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A Wastewater Heat Recovery and Utilization System: Design and Analysis

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Abstract: This study is to design a wastewater heat recovery system using heat pump for Domestic Hot Water (DHW) heating and to investigate the feasibility and the potential performance of heat recovery and utilization system in changing conditions.

Key words: Heat pump, wastewater heat recovery, domestic hot water, heat exchanging manner, operation strategy, energy simulation

INTRODUCTION

This study investigates the feasibility and the beneficial manner of utilizing energy existing in wastewater discharged from spring hotel for the purpose of heating domestic hot water for itself. The characteristics of wastewater sources including quantity, temperature, quality and place of origin could affect the technical, performance and application manner of heat pump heat recovery system. Although many researchers approved that wastewater is available and feasible in heat pump heat recovery system, as a heat source, a limited number of heat pump systems utilizing wastewater are available (Ni *et al*., 2012; Zhang *et al*., 2007; Baek *et al*., 2005; Liu *et al*., 2010). A reason of these application restrictions can be that the usage of wastewater heat recovery system is not well known by developers and they are notorious for being troublesome to operate (Kahraman and Celebi, 2009). Another barrier is some design problems, optimum energy use in a process, heat extract methods, engineering operation plans or applying patterns puzzling designers and deciders. It became necessary to develop a wastewater heat recovery simulation system with two type wastewater heat exchanger cycles operating in valley electricity operation. Therefore in this study, a simulation system with wastewater tank, exchanger, heat pump unit and hot water storage tank is presented here through a real item built in a spa center to recover the heat from waste water for water heating.

SYSTEM DESIGN

The hotel "T" is a large spring hotel in Tianjin of China, with a total area of 40,000 m^2, 6 floor and 78 spring pools with a total area of 988.2 m^2 and total volume of 882 m^3, maximum daily accommodation for 1500 people. Heat pump is designed to recover heat from wastewater discharged from spring pools, to service DHW heating for this hotel.

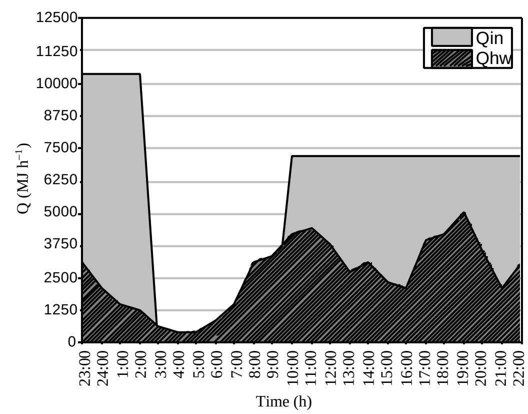

Fig. 1: Hourly heat load flow in a full load day. Q_{in} is the heat load of wastewater flow in the wastewater storage tank. Q_{hw} is the heat load of domestic hot water per hour

DHW heating load and Wastewater amount. The DHW heating load depends on the water consumption which is periodic by day and night, with variation of hourly. Figure 1 shows the distribution of the hourly mean heat load in a full load day. The heat load of the DHW consumption during peak time (17:00-18:00) is 5000 MJ h^{-1}. Then the wastewater amount during peak time (22:00-2:00) is 90 t h^{-1} (Baek *et al*., 2005).

Design of the wastewater heat recovery and utilization system. This system is composed of three parts: wastewater heat extraction system, heat pump and hot water heat supply system. The indirect wastewater

