System Simulation of an Untreated Sewage Source Heat Pump

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Abstract — **The paper studies the characteristics of heat pumps used in untreated-sewage source where the matter enters the heat pump directly in winter. The system model is established first. Then the changes of the variable parameters, including the sewage and water temperatures at the inlets of the heat pump and the compressor frequency, are simulated to assess their influence on the system performance. Then, the system is compared with those used in indirect mode to observe the different heating capacities. The results show that most parameters, except the condensation heat transfer coefficient, change as a sine wave, the same as the sewage and water temperatures at the inlets of the heat pump. COP is about 3.75 in the range of the temperature fluctuation of 1℃. The heating capacity and consumed power are 12.9 and 3.45kW when the sewage temperature is 13℃ at the inlet. When the compressor frequency increases from 25Hz, and the sewage and water temperatures at the inlet take on impulse signals, the system parameters produce rapid changes at the impulse point, and become unstable in a short time. By comparison with the indirect-mode system, it is shown that the heating capacity of direct-mode system increases by 7~8%, showing greater advantage of energy conservation.**

***Keywords** - untreated-sewage-source heat pump; direct mode; temperature at inlet; compressor frequency*

I. INTRODUCTION

Urban sewage treatment plants or sewage channels discharge a large amount of sewage every day, which is relatively warm in winter and cold [1] in summer, very suitable for heat pumps. Sewage-source heat pump systems are the ones that use sewage as the heat or cold source to heat or refrigerate. The operation costs of the systems are lower, which save the electricity and primary energy by more than 60% [2] and 50% compared to electric boilers and coal-fired units [3]. Besides, the systems are distinguished for obvious energy conservation, high COP and zero air pollution. They have been applied in some northern countries. The literature [4] about this sewage utilization in the district heating and cooling in Japan shows that the consumed power can be reduced by 34%, and the releasing of carbon dioxide and nitrogen oxide are reduced by 68% and 75% compared to an air-source heat pump.

An untreated-sewage-source heat pump (USSHP) system directly makes use of the urban sewage without any treatment by a sewage plant. The system can be set up near a sewage pumping station and delivers energy directly to customers. The initial investment of the system is lower than the one [5] which uses treated sewage as the source. The application of USSHP [6-7] greatly improves the sewage energy utilization and has greater potentials.

USSHP systems usually have two modes: sewage entering into the heat pump indirectly and directly [8]. Figure 1 [9] shows an indirect-mode system. At present most systems adopt the indirect mode to avoid harming the heat pump unit due to the sewage character itself. The untreated sewage with high viscosity and strong corrosion makes high request to the quality of the heat pump unit. However, if the direct mode can be realized, the primary energy utilization rate of the sewage will be improved greatly.

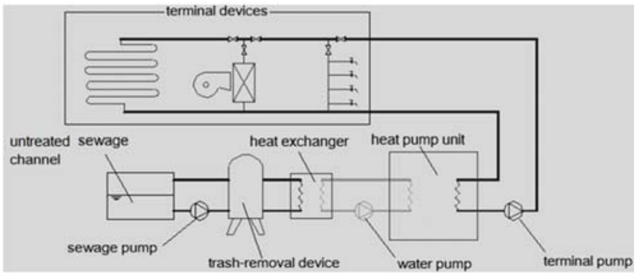

Fig.1 Indirect mode of the untreated-sewage-source heat pump system

To estimate the operation characteristics of a system with direct mode, the paper makes the system simulation to observe the parameter changes of the system in winter. The parameters observed contain COP, heating capacity, consumed power, condensation and evaporation temperature, mass flow rate, and the heat transfer coefficient of the condenser and evaporator. Their dynamic changes under the input control are observed by simulation.

II. COMPONENT MODEL

The lumped parameter method [10] is selected to establish models of the condenser and evaporator. The following assumptions [11-12] are made to simplify the models:

Firstly, it is assumed that the mass flow rates in the condenser and evaporator are the same as the one in the compressor.

Secondly, the pressure drops in the condenser and evaporator are ignored.

Thirdly, the enthalpy change of the subcooled liquid with time is the same as that of the saturated liquid.

Fourthly, the heat loss of system is ignored.

The models are established for the compressor, condenser and evaporator under these assumptions.

