Applied Energy 132 (2014) 267–275

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The design and analysis of two exhaust heat recovery systems for public shower facilities

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HIGHLIGHTS

- Two kinds heat recovery systems for public shower facilities are compared.
- The heat recovery system of absorption heat pump is proposed.
- The various components and parameters of the absorption heat pump are designed.
- Control methods of the heat recovery systems are proposed.
- Selection principles of heat recovery system schemes are proposed.

ARTICLE INFO

Article history:
Received 17 December 2010
Received in revised form 29 June 2014
Accepted 4 July 2014

Keywords:
Public shower facility
Exhaust heat recovery
Electric heat pump
Absorption heat pump

ABSTRACT

A great deal of heat is wasted in intensive public shower facilities, such as those in schools, barracks and natatoriums, which open up at specified time. It will contribute a lot to energy saving and environmental protection with significant economic benefits to recycle the exhaust heat. In this paper, we propose two different kinds of heat pumps (an electric heat pump and an absorption heat pump) in the heat recovery systems. In both system, the used shower water is drained through a pipe and collected in a gray water pool. When the wastewater reaches certain volume, the heat pump system will begin working and recycling heat. The wastewater is filtered and piped to the heat exchanger to exchange heat with the tap water whose temperature will increase from 12 °C to 25 °C with the wastewater temperature dropping from 30 °C to 17 °C. Then the wastewater is piped to the heat pump evaporator and the tap water is piped to the condenser for farther heating. According to the different characteristics of the electric heat pump and absorption heat pump, we also introduce the processes and control methods of different heat recovery systems in details in this paper. Based on a practical example, this paper analyzes and compares the economic and environmental benefits of three retrofitting schemes, including "exhaust heat recovery using electric heat pump", "exhaust heat recovery using electric heat pump + gas boiler" and "exhaust heat recovery using direct-fired heat pump". Then we find out that the heat recovery system using direct-fired absorption heat pump has lower energy consumption, less pollution, lower operating cost, and shorter payback period. And it has a promising practical application.

1. Introduction

In China, for students, soldiers, workers and other people who live a group life, providing sufficient hot water to meet daily bathing needs is an important approach to improve their standard of living. Under this circumstance, shared public shower facilities are widely used in China which is different from developed counties where people usually use private bath. Most of these public shower facilities now rely on boilers to provide hot water, which causes high energy consumption and pollution. Taking Beijing for example, there are almost 70 colleges with more than 100,000 teachers and students. This directly results in a demand for more than 6000 tons bathwater a day [1], which means 1.8 million m^3 domestic water per year. What is worse, most of the domestic waters are wasted without recycling. Some companies try to use solar water heaters as heat source. But it is difficult to find enough space to install so many solar water heaters to supply such a large

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http://dx.doi.org/10.1016/j.apenergy.2014.07.013
0306-2619/

Nomenclature

A	area of the water–water heat exchanger (m^2)
a	constant related to flows in the device
b	constant related to flows in the device
c	Heat capacity (J/(kg K))
COP_a	performance coefficient of absorption heat pump, the ratio of heat capacity and the heat generated by the gas combustion.
COP_e	performance coefficient of electric heat pump, the ratio of heat capacity and power input of the compressor-motor.
c_p	specific heat capacity of water (kJ/kg °C)
c_1	price of electricity
c_2	price of gas
F	heat-transfer area (m^2)
G	flow of heating medium (kg/h)
$(Gc)_L$	the larger equivalent of heating medium (kg/h)
$(Gc)_S$	the smaller equivalent of heating medium (kg/h)
K	generalized heat transfer coefficient (W/(m^2 °C))
K_{Ex}	heat transfer coefficient between tap water and gray water in the heat exchanger (W/(m^2 °C))
f	total tap water flow rate (L/s)
m_{in}	liquid flow into the system(L/S)
m_{out}	liquid flow out of the system(L/S)
m_p	gray water flow rate into heat pump (L/s)
n	operating days of the system, which is 300 days
Q	heat exchange(kW)
Q_{el}	heat provided to tap water by electric heat pump (kW)
$Q_{Ex,p}$	heat provided to gray water by heat exchanger (kW)
Q_{hp}	heat provided to tap water by heat pump (kW)
Q_{in}	input energy of the system (kW)
Q_{out}	output energy of the system (kW)
S	the surface area of the solar collector (m^2)
t_c	condensing temperature (°C)
t_{f1}	inlet tap water temperature of heat exchanger (°C)
t_{f2}	outlet tap water temperature of heat exchanger (°C)
t_{f3}	outlet tap water temperature of heat pump (°C)
t'_{f3}	outlet tap water temperature of heat pump in scheme 2 (°C)
$t_{f3,0}$	outlet tap water temperature of heat pump when the outlet gray water temperature is 5 °C.
$t_{f,m}$	annual average temperature of tap water (°C)
t_o	evaporating temperature (°C)
t_{p1}	inlet gray water temperature of heat exchanger (°C)
t_{p2}	outlet gray water temperature of heat exchanger (°C)
t_{p3}	outlet gray water temperature of heat pump (°C)
t'_{p3}	outlet gray water temperature of heat pump in scheme 2 (°C)
Δt_{Ex}	heat transfer temperature difference between tap water and gray water in the heat exchanger (°C)
V	heat storage tank (m^3)
V_p	volume of the gray water pool (m^3)
W	electric power of heat pump (kW)
$W_{w,pump}$	electric power of wastewater pump (kW)
Y_{sum}	total operation cost (Yuan)
ρ	water density (kg/m^3)
τ	operating time of the system (h), which is 1600 h
η_{boil}	efficiency of the gas boiler, which is 90%
Δ	maximum temperature difference between the two participated fluids (°C)

