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Study of Performance of Heat Pump Usage in Sewage Treatment and Fouling Impact on System[1]

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Abstract: A heat pump using disposed sewage as a heat source to heat raw sewage is presented to solve the problem that sewage temperature is low in sewage biologic treatment in cold region. According to the status of one medicine factory in Harbin, China, system performances are simulated. Then the impact of fouling on system performance is emulated in detail. The results show that the novel system is feasible to be utilized in sewage treatment for its energy-saving and high efficient characteristics, and that raw sewage temperature can be enhanced to 29.569 , and EER of system can reach 4.177. Fouling impact on system not only depends on the fouling thermal resistance, but also is related to heat transfer coefficient. Increased fouling leads to severely deteriorated performance of the compressor, and a decrease in EER and refrigerant mass flow rate.

Key words: sewage-source heat pump system; sewage treatment; waste heat utilization; operation performance; fouling thermal resistance

1. INTRODUCTION

The most familiar method of sewage treatment in China is the technology of an activated sludge process and the optimal sewage temperature for this biologic treatment is 25-30℃[1]. However, in cold region the raw sewage temperature is too low to satisfy the requirement and lots of energy is consumed to heat raw sewage or air flow into the aeration tank. Moreover, the disposed sewage with temperature at 25-30 ℃ usually does not be utilized effectively and discharged out directly, causing substantive low level energy wasted. So a sewage-source heat pump system using disposed sewage as a heat source to heat raw sewage is firstly presented. It is designed in detail according to the actual status of one medicine factory in Harbin, China as shown in Fig. 1. Considered the special quality of sewage and the big temperature different of heat transfer, a three-stage spray heat exchanger as condenser is adopted in such system [2]. Sewage treatment system with this heat pump can get high efficient of using energy and makes sense in energy saving and economy.

2. SIMULATION OF SYSTEM PERFORMANCE

The mathematical model of heat pump system consists of four sub-models: screw compressor, three-stage spray condenser, throttling valve and three-stage shell and tube evaporator. And in condenser sub-model developing, three-region method is adopted, i.e., in each stage, the condenser tube is divided into three regions along the flow direction of refrigerant, which are a superheat region, a two-state region and a supercool region, respectively. Four sub-models are developed respectively, and then combined to form a total system model according to mass, energy and momentum conservations[3,4]. The condition used in simulation derives from the actual situation of the medicine factory in Haerbin, China, as given in table 1. And the simulated results of system performance under this condition are presented in table 2.

3. IMPACT OF FOULING ON SYSTEM

The problem of fouling is critical and difficult for popularizing sewage-source heat

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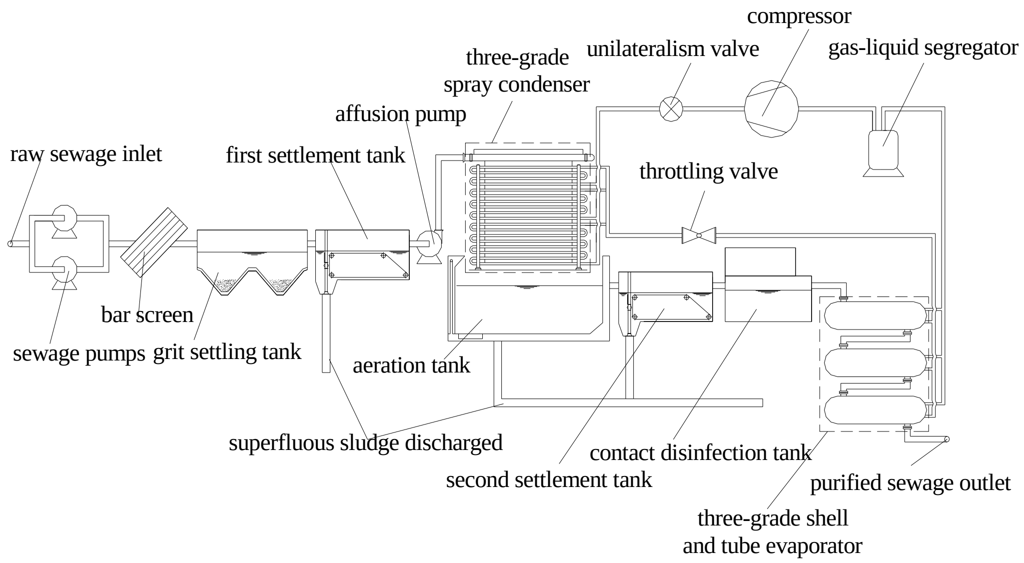

