Analysis of Energy and Soft Dirt in an Urban Untreated Sewage Source Heat Pump System[1]

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Abstract: When using urban untreated sewage as a cool and heat source of heat pump, it is unavoidable to form soft dirt. Based on the method of exergy, an analysis is given of the impact the dirt growth of a tube-shell sewage heat exchanger will have on transfer intensity, flow pressure drop and exergy loss. The conclusions are deduced by an example showing that the middle flow velocity is good for energy conservation and economical efficiency, and it is also needed to remove the dirt in time at low flow velocity.

Key words: urban untreated sewage source heat pump; soft dirt; the method of exergy

1 INTRODUCTION

The urban untreated sewage is an ideal cool and heat source for air conditioning in buildings, but the problems about jam and contamination can not be neglected when using the energy of the sewage. The contamination is that the tiny dirt and animalcule's adherence on the surface of the heat exchanger. At present the study on the character of the urban untreated sewage's soft dirt is not too much [1]. Ronghua WU [2] had tested the character of the grows of the soft dirt in the sewage heat exchanger, but it did not make a analysis deeply in the relations of the growth of the soft dirt, the heat change capability and the energy consumption. The growth of the soft dirt in the sewage heat exchanger will lead to the transformation in heat change capability and the pressure drop in flow, so the exergy losses of the heat exchanger will change [3-5]. On the contrary, the relations of them can be reflected by the exergy losses of the heat exchanger. So this paper will analyze more deeply in the relation of the growth of the urban untreated sewage soft dirt, heat change capability and the energy consumption by the methods of exergy analysis.

2 THE MODEL OF THE EXERGY LOSSES EVALUATION

When the urban untreated sewage heat pump system (UUSHPS) runs, at first it would wipe off the big filth in the sewage by special equipment, flowing that the sewage with small filth will transfer heat or cool to the intermediary water through the tube-shell sewage heat exchanger, at last the heat pump will get heat or cool from the intermediary water indirectly to heat or cool the building. In tube-shell sewage heat exchanger, the intermediary water goes in the shell and the sewage in the tube. In a tube-shell heat exchanger, the exergy losses include the following aspects[5]: The exergy loss caused by the heat convection between the flow and the inner surface of the pipe; The exergy loss caused by heat conduct of the temperature difference of the dirt layer in the pipe; ③ The exergy loss caused by the liquid flowing pressure drop in the pipe; ④ The exergy loss caused by heat conduct caused by the temperature difference between the inner and outer surface of the pipe; ⑤ The exergy loss caused by heat conduct caused by the temperature difference of the dirt layer on the outer surface of the pipe; ⑥ The exergy loss caused by heat convection out of the pipe; ⑦ The exergy loss caused by the flowing pressure drop out of the pipe. In tube-shell sewage heat exchanger of UUSHPS, the

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soft dirt grows quickly in the pipe and main exergy losses are ~ items which will be analyzed.

2.1 The Exergy Loss Caused by the Sewage Heat Convection in the Pipe

Consuming that the average temperature of the sewage is T_{ws} and that of the intermediary water is T_{zj}, the temperature difference of heat convection in the pipe is

$$\Delta T_1 = \frac{Q}{hF} \quad (1)$$

where ΔT_1 is the temperature difference of the heat convection in the pipe; Q is the capacity of heat exchange through the heat exchanger; F is the heat exchange area of the heat exchanger and h is heat exchange coefficient in the pipe.

The tests on the sewage heat convection in the sewage heat exchanger shows that the sewage heat convection coefficient is sharply more smaller than that of the clean water. Under the velocity of flow is 0.4～1m/s and the movement viscosity of the sewage is 3 times to the clean water, heat exchange coefficient is 586～800 $\mathrm{W/\left(m^2 \cdot K\right)}$ in tests. If computes based on the equation (2), the heat exchange coefficient is 772～1600 $\mathrm{W/\left(m^2 \cdot K\right)}$, and if Computes based on the modified equation (3), the heat exchange coefficient is 514～1038 $\mathrm{W/\left(m^2 \cdot K\right)}$ which is more nearly to the true result. In fact, the sewage's flow and heat exchange are very complex, so here one can adopt the equation (3) and (4) to compute approximately sewage convection heat exchange in heating and cooling separately.

