presented using mixed language programming in FORTRAN and VC++. Secondly, the performances of heat pump system will be simulated hourly in heating and cooling season. Finally, the operation optimization for heat pump system will be discussed.

2 CALCULATION MODELS AND SIMULATION PROGRAM

2.1 Calculation models

2.1.1 Municipal reclaimed water

The reclaimed water being the heat source and sink of MRWSHP is obtained from a large-scale municipal wastewater treatment plant (WWTP) which located in 3km away from the Olympic Village. The changes of temperature and discharge of the municipal reclaimed water were continuously monitored from August 2005 to January 2008. As shown in Fig.2, the daily highest and lowest temperatures were 26.4 °C in August and 12.5 °C in February. In the following calculation, the flux of reclaimed water is considered as constant, because the reclaimed water requirement of Olympic Village DHC system (3,500m³/h) is much lower than the daily average discharge of the WWTP (16,667 m³/h).

2.1.2 Fouling and its mitigation

The fouling growing faster than most people think has been acknowledged as a serious problem that effects the heat transfer performance during the process of waste heat recovery from municipal reclaimed water. A field experiment system for plate heat exchanger using municipal reclaimed water as heat-transfer medium has been operated for two years in Qinghe WWTP. The experimental results reveal that the fouling in plate heat exchanger is a composite substance mainly consisting of microbe and extracellular products. The formation process of such composite fouling is strongly depended on the water quality, water temperature, flow velocity and the shape of heat transfer plate. Under the design conditions of Olympic Village DHC, the typical curves of fouling thermal resistance taking the form of an "S" shape are shown in Fig. 3.

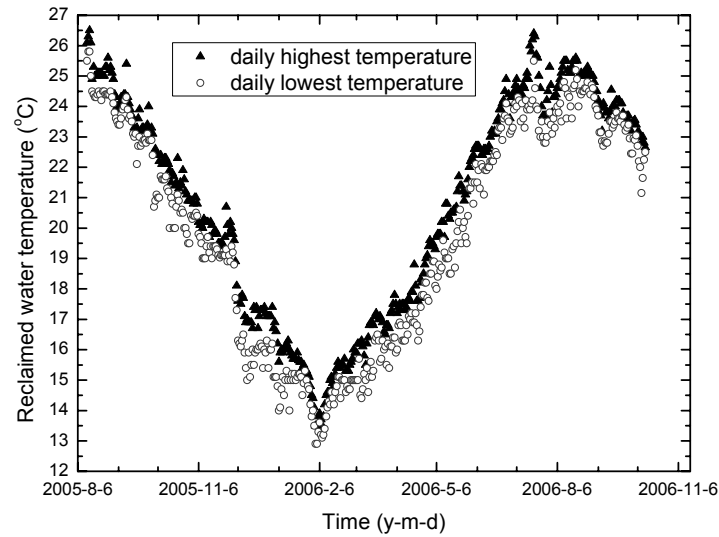


Figure 2: Municipal reclaimed water temperature in air conditioning and heating season

According to the fouling characteristics, a Clean-In-Place (CIP) method, including special cleaning agent and cleaning process, was developed by our research group for mitigating the fouling in plate heat exchanger. The field experimental results demonstrated the high efficiency of fouling mitigation by this new CIP method. The cleaning effect in cooling season is shown in Fig. 3.

