A Study on the Design of Waste Heat Utilization System for University Baths in Severe Cold Regions

Yuhang Lu, Huixing Li, Guohui Feng, Ang Xu and Weixuan He

Abstract The reduction in energy reserves in recent years has made waste heat recovery an important technical means to solve energy shortages. As an important part of campus service facilities, university baths have the characteristics of large residual heat, dense population and high energy consumption. Through field research on several college baths, we can grasp the general energy loss of existing college baths. Starting from the analysis of bathing wastewater, exhaust gas emission and energy loss in the discharge path, combined with sewage source heat exchanger, dual-source heat pump and phase-change water tank, the research on the design of a waste heat recovery system suitable for university baths in severe cold areas is carried out. Using fluent software the system's total residual heat, water temperature, flow and other parameters in the system are mastered, and finally the formula to derive the system energy utilization is used. The sewage source heat pump, the wastewater–exhaust gas dual-source heat pump and the phase-change water tank are coupled with each other to carry out step recovery of the waste heat of the bath, which provides a new idea for the utilization of waste heat of the auxiliary service of the public institution.

Keywords University bath · Waste heat recovery system · Cascade utilization

1 Introduction

In the severe cold area, the bathing water of college baths has the characteristics such as being concentrated, instantaneous water output, high temperature of wastewater discharge and being relatively stable [1]. From the perspective of national regulations and the bathing habits of teachers and students, the temperature of bathing hot water is generally around 35–40 °C [2]. Bathing wastewater containing high heat after bathing directly flows into the drainage channels. Finally, it discharges into urban

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sewage drainage pipes causing a lot of heat loss. This heat loss is most prominent in public places for centralized hot water in universities, hotels, etc. [3]. Through investigations, it is found that there are still some university baths that use coal to produce hot water, which not only has high operating costs, but also generates harmful gases that pollute the environment and seriously endanger the health of operators. This is clearly contrary to the environmental protection concept of the new era. In recent years, some of the reformed universities have purchased hot water from thermal power plants to meet the bathing requirements. The price of hot water from thermal power plants is 28–29 yuan/ton, which greatly increases the cost of bathing. Moreover, the hot water of the thermal power plant has a high heat loss due to the heat dissipation of the pipeline during the transportation process, and thus the energy saving requirements at the current stage are not met. The waste heat of the bathing wastewater is not fully utilized, and it also causes certain amount of pollution to the environment. With the consumption of fossil energy and the development of new energy, people are paying more and more attention to energy saving. The waste heat recovery with the advantages of saving energy, environmental protection and being renewable is of wide concern to scholars at home and abroad and has been promoted to some extent in some developed cities with suitable conditions [4]. Through the analysis of the characteristics of bathing areas in China's severe cold regions and colleges, combined with the advantages of dual-source heat pump, sewage heat exchanger and phase-change water tank, a waste heat utilization system suitable for university baths in severe cold regions was designed.

2 Methods

2.1 Waste Heat Recovery Technology Utilized by the System

Wastewater–exhaust gas dual-source heat pump The heat pump water heater is an important energy-saving equipment. It can use high-grade electric energy to absorb the zero-grade air energy or low-grade water source through the refrigeration cycle to produce domestic hot water of 50–55 °C [5]. In fact, due to the irreversible loss of heat pump in all aspects, the coefficient of performance COP of the heat pump is generally about 2–4.5 in one year [6]. Among them, air source heat pump has a wide range of applications, but in winter, the COP value is low. The single-source heat pump can use wastewater heat in winter and has a high coefficient of performance, but it cannot provide hot water when the water source is interrupted. Therefore, there are limitations of a single-heat-source heat pump. Air–water dual-source heat pump hot water unit has the dual advantages of high energy utilization rate of the water source heat pump and wide application range of the air source heat pump. It is suitable for use in places such as bathhouses and hotels that require domestic hot water and can be utilized by heat pumps. The temperature of bathing wastewater is from 31 to 36 °C, and that for production of hot water from 50 to 55 °C. Studies

Table 1 Performance comparison of several hot water systems

Name	Unit energy calorific value	Thermal efficiency	Actual calorific value	1 ton of water temperature increased by 40 °C energy consumption	Standard coal (kg)
Water heater	860 kcal/kWh	90%	778 kcal/kW h	52 kW h	18.8
Coal burning boiler	5000 kcal/kg	55%	2750 kcal/kg	14.5 kg	10.4
Gas boiler	8000 kcal/m^3	65%	5200 kcal/m^3	7.7 m^3	8.8
Biomass boiler	4300 kcal/kg	70%	3010 kcal/kg	13.3 kg	8.1
Solar energy	No valid sunshine weather: 100 days			15.0 kWh	5.5
Wastewater–exhaust gas dual-source heat pump unit	860 kcal/kWh	500%	4300 kcal/kWh	9.3 kWh	3.4

have shown that dual heat source heat pump water heaters with parallel water and air sources have higher COP than air source heat pump water heaters.