A. Compressor

The scroll compressor is selected in the paper for its relatively high efficiency, low noise and steady operation. The coefficient of capacity λ' and electrical efficiency η_{el} are fitted with the compressor book data [13]. The fitted results are shown in Equations (1) and (2).

$$\lambda' = -0.0011\left(\frac{p_c}{p_e}\right)^3 + 0.0105\left(\frac{p_c}{p_e}\right)^2 - 0.0539\left(\frac{p_c}{p_e}\right) + 1.0132 \tag{1}$$

$$\eta_{el} = -0.0132\left(\frac{p_c}{p_e}\right)^3 - 0.1677\left(\frac{p_c}{p_e}\right)^2 + 0.6499\left(\frac{p_c}{p_e}\right) - 0.0924 \tag{2}$$

The mass flow rate in the compressor is computed as Equation (3), where V_r is the actual displacement, m^3/h ; v_1 is the specific volume of the refrigerant at the inlet of the compressor, m^3/kg .

$$m_r = V_r / v_1 \tag{3}$$

B. Condenser

The condenser model is established based on the lumped parameter method and energy balance. It is computed as Equations (4) to (7).

$$\frac{d\bar{h}_c}{d\tau} = \frac{m_r(h_2 - h_3) - Q_c}{M'_{r,c}} \tag{4}$$

$$\bar{h}_c = x_c h_{v,c} + (1 - x_c) h_{l,c} \tag{5}$$

$$c_w M_{w,c} \frac{d}{d\tau}\left(\frac{t_{wi,c} + t_{wo,c}}{2}\right) = Q_c - c_w m_{w,c}(t_{wo,c} - t_{wi,c}) \tag{6}$$

$$Q_c = k_c A_c \left(t_c - \frac{t_{wi,c} + t_{wo,c}}{2}\right) \tag{7}$$

In Equation (7), k_c means the overall heat transfer coefficient of the condenser, $W/m^2 \cdot K$. In order to calculate its value, the heat transfer coefficients of tube inside and outside in the condenser should be known. They are computed as Equations (8) to (9) [14], where $\alpha_{o,c}$ is the heat transfer coefficient of tube outside, $W/m^2 \cdot K$; $\alpha_{i,c}$ is the heat transfer coefficient of tube inside, $W/m^2 \cdot K$.

$$\alpha_{o,c} = 0.65\left(\frac{\beta}{q_c d_{o,c}}\right)^{1/3}, \beta = \frac{\lambda_r{}^3 \rho_r{}^2 gr}{\mu} \tag{8}$$

$$\alpha_{i,c} = 0.023 \frac{\lambda_w}{d_{i,c}} R_{e_f}{}^{0.8} P_{r_f}{}^{0.4} \tag{9}$$

C. Evaporator

The evaporator model is also established based on the lumped parameter method and energy balance, shown in Equations (10) to (13).The model is similar to the condenser model.

$$\frac{d\bar{h}_e}{d\tau} = \frac{Q_e - m_r(h_1 - h_4)}{M'_{r,e}} \tag{10}$$

$$\bar{h}_e = x_e h_{v,e} + (1 - x_e) h_{l,e} \tag{11}$$

$$c_s M_{s,e} \frac{d}{d\tau}\left(\frac{t_{si,e} + t_{so,e}}{2}\right) = -c_s m_{s,e}(t_{so,e} - t_{si,e}) - Q_e \tag{12}$$

$$Q_e = k_e A_e \left(\frac{t_{si,e} + t_{so,e}}{2} - t_e\right) \tag{13}$$

The heat transfer coefficients of interior tube and external tubes in the evaporator are computed as Equations (14) to (15).

$$\alpha_{i,e} = \frac{32 v_{m,e}{}^{1.4}}{c^7 \mu'_r d_{i,e}{}^{0.54}}, c = \frac{t_o + 273.15}{t_b + 273.15} \tag{14}$$

$$\alpha_{o,e} = 0.22 \frac{\lambda_s}{d_{o,e}} R_{e_f}{}^{0.6} P_{r_f}{}^{0.33} \tag{15}$$

The overall heat transfer coefficients of the condenser and evaporator are both calculated by employing Equation (16).

$$k = \frac{1}{(\alpha_i + \gamma_i)\frac{d_o}{d_i} + \frac{\delta_{wall}}{\lambda_{wall}}\frac{d_o}{d_e} + \gamma_o} \tag{16}$$

Besides, two mediums are used in the simulation progress: the refrigerant R22 and the water. Their property changes are needed to calculate the parameters of the components in the unit. They are computed by fitting according to their property charts.