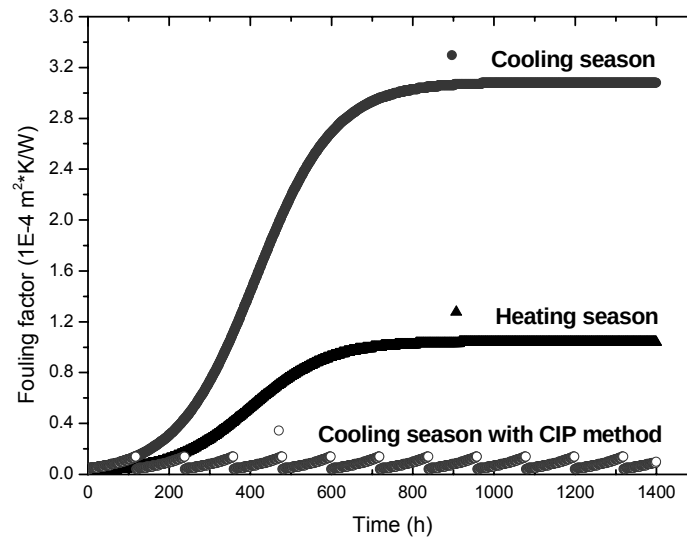


Figure 3: Fouling and its mitigation

Based on the field experimental results, the time-varying model of fouling thermal resistance with or without CIP method could be expressed as the following Equation (1).

$$R_f(\theta) = \frac{R_f^*}{1 + e^{-r\left(\theta - \frac{\theta_{ind} + \theta_{asy}}{2} - n\theta_c\right)}} \quad \theta \geq 0 \quad (1)$$

where θ (h) is time. R_f^* ($\text{m}^2 \cdot \text{K/W}$) is the asymptotic fouling thermal resistance, r is the rate of growth, θ_{ind} (h) is the induction time, θ_{asy} (h) is the time to reach asymptote, n is the cleaning times, and θ_c (h) is the cleaning frequency.

2.1.3 Heating and cooling load

In this paper, the apartment buildings in Olympic Village are considered as the simulation object. The simulation conditions of the heating and cooling load are as follow:

The heating/air conditioning area: 310,000 m²

Heat supply period: Dec 12 ~ Mar 4 (1992 hours total)

Air conditioning period: Jun 10 ~ Aug 31 (1992 hours total)

Heating terminal device: Low temperature radiant floor heating

Air-conditioning terminal device: Fan-coil unit (without fresh air)

Centrifugal heat pump units: 3

Plate heat exchanger units: 3

Design cooling and heating capacity of CHP: (cooling) 5,400kW, (heating) 5200kW

Design supply/return temperature of CHP: (cooling) 5/12 °C, (heating) 44.5/38.5 °C

The total heating and cooling capacities during the not match season are simulated hourly by the DeSTII software. The heating/cooling load per CHP unit is calculated by the following rules (Table 1). As shown in Fig.4, the distributions of cooling and heating load per unit are concentrated on the range from 50~90% and 50~75%, respectively.

Table 1: Calculation rules for heating/cooling load per unit

Total cooling load	Working units	Total heating load	Working units
<5.4MW	1	<5.2MW	1
5.4MW~10.8W	2	5.2MW~10.4W	2
>10.8MW	3	>10.4MW	3