The wastewater–exhaust gas dual-source heat pump is the main heating component in the system, providing most of the heat to the system (Table 1).

Sewage heat exchanger The immersed heat exchanger consists of a straight pipe or a spiral bend to form a heat transfer surface and is immersed in the sewage tank. In summer, the refrigerant water in the pipe releases the heat of the air-conditioned room into the sewage tank. In winter, heat is taken from the recovery tank through the refrigerant water, and the heat is released into the air-conditioned room by the heat pump unit. The immersed heat exchanger has the advantages of simple structure, convenient manufacture and repair, and easy cleaning. If corrosion-resistant materials are used, it can be applied to corrosive fluids and widely used in sewage source heat pump systems.

For immersed heat exchangers, the heat transfer coefficient per unit length can be calculated as follows:

$$K_{\mathrm{L}} = \left[\frac{1}{\alpha_{\mathrm{s}}\pi d_{\mathrm{o}}} + R_{\mathrm{s}} + \frac{1}{2\pi\lambda_{\mathrm{P}}}\ln\frac{d_{\mathrm{o}}}{d_{\mathrm{i}}} + R_{\mathrm{w}} + \frac{1}{\alpha_{\mathrm{w}}\pi d_{\mathrm{i}}}\right]^{-1} \tag{1}$$

where α_{S} is the heat transfer coefficient of the sewage side, W/(m^2 K); α_{W} is the heat transfer coefficient of the refrigerant water side, W/(m^2 K); R_{W} is the thermal resistance of the inner side of the tube, W/(m^2 K); λ_{P} is the thermal conductivity of the pipe, W/(m K); δ is the wall thickness of the pipe, *m*; d_i is the inner diameter of the tube, *m*; d_0 is the outer diameter of the tube, $d_0 = d_{\mathrm{i}} + 2\delta$, *m*.

Heat exchange capacity of sewage heat exchanger is calculate as follows:

$$Q = K_{\mathrm{L}}\Delta t L \tag{2}$$

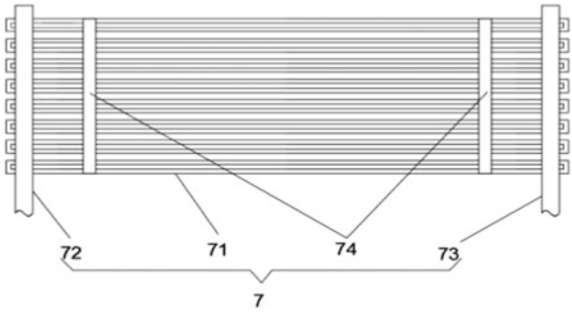

Fig. 1 Sewage heat exchanger top view

where K_L is the heat transfer coefficient of the unit length of the sewage heat exchanger, W/(m °C); L is the length of the sewage heat exchanger coil, *m*; Δt is the heat transfer temperature difference between the medium inside and outside the coil of the sewage heat exchanger, °C (Fig. 1).

Phase-change water tank For the heat recovery of bathing wastewater, a common heat recovery technology is to use heat pump technology to recover heat from the bathing wastewater. However, there is a certain time course in the process of discharge of bathing wastewater, which often has a certain mismatch with the time node of water use. At this time, the heat storage density is utilized by the phase-change material for heat storage, and the heat accumulator is compact. The utility model has the advantages of small volume, high thermal efficiency, constant temperature of heat absorption and release, easy control, etc. [7]. In many areas of energy conservation and new energy utilization, phase-change thermal storage technology that uses phase-change materials for energy storage and release is considered to be an efficient, environmentally friendly and energy-efficient energy utilization method. Phase-change thermal storage technology can solve the problem of spatial and temporal mismatch between heat supply and demand and is also one of the important technical means for the development and utilization of renewable energy and is an important method to improve energy utilization efficiency. Therefore, the addition of phase-change heat storage technology to the heat recovery of bathing wastewater can effectively improve the energy utilization efficiency and also solve the problem of spatial mismatch of bathing wastewater.