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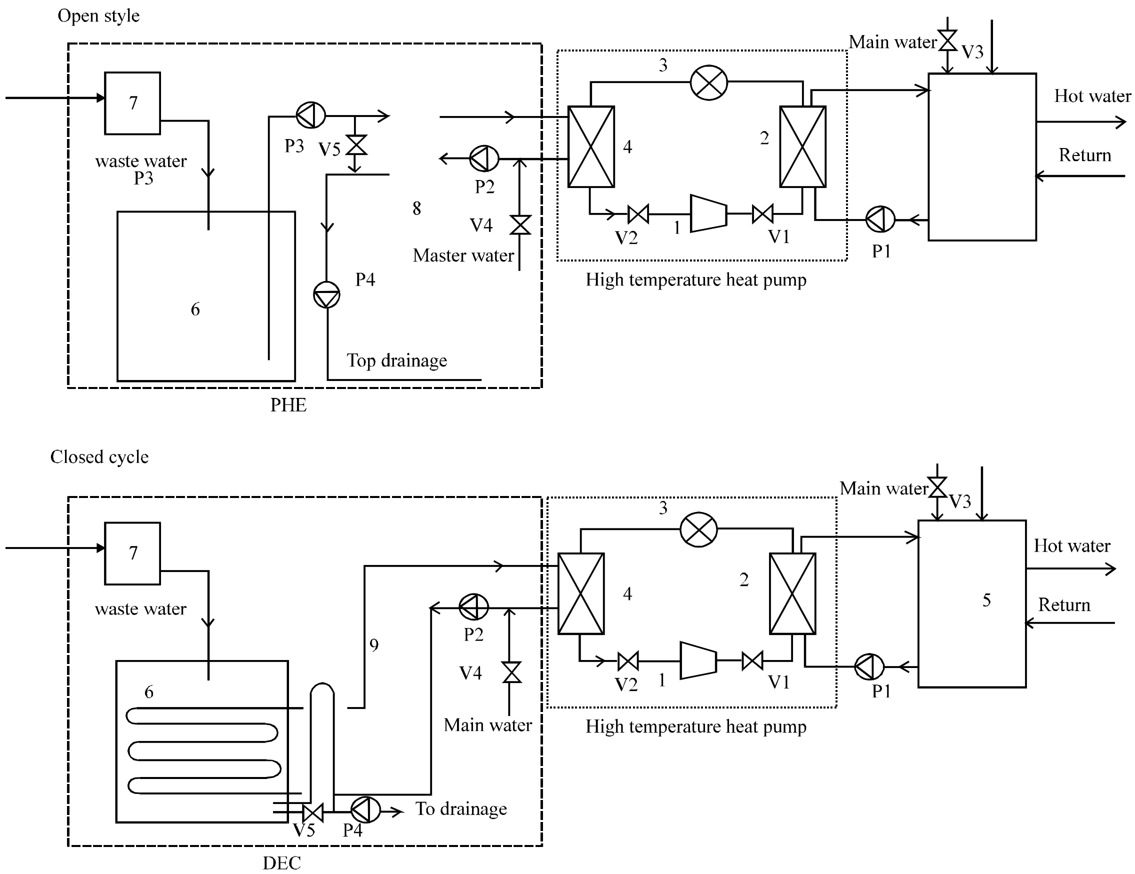

Fig. 2: Principal design of energy-recovery system from wastewater. Labels: (1) compressor, (2) condenser, (3) expansion valve, (4) evaporator, (5) hot water storage tank, (6) wastewater tank, (7) filter, (8) plate heat exchanger, (9) direct expansion coil; And there are some pumps: P1and P2 are circulating pumps; P3 is supply pump; P4 is drainage pump. V1-V5valves

Table 1: Design conditions

Item	Design conditions	Remarks
Domestic hot water temperature	323~333K	At the user port
Daily domestic hot water consumption	300m^3	Winter
Daily domestic hot water heating load	63000 MJ/d	100% load
DHW storage rate	33%	
Volume of ST	100 m^3	
Flow rate of wastewater	628~1200 m^3/d	
Volume of WWST	400 m^3	
COP	4.2	333K/303K
Wastewater temperature	303K	At the ST

heat extraction method will be chose, to avoid the pollution of the heat pump unit. Two principal designs of energy-recovery system from wastewater with different wastewater heat extraction methods: open style and closed cycle, showed in Fig. 2. The design conditions of the system are presented in Table 1.

ENERGY ANALYSIS MODEL

The main focus in this study is energy flow from wastewater tank to heat pump then to hot water storage tank. The calculations are done using steady state conditions. An instantaneous view of one day in winter process is not meat for estimations of annual energy demand. The aim of energy flow figure is to produce a “transparent” view, easy to understand for designers and deciders. Figure 3 shows the flowchart of energy consumption in this energy recovery system of wastewater.