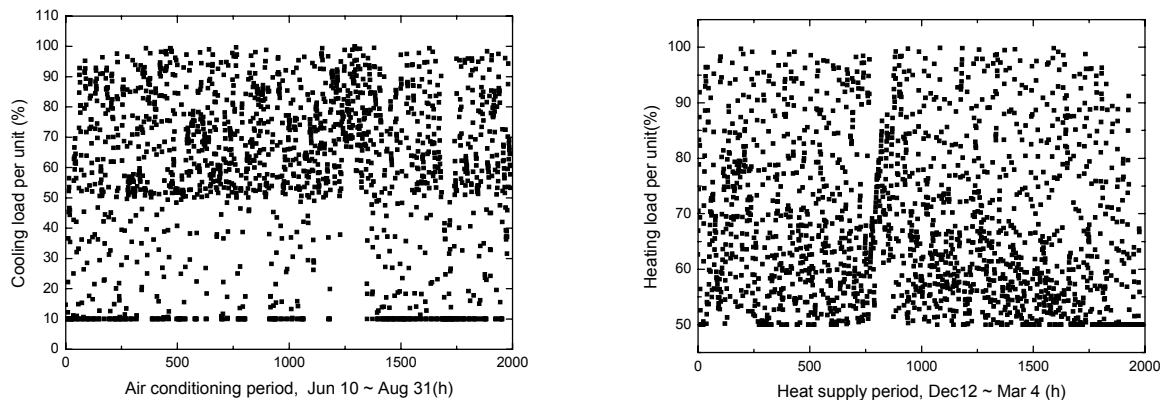


Figure 4: Heating and cooling load per unit

2.1.4 Centrifugal heat pump and plate heat exchanger

The variable condition performances of centrifugal heat pump and large-scale plate heat exchanger are calculated based on the performance curves presented by the manufacturers.

For the centrifugal heat pump with double compressors, the calculation model is expressed as:

$$\begin{aligned} COP_c &= f(\text{cooling load}, CT_{in}, ET_{out}) \\ COP_h &= f(\text{heating load}, ET_{in}, CT_{out}) \end{aligned} \quad (2)$$

where CT_{in} is the condenser inlet temperature, ET_{out} is the evaporator outlet temperature, ET_{in} is the evaporator inlet temperature, and CT_{out} is the condenser outlet temperature.

For the plate heat exchanger, the calculation model of heat convection coefficient is expressed as:

$$Nu = C Re^n Pr^m \left(\frac{Pr}{Pr_w} \right)^q ; h = \frac{Nu \times \lambda}{d_e} \quad (3)$$

where the coefficients of C , n , m and q are derived from the experimental data fitting, d_e is the equivalent distance between heat exchange plates.

2.2 Simulation program

Based on the above models, a simulation program named RWTU_SIMULATION for the heat pump system has been presented using mixed language programming in FORTRAN and VC++. Integrating the advantages of FORTRAN and VC++, the simulation program has not only a high efficiency performance on calculation, but also a good operability. The simplified mode of “one PHE plus one CHP” shown in Fig.5 is used in this simulation program.