The phase-change hot water storage tank can effectively adjust the heat peak and valley and use the excess heat of the previous working day to prepare the hot water on the second working day, reflecting the utilization characteristics of the system waste heat (Fig. 2).

3 Results

According to the composition of the traditional bath and the waste heat recovery equipment introduced above, a new type of system suitable for waste heat recovery

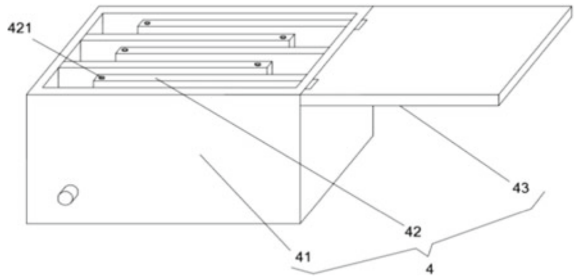

Fig. 2 Phase-change water tank structure diagram

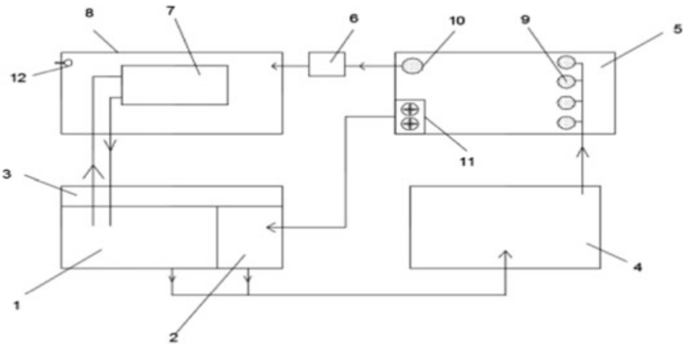

Fig. 3 Large sample map of university bath waste heat recovery system in severe cold area

in colleges and universities in the cold region is shown (Fig. 3). The system includes a water source box 1, a shower chamber 5 and a sewage pool 8. The side wall of the water source tank 1 is closely attached to the air source box 2. The water source tank 1 and the rear side wall of the air source tank 2 are closely attached to the heat pump unit 3. The water source tank 1 and the air source tank 2 are connected to the phase-change water tank through a pipeline. The output end of the phase-change water tank 4 is connected to the spray head 9 through a pipeline. The nozzle 9 is installed in the bathroom 5. There is a floor drain in the bathroom 5. The floor drain 10 is connected to the sewage pool 8 through a pipeline. Sewage tank 8 is equipped with sewage heat exchanger 7. The sewage heat exchanger 7 forms a closed loop with the water source tank 1 through the pipeline. The dehumidification fan 11 is installed in the bathroom 5. The output end of the dehumidification fan 11 passes through the pipeline together with the air source tank 2. The bathing wastewater of about 30 °C is discharged into the lagoon 8 through the floor drain 10 in the drain of the bathroom. The bathing wastewater is recovered by the sewage heat exchanger 7. After the heat is extracted, the bathing wastewater of about 8 °C is discharged into the sewage pool 8. At the same time, the wet steam generated in the bath zone recovers the heat of the excess wet steam through the dehumidifying fan 11, heats the heat in the wet steam and the heat in the sewage, and heats the tap water from the heat pump unit. In particular, a sewage outlet 12 is arranged in the sewage pool 8 to facilitate the discharge of sewage. A filter 6 is fitted to the line connecting the floor drain 10 and the sump 8.

The phase-change water tank 4 includes a tank 41, a heat storage plate 42 and a tank cover 43. The heat storage plate 42 is provided with an opening 421, and the heat storage plates 42 are vertically arranged in the casing 41. The heat storage plate 42 is hingedly mounted on the casing 41. The heat storage plate 42 is filled with a phase-change material, and after the daily bath is finished, the excess hot water generated by the heat pump unit is stored in the phase-change water storage tank 4, in the hot water. The heat is transferred to the phase-change material in the phase-change water tank 4. When the hot water is prepared on the second day, the low-temperature water is introduced into the phase-change water tank 4, and the phase-change material solidifies and releases the heat stored on the previous day for heating the low-temperature water.