Fig. 1 Sketch of the heat pump applying to the sewage treatment system

Tab. 1 Condition used in simulations derives from actual situation of medicine factory

Degree of superheat Δt_{sh} ( )	Degree of supercool Δt_{sl} ( )	Sewage flow quantity m_w (kg/h)	Sewage temperature of condenser inlet $t_{w,c,i}$( )	Sewage temperature of evaporator inlet $t_{w,e,i}$( )	Thermal resistance of fouling R_f (m^2 /W)
5	5	42000	15	20	5.28×10^{-4}

Tab. 2 Simulated results under given condition

Simulated result of compressor	Pressure ratio	Refrigerant temperature of compressor outlet（℃）	Refrigerant pressure of compressor outlet (kPa)	Input power (kW)
	2.288	47.830	1284.973	170.899
Simulated result of condenser	Sewage temperature of the first stage condenser outlet (℃)	Sewage temperature of the second stage condenser outlet (℃)	Sewage temperature of the third stage condenser outlet (℃)	Total heat transfer quality (kW)
	19.856	24.713	29.569	713.872
Simulated result of evaporator	Sewage temperature of the first stage evaporator outlet (℃)	Sewage temperature of the second stage evaporator outlet (℃)	Sewage temperature of the third stage evaporator outlet (℃)	Total refrigeration quality (kW)
	15.617	11.235	6.852	579.829
Simulated result of system	Refrigerant mass flow rate（kg/s）	Evaporation temperature （ ）	Condensing temperature （ ）	Energy efficiency ratio /EER
	3.669	4.761	33.858	4.177

pumps. Therefore it is necessary to have a detailed investigation about the impact of fouling on system performance. These investigations are expected to be useful for increasing system energy efficiency and operational reliability.

3.1 Three Denotations of Fouling

Three parameters can describe fouling [5].

(1) Fouling thermal resistance:

$$R_f = \frac{1}{K_f} - \frac{1}{K_c} \tag{1}$$

(2) Percent of redundant area:

$$a = \left(A_f / A_c - 1\right) \times 100\% \tag{2}$$

Redundant area:

$$\Delta A = A_f - A_c \tag{3}$$

(3) Cleanness coefficient:

$$C = K_f / K_c \tag{4}$$

Where K_c and K_f are heat transfer coefficients under clean condition and fouling condition, A_j and A_f are design area of heat exchanger under under clean condition and fouling condition.

Redundant area represents the additional area of heat exchanger surface increased in design due to fouling. The higher the redundant area percent and the lower the cleanness coefficient and the greater thermal resistance, the more severely fouling impact on heat transfer.

Heat transfer quantity equations under clean condition and fouling condition can be expressed respectively by

$$Q_c = K_c A_c \Delta t \tag{5}$$

$$Q_f = K_f A_f \Delta t \tag{6}$$

Where Δt is the difference of temperature. And heat transfer quantity is demand to be the same in spite of the surface is clean or polluted, namely

$$Q_j = Q_c \tag{7}$$

From Eqs. (1) ~ (7) the correlation of these three parameters can be gotten as follows

$$R_f = \frac{1-C}{CK_j} \tag{8}$$

$$a = K_j R_f \tag{9}$$

$$C = \frac{1}{a+1} \tag{10}$$

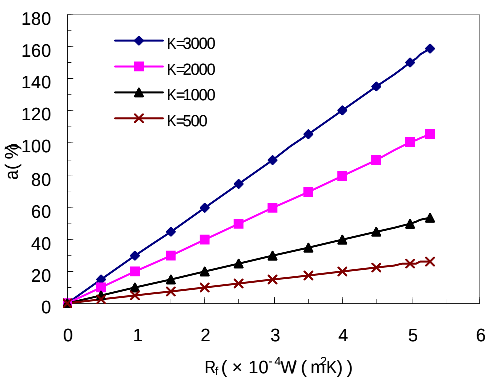

Fig. 2 Redundant area percent vs. fouling thermal resistance under different heat transfer coefficients