III. SIMULATION REALIZATION

The simulation is realized on the platform of SIMULINK. The established component models are packaged first and then the signal line connects every component to form a holonomic system. The untreated sewage is connected directly to the evaporator to realize the direct mode. The design and investigated values in the heating mode are set in Table 1. The output results are simulated through the input signal changes.

TABLE 1 SETTING VALUES

x_c	0.5
x_e	0.7
$t_{si,e}$	12
$t_{wi,c}$	40
$M_{s,e}$	6
$M_{w,c}$	7
$m_{s,e}$	0.63
$m_{w,c}$	0.8
M_{eva}	1
M_{con}	3
A_c	8
A_e	3
f	18-32
γ_i	0.00009
γ_o	0.00009
d_i	20
d_o	22
λ_{wall}	380

IV. ENERGY ANALYSIS

A. Temperatures at the Inlets in the Form of the Sine Wave

Figure 2 and Figure 3 show the input signals of the sewage and water temperatures at the inlets, where the sewage temperature at the inlet ranges from 12 to 13℃, and the water temperature at the inlet is in a range of 40 to 41℃. They are in the form of the sine wave. The system operation is under the compressor frequency of 25Hz.

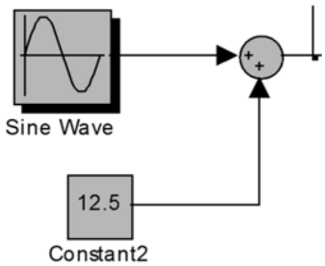

Fig.2 Input signal of sewage temperature at inlet

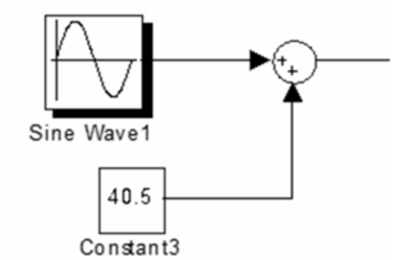

Fig.3 Input signal of water temperature at inlet.

Figure 4 and Figure 5 show the temperatures of the sewage and water at the outlets which change with time in the form of sine wave, the same as the temperatures at the inlets. The results show the sewage temperature from 7 to 8℃ and water temperature from 44 to 45℃.

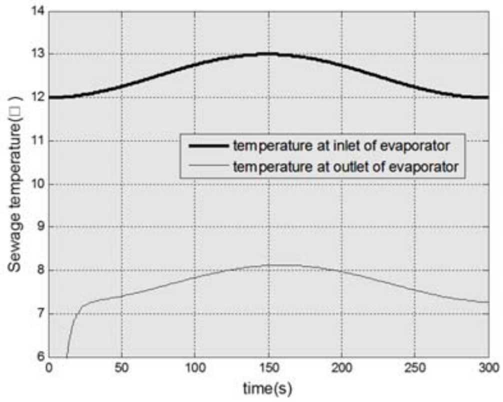

Fig.4 Sewage temperatures at inlet and outlet.

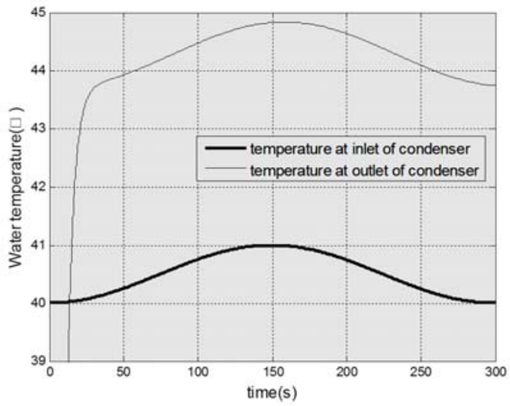

Fig.5 Water temperatures at inlet and outlet.

The changes of the system parameters are reflected in Figure 6 to Figure 11. The compressor consumed power increases from 3350 to 3450kW, and then reaches the previous value of 3350kW, shown in Figure 6. Figure 7 shows the change of heating capacity. It can be obtained that the heating load of 12.9kW is the highest value when the sewage and water temperature at the inlets are 13 and 41℃. The consumed power by compressor and heating capacity increase by 3% and 3.2% after the temperature at the inlet goes up to 13℃. Figure 8 shows the value of COP of the heat pump unit. It can be seen that the value is around 3.75 without changing obviously. The reason lies in the similar increased percent in the consumed power and heating capacity. Figure 9 shows the change of the refrigerant mass flow. The refrigerant mass flow is affected by the consumed power with the same change trend. The highest value of the mass flow is around 0.092 kg/s when the consumed power reaches its maximum of 3450kW. The evaporation and condensation temperature are shown in Figure 10 and Figure 11. Both of them show the same pattern as the temperatures at the inlets, and have the highest values of 7.4 and 49℃.