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}, T_{ws} > T_{zj} \quad (2)$$

$$Nu = 0.023\,\mathrm{Re}^{0.75}\,\mathrm{Pr}^{0.3}, T_{ws} > T_{zj} \quad (3)$$

$$Nu = 0.023\,\mathrm{Re}^{0.75}\,\mathrm{Pr}^{0.4}, \quad T_{ws} < T_{zj} \quad (4)$$

where Nu is Nusselt number; Re is Reynolds number and Pr is Prandtl number.

At heating condition, the sewage is hot liquid and the intermediary water is the cool liquid. By equation (1) and equation (3), the temperature under the soft dirt at heating condition can be obtained as equation (5).

$$T_{w1} = T_{ws} - \frac{13.85 Q \mu^{0.4}}{\left(\rho u d_1\right)^{0.75} \lambda^{0.6} c_p^{0.4} L n} \quad (5)$$

where T_{w1} is the temperature of inner surface of the pipe; λ is heat conduct coefficient of the sewage; μ is the dynamical viscosity of the sewage; ρ is the density of the sewage; u is the vicinity of the sewage; c_p is the specific heat of the sewage; d_1 is the inner diameter of the sewage pipe with soft dirt; L is the length of each pipe and n is the total number of the pipe.

Entropy generation and exergy loss caused by heat convection in the sewage pipe are

$$\Delta S_1 = Q\left(\frac{1}{T_{w1}} - \frac{1}{T_{ws}}\right) \quad (6)$$

$$\Delta E_1 = T_0 \Delta S_1 = Q T_0 \left(\frac{1}{T_{w1}} - \frac{1}{T_{ws}}\right) \quad (7)$$

where ΔS_1 is entropy generation caused by heat convection in the sewage pipe; T_0 is the temperature of the circumstance and ΔE_1 is exergy loss caused by heat convection in the sewage pipe.

The total exergy loss in the sewage heat exchanger is

$$\Delta E = Q\left(1 - \frac{T_0}{T_{ws}}\right) \quad (8)$$

where ΔE is the total exergy loss in the sewage heat exchanger.By the definition on the exergy losses coefficient, one can get exergy loss coefficient of sewage heat convection in the pipe, which is

$$\xi_1 = \frac{\Delta E_1}{\Delta E} = \frac{T_0\left(T_{ws} - T_{w1}\right)}{T_{w1}\left(T_{ws} - T_0\right)} \quad (9)$$

where ξ_1 is exergy loss coefficient caused by sewage heat convection in the pipe.

At cooling condition, the sewage is cool liquid and the intermediary water is hot liquid. By the same methods, the temperature at cooling condition can be obtained as equation (10).

$$T_{w1} = T_{ws} + \frac{13.85Q\mu^{0.45}}{\left(\rho u d_1\right)^{0.75}\lambda^{0.7}c_p^{0.3}Ln} \quad (10)$$

Entropy generation and exergy loss caused by heat convection in the sewage pipe are

$$\Delta S_1 = Q\left(\frac{1}{T_{ws}} - \frac{1}{T_{w1}}\right) \quad (11)$$

$$\Delta E_1 = T_0 \Delta S_1 = QT_0\left(\frac{1}{T_{ws}} - \frac{1}{T_{w1}}\right) \quad (12)$$

The total exergy loss in the sewage heat exchanger is

$$\Delta E = Q\left(1 - \frac{T_0}{T_{zj}}\right) \quad (13)$$

And one can get exergy loss coefficient of sewage heat convection in the pipe, which is

$$\xi_1 = \frac{\Delta E_1}{\Delta E} = \frac{T_0 T_{zj}\left(T_{w1} - T_{ws}\right)}{T_{ws}T_{w1}\left(T_{zj} - T_0\right)} \quad (14)$$

2.2 The exergy loss caused by heat conduct of the temperature difference of the soft dirt layer

The temperature difference between the two sides of the dirt layer can be got through heat conduct equation of cylindrical cliff,

$$\Delta T_2 = \frac{Q}{2\pi\lambda_s Ln}\ln\frac{d}{d_1} \quad (15)$$

where ΔT_2 is the temperature difference between the two sides of the dirt layer; λ_s is heat conduction coefficient of the dirt layer，here consumes it as 1.41 $\mathrm{W/(m \cdot K)}$; d is inner diameter of the clean pipe. By equation (15), one can get

$$T_{w2} = T_{w1} - \frac{Q}{2\pi\lambda_s Ln}\ln\frac{d}{d_1} \quad (16)$$

where T_{w2} is the temperature on the boundary of the soft dirt layer and the pipe.