As can been notated that besides the three parameter mentioned above, there is K_j in Eqs.(8) ~ (10). Fig. 2 and Fig. 3 present the calculated results of redundant area percent and cleanness coefficient with the change of fouling thermal resistance under different heat transfer coefficient. It can be seen that fouling impact on heat transfer is not only decided by fouling thermal resistance, but also related to heat transfer coefficient. Under the same fouling thermal resistance, the higher heat transfer coefficient, the higher the redundant area percent and the lower the cleanness coefficient, namely the greater negative impact of fouling on heat transfer.

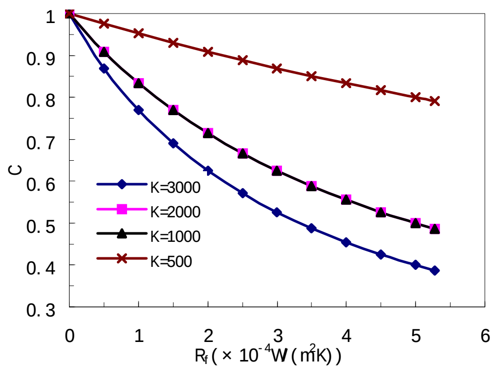

Fig. 3 Cleanness coefficient percent vs. fouling thermal resistance under different heat transfer coefficients

In order to validate the conclusion gained above quantitatively, the values of redundant area, percent of redundant area, cleanness coefficient and heat transfer coefficient of three-stage spray condenser are calculated as predicted in table 3. Sewage thermal resistance takes the constant value of $5.28\times10^{-4}m^2K/W$ in design calculation which comes from the TEMA Standard. As can been seen from table 3, fouling with the value $R_f=5.28\times10^{-4}m^2K/W$ makes the three stage spray heat exchanger area increase 83.3%，83.4%，73.58% of cleaning surface area, respectively. The heat transfer coefficient of two-state region is 968.6 $W(m^2K)^{-1}$, the largest of three regions, and the cleanness coefficient of two-state region is 0.49, the lowest of thee regions.

3.2 Simulation the Impact of Fouling Thermal Resistance on System Performance

With the fouling accumulation and desquamate, fouling thermal resistance is not constant. In order to

Tab. 3 Calculation of redundant area percent and cleaning coefficient of three-stage spray condenser

		K_j W(m^{2}K)$^{-1}$	K_f W(m^{2}K)$^{-1}$	C	
	superheat region	409.6	522.7	0.78	
	two-state region	968.6	1983.1	0.49	
	supercool region	483.1	648.6	0.74	
		A_j /m^2	A_j /m^2	ΔA /m^2	a
The first grade condenser	superheat region	2.03	1.59	0.44	27.7%
	two-state region	14.10	6.89	7.21	104.6%
	supercool region	1.58	1.18	0.40	33.9%
	Total	17.71	9.66	8.05	83.3%
The second grade condenser	superheat region	2.53	1.98	0.55	27.8%
	two-state region	20.12	9.83	10.29	104.7%
	supercool region	2.72	2.02	0.70	34.7%
	Total	25.36	13.83	11.53	83.4%
The third grade condenser	superheat region	3.34	2.62	0.72	27.5%
	two-state region	34.83	17.01	17.82	104.8%
	supercool region	13.99	10.43	3.56	34.1%
	Total	52.16	30.05	22.11	73.58%

Tab. 4 Conditions with three typical fouling thermal resistance

	Fouling thermal resistance R_f (m^{2}K/W)	Sewage temperature of condenser inlet $t_{w,c,i}$ ( )	Sewage temperature of evaporator inlet $t_{w,e,i}$ ( )	Sewage flow quantity m_w (m^3/h)	Degree of superheat Δt_{sh} ( )	Degree of supercool Δt_{sl} ( )
A	0					
B	5.28×10^{-4}	15	20	42000	5	5
C	8.60×10^{-4}					

convenience to compare, the performance of system is calculated under three conditions with different value of three typical fouling thermal resistances, which are listed in Table 4.