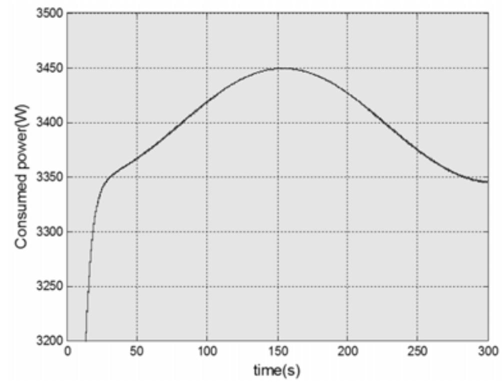

Fig.6 Compressor consumed power

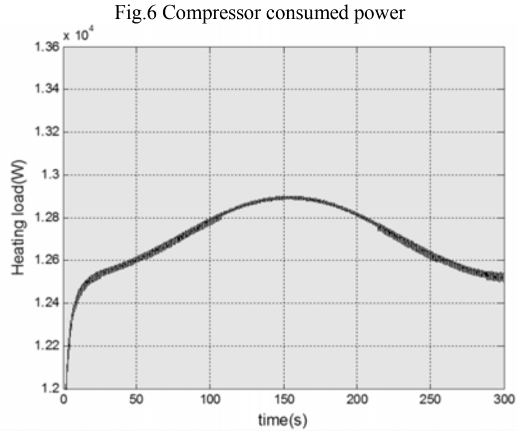

Fig.7 Heating load

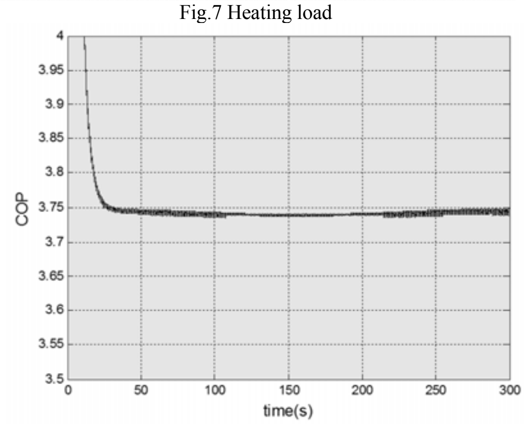

Fig.8 COP of heat pump

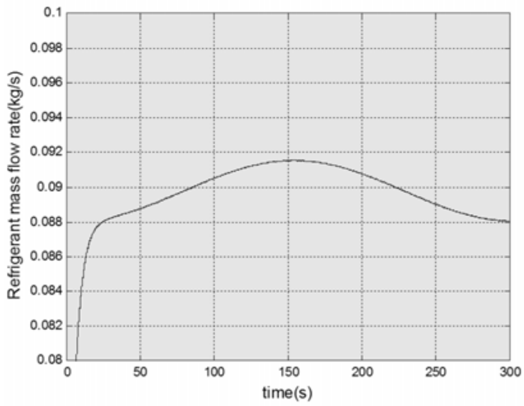

Fig.9 Refrigerant mass flow rate

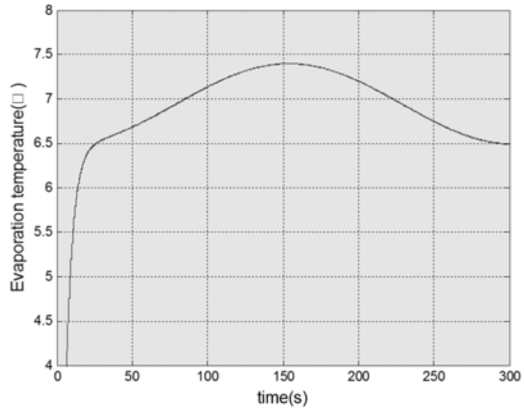

Fig.10 Evaporation temperature

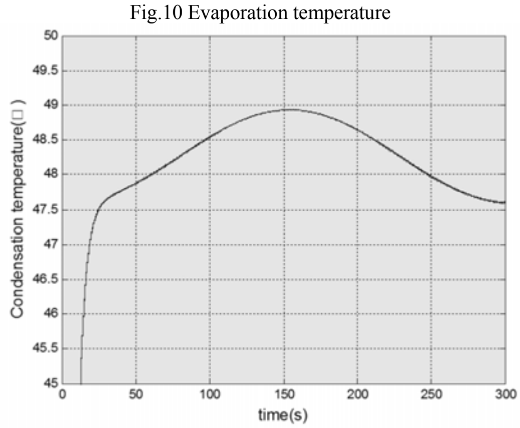

Fig.11 Condensation temperature

Figure 12 and Figure 13 show the heat transfer coefficients of the condenser and the evaporator. From the two figures we can see that, as the heating load increases, the heat transfer coefficient of the condenser decreases from 274 to 268 $W/m^2.K$, while the evaporator heat transfer coefficient rises to the value of 1360 $W/m^2.K$.

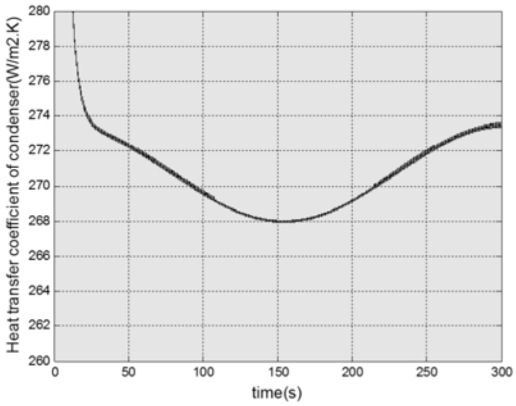

Fig.12 Heat transfer coefficient of condenser