Entropy generation, exergy loss and exergy loss coefficient caused by the temperature difference of the dirt layer are

$$\Delta S_2 = Q\left(\frac{1}{T_{w2}} - \frac{1}{T_{w1}}\right) \quad (17)$$

$$\Delta E_2 = T_0 \Delta S_2 = QT_0\left(\frac{1}{T_{w2}} - \frac{1}{T_{w1}}\right) \quad (18)$$

$$\xi_2 = \frac{\Delta E_2}{\Delta E} = \frac{T_0 T_{ws}\left(T_{w1} - T_{w2}\right)}{T_{w1}T_{w2}\left(T_{ws} - T_0\right)} \quad (19)$$

where ΔS_2 is the entropy generation caused by the temperature difference of the soft dirt layer; ξ_2 and ΔE_2 are the exergy loss coefficient and the exergy loss caused by heat conduct of the temperature difference of the soft dirt layer.

The temperature on the boundary of the soft dirt layer and pipe cliff at cooling condition is

$$T_{w2} = T_{w1} + \frac{Q}{2\pi\lambda_s Ln}\ln\frac{d}{d_1} \quad (20)$$

Entropy generation exergy loss and exergy loss coefficient caused by the temperature difference of the soft dirt layer are:

$$\Delta S_2 = Q\left(\frac{1}{T_{w1}} - \frac{1}{T_{w2}}\right) \quad (21)$$

$$\Delta E_2 = T_0 \Delta S_2 = QT_0\left(\frac{1}{T_{w1}} - \frac{1}{T_{w2}}\right) \quad (22)$$

$$\xi_2 = \frac{\Delta E_2}{\Delta E} = \frac{T_0 T_{zj}\left(T_{w2} - T_{w1}\right)}{T_{w1}T_{w2}\left(T_{zj} - T_0\right)} \quad (23)$$

2.3 The Exergy Loss Caused by the Sewage Flowing Pressure Drop

Here adopts tube-shell heat exchanger of fixed board type, sewage flowing pressure drop including sewage pressure drop of along the pipe and the pressure drop of the connection pipe which is at the inlet and outlet of the pipe. So the total pressure drop is

$$\Delta P = \Delta P_1 + \Delta P_2 \qquad (24)$$

Where ΔP_1 denotes sewage pressure drop along the pipe, ΔP_2 denotes pressure drop of the connection pipe which is at the inlet and outlet of the pipe, ΔP denotes the total pressure drop.

When one neglects the physics effects caused by the asymmetry in sewage flowing in the pipe, the flowing pressure drop is

$$\Delta P = \left(4 f_i L / d_1 + 1.5\right) Z \frac{\rho u^2}{2} \qquad (25)$$

where Z denotes the number of the pipe pass, f_i denotes the pressure drop coefficient along the pipe.

Through analysis on the test data, when the sewage is turbulent in the pipe, the coefficient of along the pipe resistance can be computed approximately based on the following equation:

$$f_i = 0.0122 d_1^{-0.35} \qquad (26)$$

At heating condition, exergy loss and exergy loss coefficient caused by the pressure drop along the pipe are

$$\Delta E_3 = \frac{m T_0 \Delta P}{\rho T_{ws}} \qquad (27)$$

$$\xi_3 = \frac{\Delta E_3}{\Delta E} = \frac{m T_0 \left(4 f_i L / d_1 + 1.5\right) Z u^2}{\left(T_{ws} - T_0\right) Q} \qquad (28)$$

where m is mass flux of the liquid in the pipe; ΔE_3 is exergy loss caused by the pressure drop along the pipe; ξ_3 is exergy loss coefficient caused by the pressure drop along the pipe.