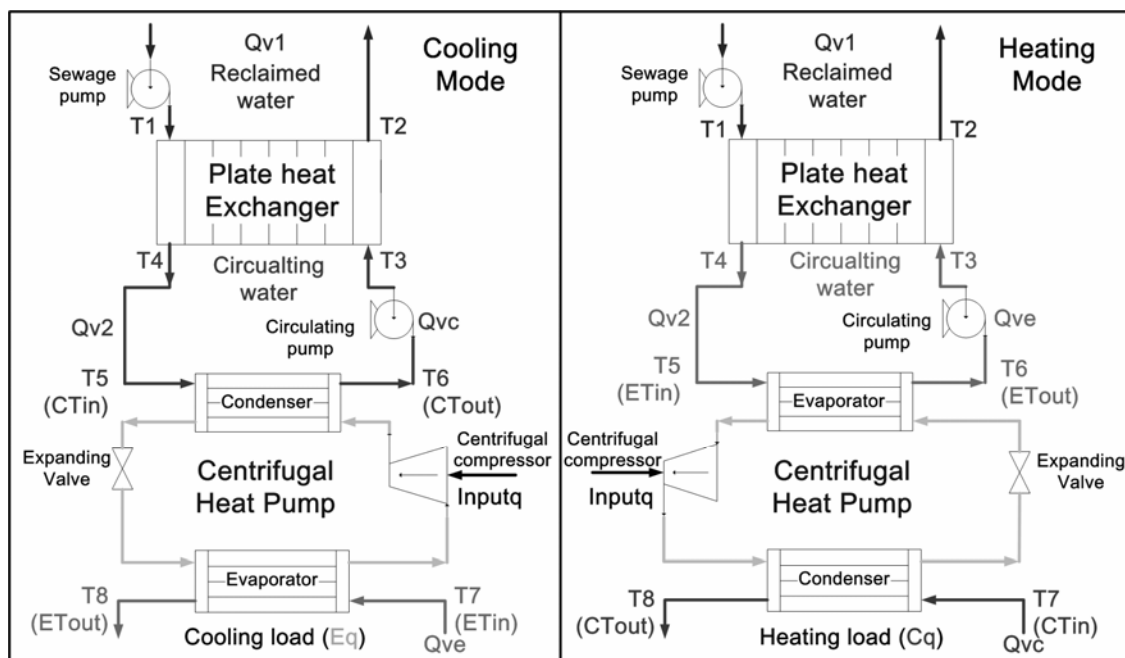


Figure 5: Flow sheet of heat pump system in simulation program

3 SYMULATION OF THE OLYMPIC VILLAGE MRWSHP SYSTEM

The system performances relating to the PHE and the CHP in Olympic Village DHC system were simulated hourly by the RWTU_SIMULATION software.

3.1 Air conditioning period

Under the design conditions, the evaporator outlet temperature regarded as constant is 5°C. The simulation results of instantaneous COP_c and heat-transfer coefficient of PHE are shown in Fig.6.

The Seasonal Energy Efficiency Ratio (SEER) is defined as:

$$SEER = \frac{\text{Total cooling capacity in air conditioning period (GJ)}}{\text{Total power input in air conditioning period(GJ)}} \quad (4)$$

where the power consumption of pump system is not included in the total power input.

For the Olympic Village DHC system, the *SEER* is served as a function of environmental and equipment factors such as reclaimed water temperature, cooling load, performance of CHP, and heat transfer performance of PHE. Under the non-fouling condition, the *SEER* is 5.43.

During the air conditioning period, the working conditions including temperature and flow velocity in the PHE are quite suitable for the rapid growth of the microbial fouling. Thus, the composite fouling occurring in the PHE has a strong effect on the seasonal performances. Under the fouling condition, the majority of instantaneous COP_c is significantly decreased caused by the sharply reduction of heat-transfer coefficient. In the result, the *SEER* is reduced to 5.09 under fouling condition. Compared with the fouling problem, the temperature change of municipal reclaimed water has less effect on the system performance.

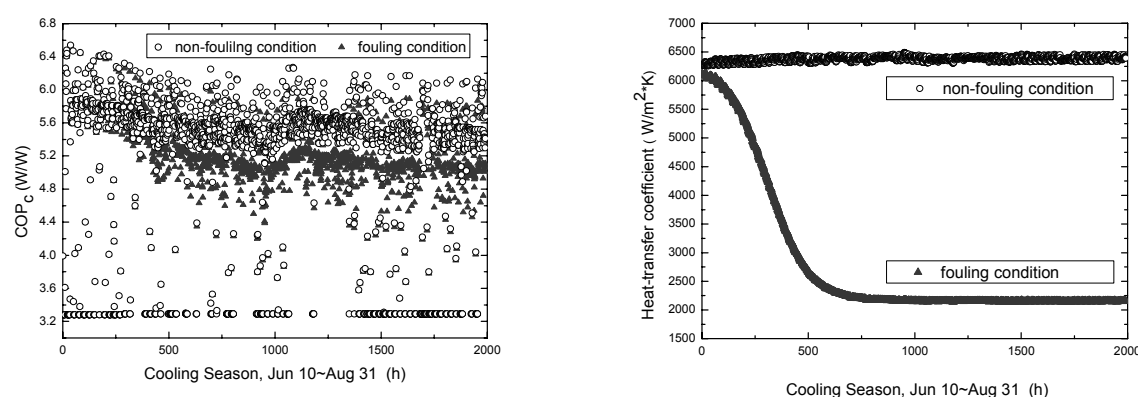


Figure 6: Comparison of system performances with and without fouling in air conditioning period

3.2 Heat supply period

Under the design conditions, the condenser outlet temperature regarded as constant is 44.5°C. The simulation results of instantaneous COP_h and heat-transfer coefficient of PHE are shown in Fig.7.

The Heating Seasonal Performance Factor (*HSPF*) is defined as:

$$HSPF = \frac{\text{Total heating capacity in heat supply period (GJ)}}{\text{Total power input in heat supply period(GJ)}} \quad (5)$$

where the power consumption of pump system is not included in the total power input.