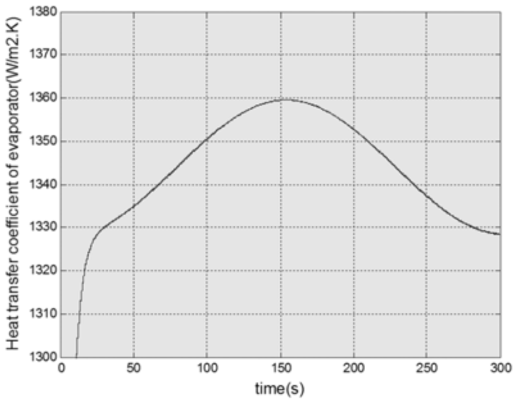

Fig.13 Heat transfer coefficient of evaporator

B. Temperature at the Inlets in the Form of Square Wave

In this section the effect of the compressor frequency which starts to rise from 25Hz is researched. The patterns of the sewage and water temperatures at the inlets are in the form of square wave. Figure 14 shows the sewage temperature at the outlet. From the figure we can see that the temperature at the outlet decreases first and then increases at the impulse point of the temperature increment at the inlet. There is still a downtrend in the temperature at the outlet when the temperature at the inlet is stable. Figure 15 shows the water temperature at the outlet. From the figure we can see there is an uptrend in the temperature at the outlet when the temperature at the inlet is stable.