amount of hot water, let alone the significant influence of the weather. For these bathrooms which open at fixed-time, heat use and heat rejection are relatively concentrated, and a great deal of heat is contained in the wastewater. It will contribute a lot to energy conservation and environmental protection to recycle the exhaust heat. Currently there are various kinds of heat pump systems widely used to recover and recycle exhaust heat [2–4]. For example, heat pump system is used to recover urban wastewater more and more frequently [5–8]. Unfortunately, the urban wastewater temperature is relatively low (generally around 10 °C) in winter, causing higher recycling costs [8]. Thus, an alternative method is necessary to reduce the high recycling costs of exhaust heat recovery of low temperature urban wastewater in order to maintain energy-saving of the sewage source heat pump. There are also some researches on the exhaust heat recovery using heat pump in indoor swimming pool [9–12]. Lazzarin and Longot [9] compared the energy utilization of different heat recovery systems. Johansson and Westerlund [10] compared the energy performance between adsorption heat recovery system and heat pump. Lam and Chan [11] analyzed the energy utilization of a hotel swimming pool with heat pump by using life cycle energy cost method. Lee and Kung [12] utilizes particle swarm algorithm to optimize the design of heat pump system in order to reduce the cost in energy consumption. But all these heat recovery systems are used to recover the heat of the exhaust air. The author has presented and analyzed a heat recovery system, which starts with solar energy, recycles the exhaust heat using an electric heat pump and this is different from the urban wastewater and exhaust air in swimming pool heat recoveries [13]. On this basis, this paper will present a heat recovery system using absorption heat pump and introduce the process and control of two different heat pump systems based on different characteristics of electric heat pump and absorption heat pump. Then through an example, this paper will analyze the economic performance and environmental protection performance of these two kinds of exhaust heat recovery systems.

2. System descriptions

2.1. Exhaust heat recovery system using electric heat pump

As shown in Fig. 1, the electric heat pump system consists of storage tanks, electric heaters, a water pool, filters, heaters, pumps and an electric heat pump. At the beginning of bathing, because there is no wastewater in the pool, the heat pump will not work. Instead, the electric heater is started to heat the water in the storage tank, providing hot water for the first users. When the wastewater drains into the water pool to a certain amount, the heat pump starts. Then the wastewater is filtered through by water filters, after which the wastewater is pumped to the water–water heat exchanger for heat exchange with cold tap water. The cold tap water is heated from 12 °C to 25 °C, and the excluded wastewater temperature drops from 30 °C to 17 °C. Respectively, they enter the heat pump's condenser and evaporator, then the heat pump extract heat from the excluded wastewater. The cold tap water will eventually be heated to the required temperature.

As previously mentioned, the heat pump will not work at the begging. At the end of each day, the wastewater from the last group of users is used to produce hot water, which is stored in the heat storage tank. This will reduce the initial electricity consumption of electric heat pump for the next day. The heat generated by electricity is used to maintain the room temperature of the bathroom. So, to ensure that the system will perform well, bathroom ventilation, insulation and control volume are all