The sewage heat exchanger 7 includes a heat exchange plate 71, an inlet pipe 72, an outlet pipe 73 and a strip plate 74, which are uniformly fixed to the lower surface of the strip plate 74 and the upper surface of the heat exchanger plate 71. The inlet pipe 72 and the outlet pipe 73 are fixedly mounted on the left and right sides, respectively, and the inlet pipe 72 and the outlet pipe 73 are connected to the inner cavity of the heat exchanger plate 71 and the water source tank 1, and the sewage heat exchanger 7 is made of a nonmetallic main material and added. The nonmetallic heat-conducting material has characteristics of being non-corrosive, antimicrobial, etc., on the basis of ensuring heat conduction. The inlet pipe 72 and the outlet pipe 73 are circular, high in strength, good in pressure; and the external heat exchange surface is circular, which increased heat transfer area.

Working principle is as follows: When in use, the bathing wastewater in the floor drain of the bathroom is about 30 °C, discharged into the sewage tank 8 through the drain pipe 10, and the waste water after the bath is recovered by the sewage heat exchanger 7 to extract heat, and the bath wastewater discharged at about 8 °C is discharged. At the same time, the wet steam generated in the bath zone recovers the heat of the excess wet steam through the dehumidifying fan 11, heats the heat in the wet steam and the heat in the sewage, and heats the tap water of the heat pump. After the daily bathing, the excess hot water generated by the heat pump unit is stored in the phase-change water storage tank 4, and the heat in the hot water is transferred to the phase-change material in the phase-change water tank 4, and when the hot water is prepared on the second day, the low-temperature water is introduced into the phase-change water tank 4, and the phase-change material solidifies to release the heat stored on the previous day for heating the low-temperature water.

The system uses the sewage heat exchanger and the wastewater–exhaust gas dual-source heat pump to extract and recover a large amount of waste heat from the bathing wastewater for the high temperature and instantaneous water discharge of the university bath wastewater. In view of the characteristics of water concentration, the phase-change material is added to the hot water storage tank to store excess heat generated by the heat pump for preheating of the bath water on the second working day.

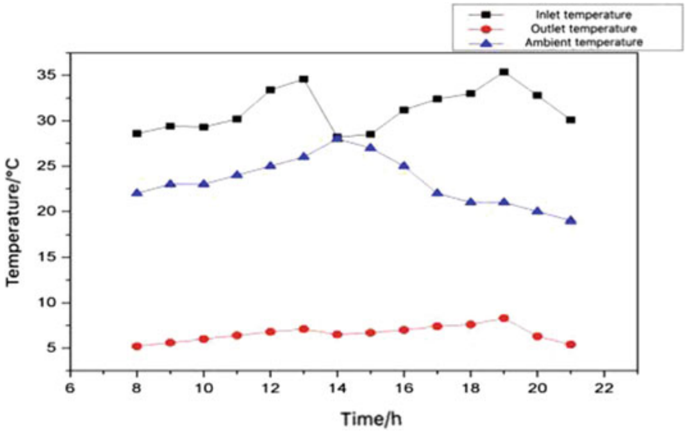

Fig. 4 Bathing wastewater inlet and outlet and changes in ambient temperature

It can meet the requirements of normal bath water preparation and meet the expected waste heat recovery effect. In order to obtain the system waste heat utilization rate, it is necessary to master the heat contained in the bath water and wastewater (Fig. 4).

System waste heat utilization formula:

$$\Theta = \frac{Q_r}{Q_t} \times 100\% \quad \text{(Ambient temperature is } 0\,^\circ\text{C)}$$

Θ Waste heat recovery
Q_r Recycling waste heat
Q_t Total waste heat from bathing wastewater

among them:

$$Q_r = \int_{T2}^{T1} m_g c_p T \, dT + m_{\text{Wet steam}} r_{\text{Condensation phase transition}} \times \text{Phase change ratio}$$

$$Q_t = \int_{0}^{T1} m_g c_p T \, dT$$

4 Discussion and Conclusions

In the process of selecting each link equipment and designing the system, it is found that the following deficiencies of the system have yet to be resolved:

(1) Sewage heat exchangers are required to use corrosion-resistant materials to facilitate the application of corrosive fluids. However, the immersed heat exchanger is not sensitive enough to the change in working conditions, the heat transfer coefficient is low, and the volume is large, so the volume of the sewage pool is required to be large, which is its fundamental weakness.
(2) The wet steam heat recovery of the heat pump evaporator is prone to severe heat loss, and the surface of the transportation pipeline is prone to frost formation.
(3) The selection of the solidification point of the phase-change material in the phase-change hot water tank is more important and should be slightly lower than the bathing hot water temperature produced by the heat pump.

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