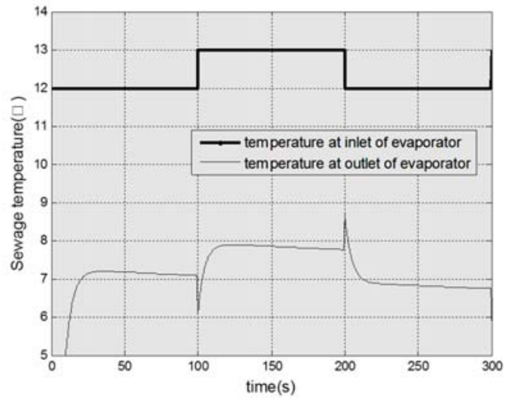

Fig.14 Sewage temperatures at inlet and outlet

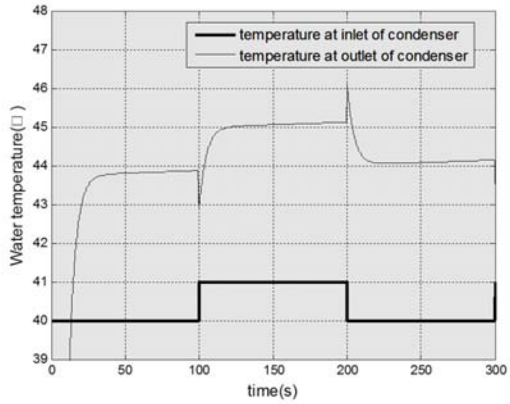

Fig.15 Water temperatures at inlet and outlet

Figure 16 shows the unstable change of the power consumed by the compressor due to the increase of the frequency. The consumed power rises to 3550kW at the sewage temperature of 12℃ at the inlet and then it rises to 3850kW at the sewage temperature of 13℃ at the inlet. The consumed power continues to rise even the sewage temperature at the inlet drops 1℃ at 200s. The heating capacity, which rises from 12.6 to 13.9kW gradually, reflects the same change trend as the consumed power, shown in Figure 17. Figure 18 shows the value of COP of the heat pump unit. The value falls with time because of the larger increased percent of the consumed power. The refrigerant mass flow, the value of which rises from 0.089 to 0.099kg/s gradually, is affected mainly by the consumed power. So the mass flow reflects the same change trend as the consumed power, shown in Figure 19.

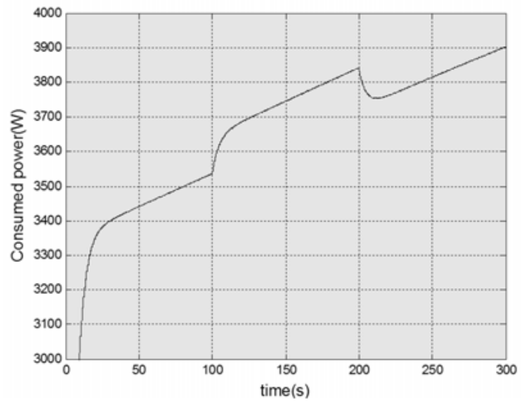

Fig.16 Consumed power

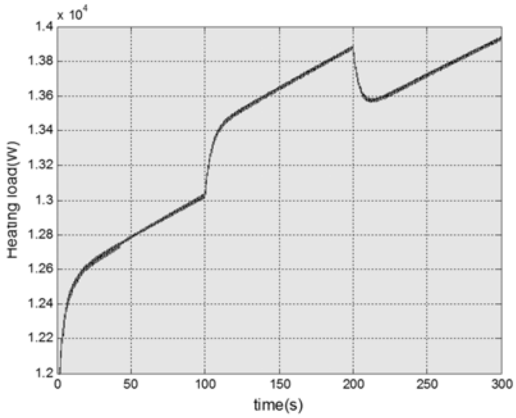

Fig.17 Heating load

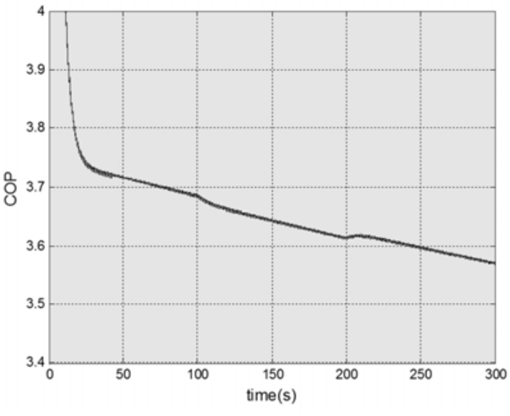

Fig.18 COP of heat pump

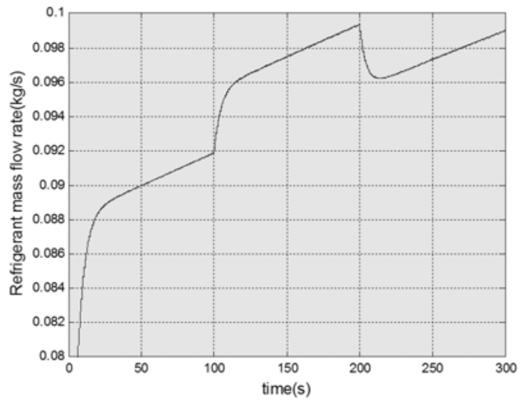

Fig.19 Refrigerant mass flow rate

Figure 20 shows the evaporation temperature which is around 6.5℃ at the sewage temperature of 12℃ at the inlet. When the sewage temperature at the inlet falls from 13 to 12 ℃, the evaporation temperature is lower than 6.5℃ under the influence of the compressor frequency. The change of condensation temperature shown in Figure 21 is opposite to the one of evaporation temperature. It is higher than 48℃with the frequency increase after 100s.