Table 5 presents the simulated performance of system under conditions A, B and C, respectively. It can been seen that with the increase of fouling thermal resistance, the refrigerant temperature and pressure of compressor outlet both increase, and the pressure ratio and the input power of compressor also increased obviously. When fouling thermal resistance increase from 0 to 5.28×10^{-4}m^{2}K/W, the input power increases 18.02%. These all proves that with the increase of fouling, the performance of compressor is severely deteriorated. And the other conclusions can be observed as followed.

1) With the increase of fouling thermal resistance, the condensing temperature increases and evaporating temperature decreases. It can be calculated that when the fouling thermal resistance is 0.0012m^{2}K/W, the evaporating temperature is tend to be 0 , which would be danger for system operating in cold climate. Therefore, removing fouling in time is necessary and the evaporating temperature is not suitable to be too low to ensure the security of system operating in winter.

2) Increasing fouling thermal resistance leads to system energy efficiency ratio (EER) decrease. This can be explained by the fact that with fouling thermal resistance increasing, the input power increases and the heat transfer quantity of condenser decreases (see Fig. 6).

Tab. 5 Simulation results of system in different fouling thermal resistance

	t_c (℃)	t_e (℃)	m_r (kg/s)	EER	Refrigerant temperature of compressor outlet (℃)	Refrigerant pressure of compressor outlet (k Pa)	Pressure ratio of compressor	Input power of compressor (kW)
A	30.340	15.041	5.173	6.415	40.026	1188.768	1.520	155.260
B	33.858	4.761	3.669	4.177	47.830	1284.973	2.288	170.900
C	37.225	1.804	3.308	3.495	53.305	1387.089	2.738	183.244

3) Increasing fouling thermal resistance also results in the mass flow rate of refrigerant decrease. This is because that evaporating temperature decreasing leads to the refrigerant specific votume of compressor inlet (v_1) increase, and pressure ratio increasing leads to the cubage efficiency (η_v) decrease. Compressive volume (V) is constant. So it can be derived from the equation $m_r = \frac{V}{v_1}\eta_v$ that refrigerant mass flow rate decreases.

Fig. (4) ~ Fig. (8) present the performance of two heat exchangers with increasing of fouling thermal resistance. Some detailed analysis can be observed as follows.

1) heat transfer coefficients and heat transfer quantity of two heat exchangers all decrease with the increase of fouling thermal resistance, and the temperatures of condenser outlet and evaporator outlet all increase.

2) As shown in Fig. 4, heat transfer coefficient curve of two-phase region is steeper than two others. When the fouling thermal resistance increases from 0 to 0.001 m^2 ℃/W, the heat transfer coefficient of two-phase region dropped from 1890.37 W/(m^2 ℃) to 636.91 W/(m^2 ℃), which decrease about 66.3%, much faster than other regions. It indicates that the greater initial heat transfer coefficient, the quicker the heat transfer coefficient decreases with the increase of fouling thermal resistance.

3) The purpose of using this system is to increase sewage temperature of condenser outlet to about 30 , so it can be seen as a symbol of removing fouling. As can be seen from Fig. 7, when the sewage temperature of condenser outlet temperature is below 30 ℃, removal of fouling is suggested to be implemented, and when it is below 25 ℃, removal of fouling must be implemented, or it cannot satisfy the requirement of biologic treatment.

4) Form Fig. 8 it is can be seen more clearly that the temperature change of sewage and refrigerant in condenser. Under condition A, with the least fouling thermal resistance, the sewage temperature of outlet is higher and the average refrigerant temperature is lower than two other conditions. It is proved that if the fouling thermal resistance is less, refrigerant can with lower average temperate heat up sewage more degrees.