For the Olympic Village DHC system, the *HSPF* is also served as a function of environmental and equipment factors such as reclaimed water temperature, heating load, performance of CHP, and heat transfer performance of PHE. Under the non-fouling condition, the *HSPF* is 5.31.

During the heating supply period, the working conditions in the PHE are disadvantageous to the growth of the microbial fouling. Thus, the fouling being different from the air conditioning period has less effect on the seasonal performance. Under the fouling condition,

the *HSPF* is slightly reduced to 5.26. However, the temperature change of municipal reclaimed water plays an important role on the instantaneous COP_h . Compared with the Fig. 7 and Fig. 2, instantaneous COP_h is significantly reduced by the temporary low-temperature of municipal reclaimed water from Feb 2 to Feb 10 (1250~1450h).

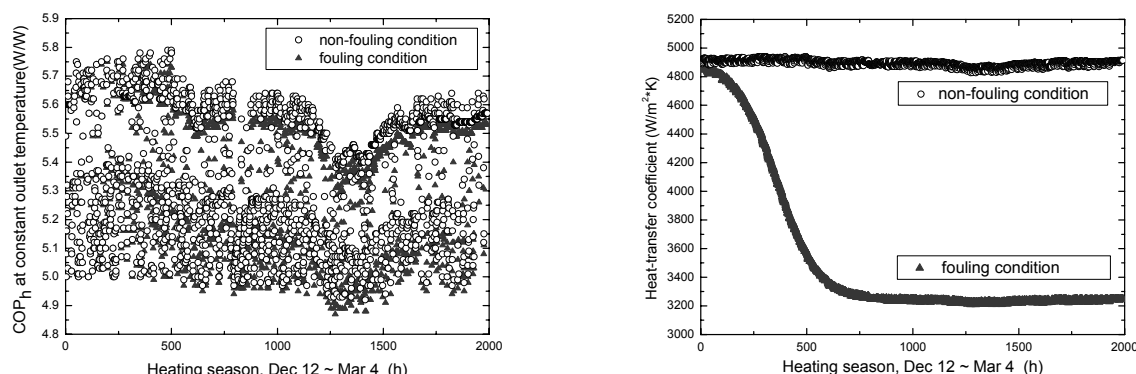


Figure 7: Comparison of system performances with and without fouling in heating period

4 OPERATION OPTIMIZATION

4.1 Fouling mitigation in air conditioning period

Field experience has shown that the composite fouling on the plate heat exchanger surfaces is comprised of silt, calcium-containing compounds, and biological fractions. The composite fouling can results in not only the reduction of heat transfer efficiency and but also the increase in flow resistance. Moreover, the build-up of deposits can lead to under-deposit corrosion. Thus, a new Clean-In-Place (CIP) method was developed for mitigating the fouling in plate heat exchanger using municipal reclaimed water as heat-transfer medium.

According to the cleaning effect shown in Fig. 3, the instantaneous COP_h and heat-transfer coefficient of PHE were simulated hourly in air conditioning period. As shown in Fig.8, the PHE could be continuously operated with high efficiency. Benefiting from continuous application of the CIP method, the *SEER* could be improved from 5.09 to 5.42. In addition, the CIP method could also be effective on fouling mitigation in heat supply period.