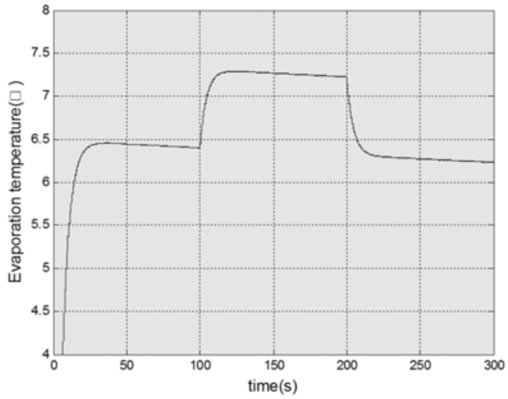

Fig.20 Evaporation temperature

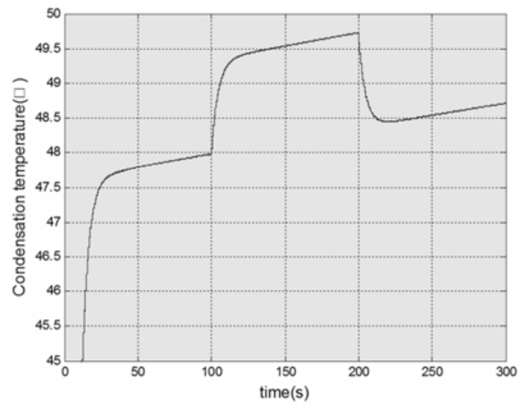

Fig.21 Condensation temperature

Figure 22 shows the heat transfer coefficient of the condenser which goes up to the value of 265W/(m^2·K) at 200s under the influence of the compressor frequency. The curve in Figure 22 displays the downtrend with time. However, the heat transfer coefficient of the evaporator shown in Figure 23 displays the opposite change trend. It is down to the value of 1440 W/(m^2·K) under the influence of the compressor frequency and the temperature decease of water and sewage at the inlet after the time of 200s.

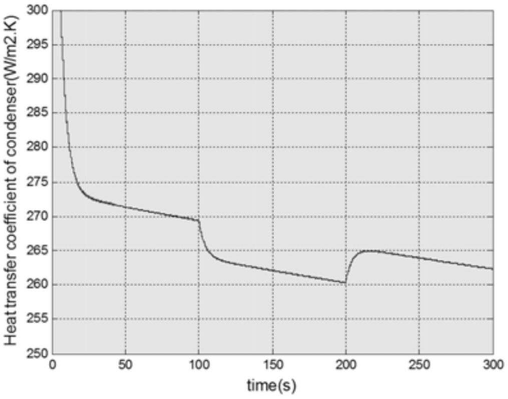

Fig.22 Heat transfer coefficient of condenser

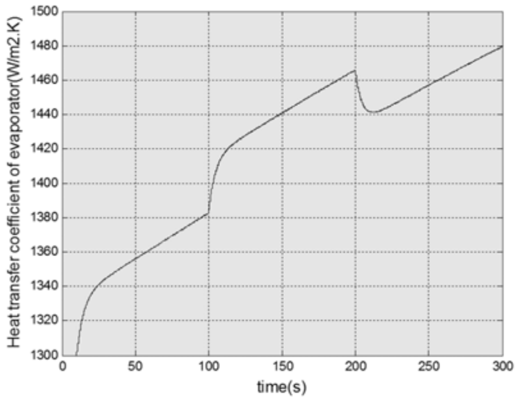

Fig.23 Heat transfer coefficient of evaporator

C. Comparison with the Indirect Mode

The untreated sewage usually enters a heat exchanger for avoiding the harmful impact on the heat pump unit. In doing so the sewage temperature at the inlet of the evaporator is certainly lower than that in direct mode, so the energy efficiency of the sewage utilization is reduced in spite of the reduction in the processing technic complexity of the heat pump unit.

Figure 24 reflects the higher heating capacity of the heat pump system which directly uses the untreated sewage. The heating capacities are obtained on the basis of the untreated sewage temperature of 14℃, the temperature at the inlet of the evaporator of 12℃ in the indirect mode and the variable frequency of the compressor from 18 to 32Hz. Compared to the heating capacity of 9.4~15.3kW supplied by the heat pump system with indirect mode, the heating capacity is 10.2~16.4kW, rising by 7~8% from Figure 25.