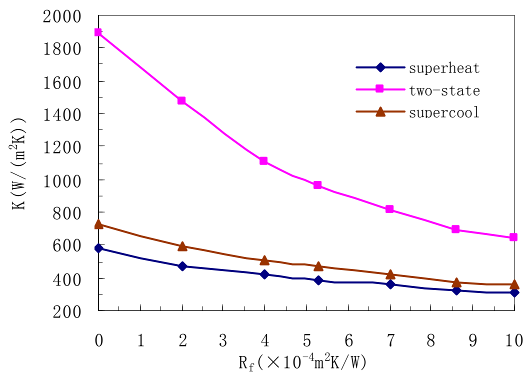

Fig. 4. Condenser heat transfer coefficient vs. fouling thermal resistance

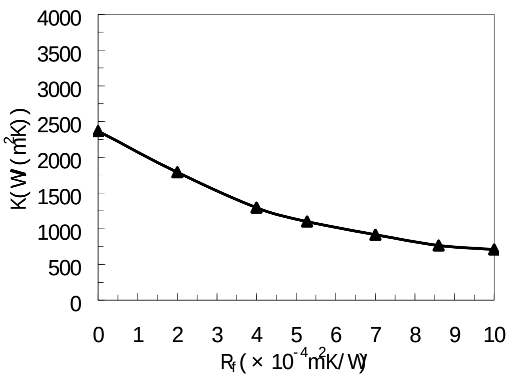

Fig. 5. Evaporator heat transfer coefficient vs. fouling thermal resistance

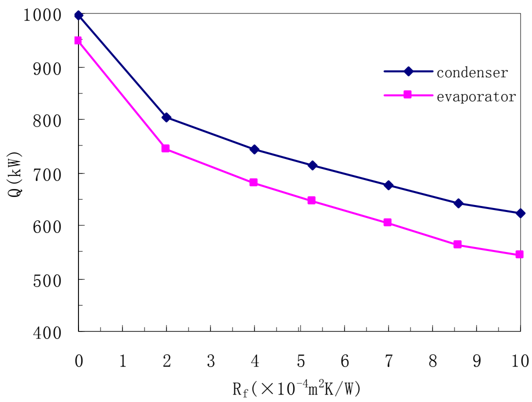

Fig. 6 Heat transfer quantity vs. fouling thermal resistance

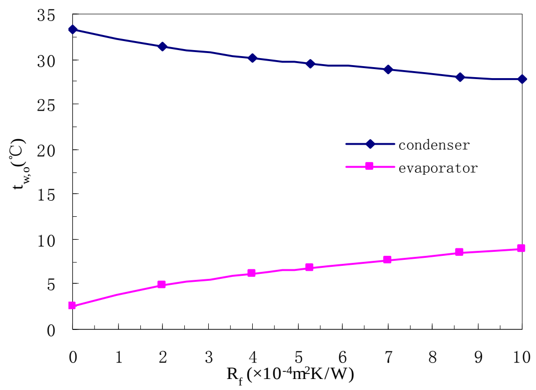

Fig. 7 Sewage temperature of heat exchangers outlets vs. fouling thermal resistance

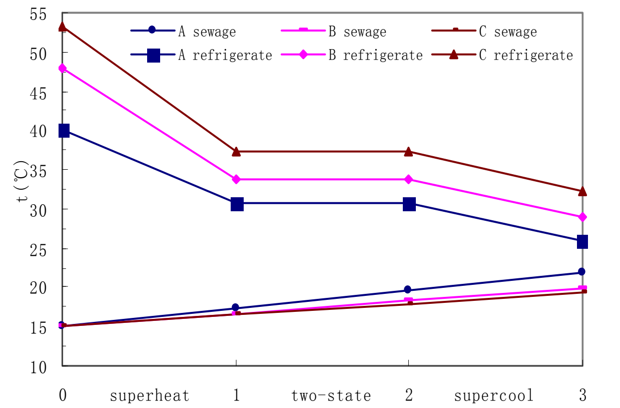

Fig. 8 Refrigerator and sewage temperature change of condenser under different fouling thermal resistance

4. CONCLUSIONS

In this paper a heat recovery plan with heat pump has been presented applying to sewage treatment system. And the performance of system and impacts of fouling on system have been evaluated. The following conclusions can be drawn.

Raw sewage temperature is enhanced from 15℃ to 29.569℃, each stage about 4~5℃, which is satisfied for the demand of sewage biologic treatment and indicates the technical feasibility of system. The input power of compressor is 170.899kW, and the EER of system can reach 4.177, which illustrates that using this system could reduce energy consumption and operation cost for its energy-saving and high efficient characteristic.

Fouling could make heat exchanger surface increase in design and system performance decrease in operating. Fouling impact on system not only depend on the fouling thermal resistance, but also is related to heat transfer coefficient, the higher heat transfer coefficient, the greater negative impact of fouling on heat transfer.

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