At cooling condition, exergy loss and exergy loss coefficient caused by the pressure drop along the pipe are

$$\Delta E_3 = \frac{m T_0 \Delta P}{\rho T_{zj}} \qquad (29)$$

$$\xi_3 = \frac{\Delta E_3}{\Delta E} = \frac{m T_0 \left(4 f_i L / d_1 + 1.5\right) Z u^2}{2\left(T_{zj} - T_0\right) Q} \qquad (30)$$

2.4 The Sum of the three Exergy Losses

Through the equation (9)、(19) and (28), one can get the sum of the three exergy losses which are relation with the soft dirt at heating condition ξ is

$$\xi = \sum_{i=1}^{3} \xi_i = \frac{T_0}{T_{ws} - T_0} \left(\frac{T_{ws}}{T_{w2}} + \frac{m \Delta P}{\rho Q} - 1 \right) \qquad (31)$$

And the sum of the three exergy losses at cooling condition ξ is

$$\xi = \frac{T_0}{T_{zj} - T_0} \left(\frac{T_{w2} - T_{ws}}{T_{w2} T_{ws}} + \frac{m \Delta P}{\rho Q} \right) \qquad (32)$$

3 ANALYSIS OF AN EXAMPLE

Taking an urban untreated sewage heat pump project in Harbin for example, we have an analysis on the exergy loss based on condition of the soft dirt in the sewage heat exchanger at the heating condition in winter. The heat pump system adopts 2 parallel connection tube-shell heat exchangers in which pipes are 25/20mm carbonize steel seamless pipe, the number of every pipe pass is 65, and the intermediary water goes in the shell pass and flux is 200 m^3/h. In winter the circumstance temperature is 263.5 K. Table 1 shows the test parameters. In the table the balance thickness of the soft dirt is defined as the unalterable thickness when ultimately it stops growing at one velocity of flow.

From tab.1, one can know that the balance thickness of the soft dirt fall gradually when the velocity of flow increases. The soft dirt will get the balance thickness under different flow velocities and the soft dirt grows at the relation to velocity, the main reasons are: (1) wall shear stress is different under different velocity and film of the soft dirt would fall off when it grows; (2)There are many of microorganisms in the soft dirt and the microorganisms nearby the heat exchange pipe will die because of lacking of nutrition at long time, then the layer of the dead microorganisms will lose ability to hold on the cliff, at last the whole biology dirt layer will fall off naturally[2]

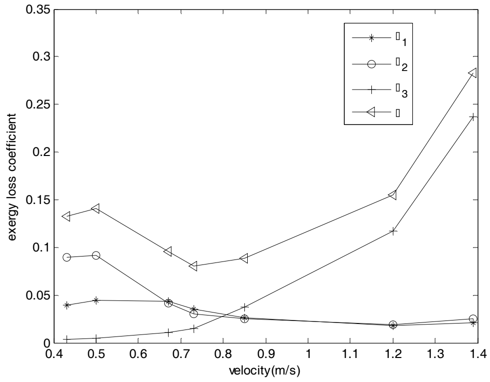

Fig. 1 Exergy loss coefficient under balance thickness of the soft dirt

Fig.1 shows the exergy loss coefficient changes relation with different sewage velocity. At group (6)、(7) in the tab.1, the velocities are lower, exergy loss coefficient caused by the temperature difference of heat convection in the pipe is dominant, at group (4)、(5) the velocities are middle, exergy loss coefficient caused by the temperature difference of soft dirt layer in the pipe and exergy loss coefficient caused by the temperature difference of heat convection in the pipe are bigger and at group (1)～(3)the velocities are higher, exergy loss coefficient caused by flowing pressure drop in the pipe is dominant. From the changes in the sum of the three exergy loss coefficient relation to soft dirt, one can choose a moderate velocity to make the sum of the three exergy loss coefficient smaller for saving energy. Here, we adopt group (4) whose velocity of flow is middle.