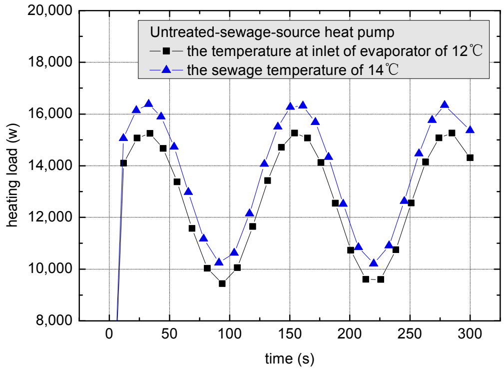

Fig.24 Comparison of heating load.

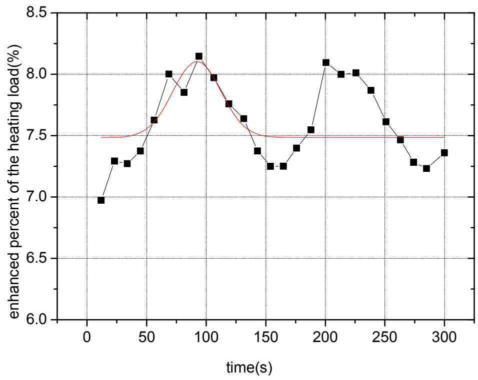

Fig.25 Enhanced percent of heating load.

V. CONCLUSIONS

The paper simulates the untreated sewage source heat pump system. The related parameter changes of the system are observed with the changes of the sewage and water temperatures at the inlet and the compressor frequency. The system is also compared to the one with the indirect mode to observe the heating potential of the sewage energy. Some conclusions are drawn from the research.

The first condition is when the compressor frequency keeps 25Hz. The sewage and water temperatures at the inlets change in the form of sine wave with the amplitude of 1℃. The parameters studied contain the sewage and water temperatures at the outlets, the heating capacity, the consumed power, refrigerant mass flow rate, temperatures of condensation and evaporation, and the heat transfer coefficient of the evaporator. Most of them show the similar changes to the temperatures of the water and sewage at the inlets. The COP of the heat pump is about 3.75.

The second condition is that the sewage and water temperatures at the inlets change in the form of square wave while the compressor frequency increases slowly with time from 25Hz. The temperatures of the water and sewage at the outlets decrease first and then increase at the impulse point when the temperatures of the water and sewage at the inlets go up. The system parameters all reflect unstable changes under the influence of the compressor frequency. Most of them show the uptrend with time except the sewage temperature at the outlet, the COP of the heat pump, the heat transfer coefficient of the condenser and the temperature of the evaporation.

By comparison with a system with indirect mode, it can be obtained that the heating capacity supplied by the system which directly uses the sewage with 14℃ is 10.2~16.4kW, increased by 7~8%. Directly using the sewage shows greater heating capacity than the indirect use.

Nomenclature

p —pressure， Pa
m —mass flow rate， kg/s
f —frequency， Hz
V_r —actual displacement, m^3/h
M' —charge， kg
h —enthalpy， kJ/kg
$\bar{h}$ —mean enthalpy， kJ/kg
x —dryness factor
c —specific heat， $kJ/kg \cdot K$
t —temperature，℃
t_c —condensation temperature，℃
t_e —evaporation temperature，℃
Q —heat convection， W
M —mass， kg
k —total heat transfer coefficient， $W/m^2 \cdot K$
A —heat transfer area， m^2
g —acceleration of gravity， m/s^2
r —latent heat of vaporization， kJ/kg
R_e —Reynolds number
P_r —Prandtl number
v_m —mass flow velocity， $kg/m^2 \cdot s$
t_b —normal boiling point，℃
d —diameter of heat exchange tube， m
N_{in} —consumed power，W

Greek

λ' —coefficient of capacity
η —efficiency
v —the specific volume of compressor, m^3/kg
τ —time， s
α —heat transfer coefficient of medium， $W/m^2 \cdot K$
λ —thermal conductivity， $W/m \cdot K$
ρ —density， kg/m^3
μ —kinetic viscosity， $N \cdot s/m^2$
μ' —Molecular Weight
γ —thermal resistance， $m^2 \cdot K/W$
δ —thickness， m

Subscripts

el —electric
r —refrigerant
1— evaporator inlet
2— condenser inlet
3— condenser outlet
4— evaporator inlet
c —condenser side
e —evaporator side
si —sewage at inlet
so —sewage at outlet
wi —water at inlet
wo —water at outlet
v —saturated gas
l —saturated liquid
i —tubes inside
o —tubes outside
f —equivalent
$wall$ —heat transfer tubes in the heat exchanger

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