Temperature models of Tank. The temperature models of water in water tank are important in this system. Using the conservation of mass and energy, the temperature of water in wastewater tank can be determined by:

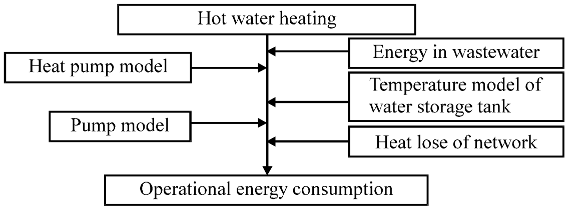

Fig. 3: The flowchart of energy consumption in this energy recovery system of wastewater

open style

$$T_1 = \frac{V_0 T_0 + dtL_w T_w}{V_0 + dtL_w} \quad (1)$$

closed cycle

$$T_1 = \frac{V_0 T_0 + dtL_w T_w}{V_0 + dtL_w} - \frac{Q_{ex}}{c\rho\left(V_0 + dtL_w\right)} \quad (2)$$

hot water tank

$$c\rho V_0 \frac{dT}{dt} = Q - Lc\rho\left(T_1 - T_0\right) \quad (3)$$

T_w is the temperature of wastewater flow into the tank. It does not vary greatly in a day. T_0 and T_1 are start temperature and final temperature of water in the tank (centigrade), respectively. L_w is the flow rate of wastewater (m^3/h). Q_{ex} is the exchanged heat from the tank (kJ).

Heat pump models. The ratio of heating load to input power is defined as the Coefficient of Performance (COP). The COP varies with the temperature of the wastewater into evaporating and the temperature of the DHW out from condenser. According to the experimental data supplied by the manufacturers, the COP simulated equation is represented in this formula (Allen and Hamilton, 1983).

$$COP = 5.3609477+0.1125383Tco-0.0046644Tco^2-0.2886778Tei-0.0125538Tei^2+0.015759Tco*Tei \quad (4)$$

where, T_{ei} is the temperature of water into evaporator and T_{co} is the temperature of water out from condenser. $R^2 = 0.996$.

Pump models There are 4 pumps in this system: P1and P2 are circulating pumps; P3 is water supply pump; P4 is drainage pump. The energy consumption of pump is calculated as:

$$N = \frac{QH}{367\eta_p \eta_m \eta_{VFD}} \quad (5)$$

where N is the pump power (kW), Q is pump flow (kg/h), H is pump head (mH2O), ç$_p$ is pump efficiency, ç$_m$ is motor efficiency and ç$_{VFD}$ is the frequency converter efficiency. The heat loss of network. The heat loses of network can be calculated as:

$$q_l = \frac{\left(t_1 - t_0\right)\left(T_{b1} + R_{s1}\right) - \left(t_2 - t_0\right)R_k}{\left(R_{b1} + R_{s1}\right)\left(R_{b2} + R_{s2}\right) - R_k^2} \quad (6)$$

where q_l is the heat loss of water supply pipe (W/m), t_1 is medium temperature of water supply pipe (centigrade), t_2 is medium temperature of water return pipe (centigrade), R_{b1} is thermal resistance of insulation layer on the water supply pipe (mcentigrade/W), R_{b2} is thermal resistance of insulation layer on the water return pipe (mcentigrade/W), R_{s1} is soil thermal resistance of water supply pipe (mcentigrade/W), R_{s2} is soil thermal resistance of water return pipe (mcentigrade/W), R_k is thermal resistance between water supply and return pipe (mcentigrade/W) and t_a is ambient temperature (centigrade).

RESULTS AND DISCUSSION

The comparison of two wastewater heat exchanging manners. The change of operation conditions (the temperature of water into the evaporator and out of the condenser) impacts the performance of heat pump. In this system, different heat exchanging methods make the temperature of evaporator change differently. In the open styel, a constant flow of water in the WWST was pumped into the plate heat exchanger. Then the temperature of water into the evaporator is constant. In the closed cycle, the circulating water in the submerged-pipe coil extracts the heat from the wastewater, while the temperature of the wastewater decreases gradually. The performance of heat pump systems with different heat exchanging methods is showed in Fig. 5. They both operate in valley electricity period in a full load day. Figure 5a shows that the temperature of hot water in ST grows up with the heat pump operating in night and drops down in daytime because of the heat lost and supply of low temperature return water from network. Tco increases gradually and COP decreases slightly. In the same heat load, the heat exchanging method ¢òmakes COP decrease greatly in Fig. 5b.