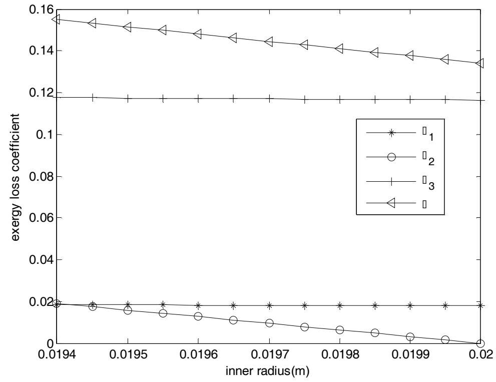

Fig. 2 Exergy loss coefficient at u=1.2m/s

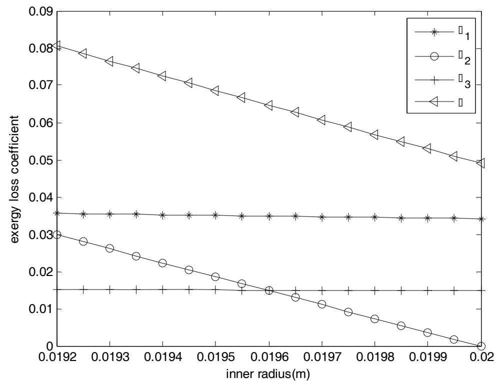

Fig. 3 Exergy loss coefficient at u=0.73m/s

Fig. 2~4 show that at group (2), (4) and (7) in the tab.1, exergy loss coefficient changes with the soft dirt rises when heat load of the sewage heat exchanger is invariable. And exergy loss coefficient caused by the heat convection in the pipe will slowly rise with the soft dirt grows at the same velocity for which the growth of the soft dirt will minish heat exchange area of heat convection to raise the temperature difference of heat convection slowly. While the thickness of the soft dirt is very small, exergy loss coefficient caused by heat convection in the pipe is almost invariable. The exergy loss caused by heat conduct caused by the temperature difference

Tab. 1 The system parameters tested under heating condition

Test group	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Sewage velocity(m/s)	1.39	1.2	0.85	0.73	0.67	0.5	0.43
Sewage supply-return temperature (℃)	10/6.8	14.2/10	12.8/7.2	14/8.5	11.5/8.5	14.2/8.1	14.0/8.9
Intermediary water supply- return temperature(℃)	6/3.2	9/6.4	6.8/4.5	7.6/4.7	8.0/5.0	8.3/6.1	9.0/7.4
Balance thickness of soft dirt(mm)	0.3	0.3	0.4	0.4	0.5	1.5	2.0
Heat load of the heat exchanger (KW)	651.28	604.76	534.98	674.54	697.8	511.72	534.98

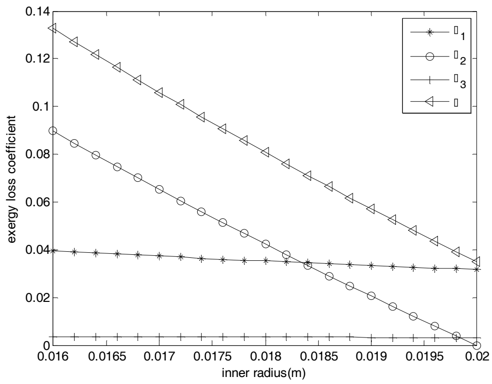

Fig. 4 Exergy loss coefficient at u=0.43m/s

in the soft dirt layer linearity rise with the soft dirt grows.The exergy loss caused by the liquid flowing pressure drop in the pipe is almost invariable for which the growth of the soft dirt has little effect to sewage mass flux when the velocity of flow is invariable. The sum of three exergy loss coefficient changes the same with the variety of exergy loss caused by heat conduct of the temperature difference in the soft dirt layer.

4 CONCLUSIONS

The paper analyzes the variety of exergy loss coefficient based on tube-shell sewage heat exchanger at different soft dirt condition, and one can get the following conclusions:

(1)The tube-shell sewage heat exchanger's exergy losses change with the growth of the sewage soft dirt on the side of pipe, and their magnitudes can reflect the soft dirt increase's effect on heat exchange loss and flowing pressure drop generally.

(2)The higher the sewage velocity, the bigger exergy loss coefficient caused by the liquid flowing pressure drop in the pipe as well as the smaller exergy loss coefficient caused by difference in temperature in the soft dirt layer in the pipe. When the velocity is middle, the sum of the three exergy loss coefficient relation to soft dirt is less. If the sewage velocity can be satisfied, it is good for saving energy and economics to choose the middle velocity.

(3)When the velocity is invariable, with the increase of the soft dirt, the exergy loss coefficient caused by heat conduct of the temperature difference in the soft dirt layer will sharply raise linearly while the changes of the exergy loss coefficient caused by flowing pressure drop along the pipe is slow relatively. If one can not get the middle velocity in (2), one must adopt effective methods to wipe off the dirt for ensuring the heat exchanger the effect of heat exchange, such as using the liquid of a high velocity to wash the sewage pipe in a short time reversely.

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