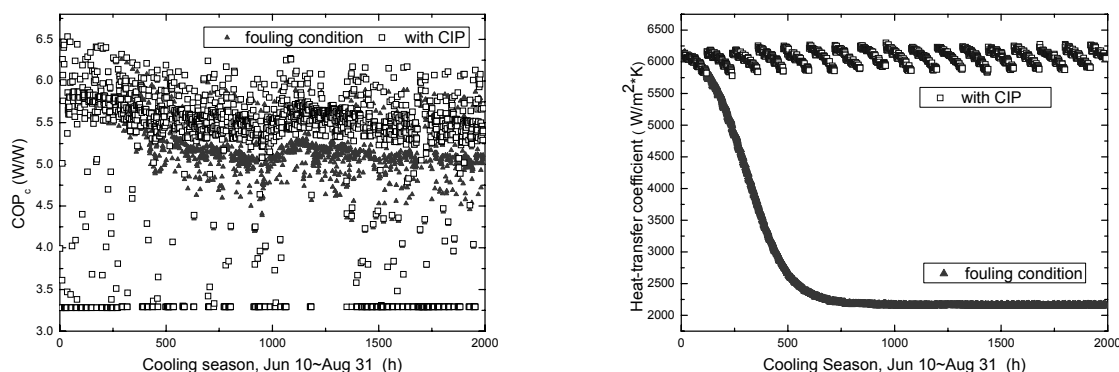


Figure 8: Comparison of system performances with and without CIP in air conditioning period

4.2 Adjustment of outlet temperature in heat supply period

In order to improve the system performance in heat supply period, a scheme was presented in respect of adjustment of condenser outlet temperature. The adjusting

means referring to the outdoor temperatures are specified in Table 2.

Table 2: The means of outlet temperature adjustment in heat supply period

Outdoor temperature	Outlet temperature
> 3 °C	38.5 °C
≈ 0 °C	40.5 °C
≈ -5 °C	42.5 °C
> -7 °C	44.5 °C

Under the condition with CIP and temperature adjustment, the instantaneous COP_h and heat-transfer coefficient of PHE were simulated hourly in heat supply period. The simulation results demonstrated that the system performance could be significantly improved by the rational adjustment of condenser outlet temperature, as well as slightly picked up by CIP application. As shown in Fig.9, the *HSPF* could be raised from 5.26 to 5.58.

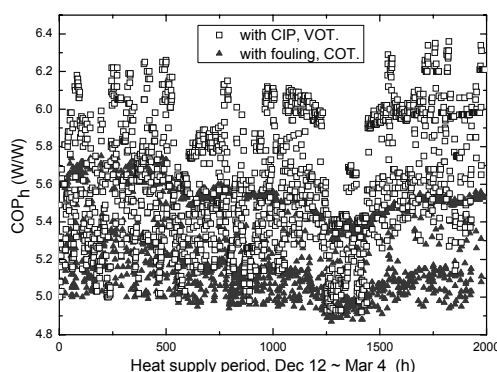


Figure 9: Comparison of system performances with and without outlet temperature adjustment in heat supply period. VOT: Variable Outlet Temperature; COT: Constant Outlet Temperature

5 CONCLUTIONS

The municipal reclaimed water source heat-pump system (MRWSHP) is introduced into Beijing Olympic Village District Heating & Cooling (DHC). In this paper, an investigation with variable conditions was conducted using RWTU_SIMULATION software in respect of the operation performance and energy-saving potential of this DHC system.

The simulation results are summarized as follow: firstly, the *SEER* and *HSPF* of the Olympic Village DHC system are both larger than 5 under the design conditions; secondly, the temporary low-temperature of municipal reclaimed water has an significant effect on the instantaneous COP_h during heat supply period; third, the *SEER* could be reduced by 6.3% due to the fouling during air conditioning period; Finally, the *SEER* and *HSPF* could be increased by 6% through fouling mitigation and adjustment of heat supply water temperature.

6 REFERENCES

- Zan C., Shi L. 2008. "Large-scale application of municipal reclaimed water source heat pump to a DHC system in the Beijing Olympic Village," 9th International IEA Heat Pump Conference, Conf-ID 5.6.
- Zan C., Shi L. 2007. "Temperature characteristics of secondary effluent and its thermal application," *Journal of North China Electric Power University*, Vol. 42, Part 2, pp. 31–35.
- Bloomfield D. P. 1999, "An overview of validation methods for energy and environmental software," *ASHRAE Transactions*, Vol. 105, Part 2, pp.685–693.