Operating status Fig. 5 and 6 show operating status of system with open style in valley electricity period, normal electricity and peak electricity period in a full load day. The temperature of hot water in ST is between 54~60 centigrade and the temperature of water

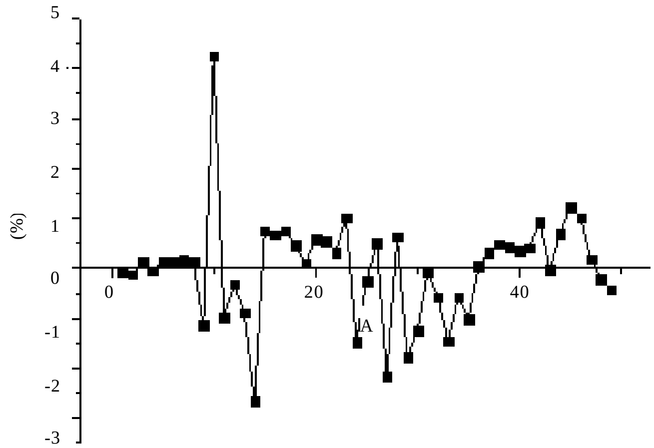

Fig. 4: Deviation between experimental results and theoretical calculation

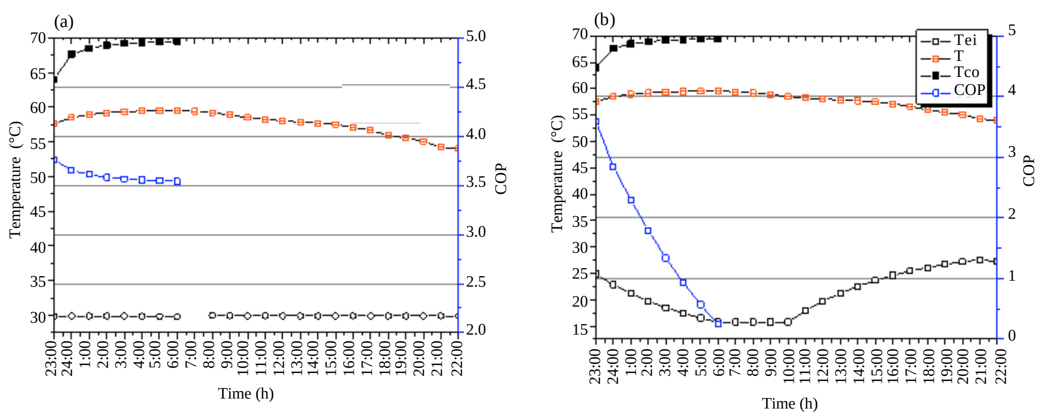

Fig. 5(a-b): COP and operating temperature of system with different heat exchanging methods in valley electricity period in a full load day

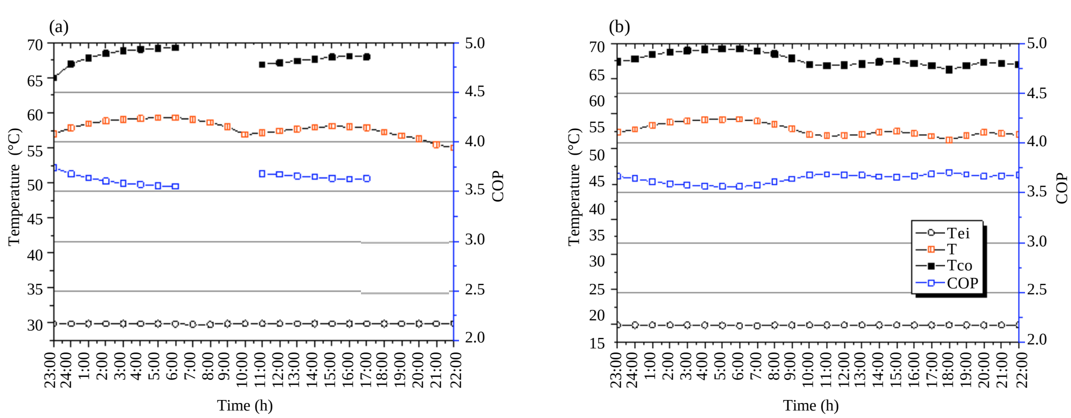

Fig. 6(a-b): Operating temperature and COP of heat pump system with open style in different periods of a full load day out from condenser is between 64~70 centigrade. The full time style in Fig. 6b has the smallest fluctuations. The amplitude of COP variation is 3.5~3.8.

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