A design of multilevel utilization system for thermal energy of wastewater based on ORC

Xuetao Liu, Weigang Zheng*  
1 School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, Hubei, 430063, China  
2 School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan, Hubei, 430070, China  
* Corresponding author’s e-mail: 1209704579@qq.com

Abstract In allusion to a systematic test for the ordinary bathing system: the temperature of outflow is about 40℃, but the waste water has an average temperature of about 36℃, so we can know the use rate is just 16.7%, and the rest heat is let out. There is research finds that ORC is the best way to promote the use rate. Look into the case from the first law of thermodynamics. If we use one type or two types of pure refrigerants such as R123, R600a, R600 and mix at free percentage, the products are the fittest for the temperatures from 30℃ to 100℃ in the bathroom. Under the circumstances in nowadays bathroom, the multi-level energy exploitation system based on ORC can promote the heat use rate from waste water to 25%, and the mixed refrigerants have superiorities in the heat utilization of ORC system.

1. Introduction  
Along with the civilization of human society, energy problem is more and more concerned by society. The exhaustion of resources and the deterioration of environment are becoming more and more serious. The establishment of the sustainable development mode of national economy and the stable system of natural environment has become an urgent task in the progress of human civilization. Therefore, how to use energy efficiently, develop new energy and recycle energy has become the main research direction of the world researchers.  

At present, there are a lot of waste heat resources in the world which have not been properly used. Thermal energy is one of them.  

Hot water is destructive to the ecological balance of water. According to the national regulations on sewage discharge, the discharge temperature of sewage shall not be higher than 35℃. However, the average temperature of the waste water in most of the bath centers is higher than the prescribed 35℃, and the heat utilization rate is only about 16.7%. The remaining heat is lost in the air due to the direct discharge of waste water. As a result, large amounts of waste heat can be used in large bath centers. The potential of recycling heat energy is great, and the benefits are remarkable.

The common methods of waste water treatment in bath centers are based on the pollutants (human fur and its secretions, synthetic detergents, spices, fungi and viruses, etc.) contained in waste water. The thermal energy contained in waste water is not utilized.

The common methods of waste water treatment in bath centers mainly focus on handling the pollutants (human fur and its secretions, synthetic detergents, spices, fungi and viruses, etc.) contained in the waste water. The thermal energy contained in waste water is not utilized.

Considering that the flow of bath wastewater is pretty large, the optimization of energy saving and
consumption reduction as well as the cascade utilization of the remaining energy can be realized if the existing energy system is reformed. The ORC system described in this paper carries out waste water recovery and heat treatment in the bath centers, which significantly improves the recycling and utilization of waste water thermal energy, meanwhile protecting the environment. This system can effectively improve people's living standards and transform household waste water into resources.

Using one of R123, R600a and R600 or any proportion of two or more of them as working mediums, a multistage utilization system of wastewater thermal energy based on Rankine's cycle is designed to fit in the special environment (temperature, flowrate, etc.) of bathrooms. The changing condition of the thermal efficiency of ORC system would be studied under the temperature between 30 ℃ to 60 ℃.

2. Multi-stage utilization system of wastewater’s thermal energy based on Rankine Cycle

2.1 Multi-stage utilization of thermal energy in bathroom wastewater by ORC system

Starting from the field study, pipeline lines of many bath centers are investigated, and a simplified design of the ORC system, which can be widely applied to the multi-stage utilization of thermal energy of bathroom wastewater, is shown in Figure 1, including evaporator C (1), evaporator B (2), expansion machine (3), steam engine (4), pump (5), condenser (6) and evaporator A (7). The features are as follows: evaporator A (7) and evaporator B (2) are installed successively in the flue at the end of the boiler, and evaporator C (1) is laid under the bathroom. Cold water (9) first passes through evaporator A (7), and secondary warm water (11) will flow out after the first grade of wastewater (13) is heated. The condenser (6) flows out of the first grade of warm water (10) by releasing the heat in recycled mass through condensation. First grade of warm water (10) flows into the evaporator C (1) and is heated by the first-grade wastewater (13). The first-grade wastewater (13) becomes secondary wastewater (16) and is discharged. Liquid recycled mass (14) flows into evaporator B (2) in turns through the pump (5), absorbs waste heat and changes into gaseous recycled mass (12), which flows into the expansion machine. The steam engine (4) is driven by the expansion machine to generate electricity. After that, gaseous recycled mass flows through the condenser and exhales, and is converted into liquid recycled mass, which is stored and prepared for recycling. Finally, the hot water should be recycled into the boiler and mixed with cold water. After being reheated, it can be directly used for bathing. The waste heat collected in this part will be recycled in the form of energy stored in hot water.
2.2 Waste water circulation pipe line based on Rankine cycle

The boiler is used to heat cold water so that it is supplied with hot water for bathing. The waste heat recovery system mainly consists of circulation pipeline, evaporator, reservoir, condenser and pump. The evaporator, steam turbine, condenser and pump constitute the ORC system. The incoming cold water first condenses the recycled mass through the condenser in the ORC system, and the cold water is heated in first grade. The cold water then flows into the first-stage evaporator, absorbing the high-grade energy from the boiler's exhaust gas, and the cold water is then heated in second grade. At this point, the temperature of the warm water is close to 35°C. Finally, the warm water is heated in third grade, which means heating by boiler, and it can be used for bathing. The medium-temperature gas obtained from the first-grade bath wastewater is connected to the ORC system through the evaporator, to utilize the hot water.
At the same time, the circulation absorbs low-grade waste heat and the media circulates after vaporization. At last, the generator is driven by the steam turbine, and after certain adjustment, the stable current is generated. The energy is stored in the battery, and then the power is respectively connected with the lighting system and exhaust ventilation system of the bathhouse, so as to be used by the bathhouse itself. The waste heat collected in this part is recycled in the form of electrical energy.

3. ORC system under the temperature between 30℃ and 60℃ (in general bath centers)

3.1 selection of working medium
Considering the specific situation of general bath centers, we select three working mediums R245ea, R600a and R600 to compare:

![Variations of system efficiency with turbine-inlet temperature.](image1)

![Variations of the waste heat final temperature with turbine-inlet temperature.](image2)

![Variations of the power output with turbine-inlet temperature](image3)
3.2 ORC system state analysis

The ORC system of coupled heat source is used in the multi-stage utilization system of waste water thermal energy based on Rankine cycle (As shown in Fig. 1).

According to the ORC thermodynamics research method of coupled heat source, the system state is analyzed as follows:

1) The net output work of the system is the work in adiabatic expansion minus the work in adiabatic compression.

After passing through the condenser, the state point 1-2 represents the adiabatic expansion process, and the ORC output work is:

$$ W_{T-Z} = m(h_2 - h_1)\eta $$

2) After passing the evaporator a, b and c, the state point 4-5 represents the adiabatic compression process, and the output work of the working medium pump is:

$$ W_{p-Z} = \frac{m(h_5 - h_3)}{\eta} $$

In conclusion, the net output work of the system is:

$$ W_{net-z} = W_{T-Z} - W_{p-Z} $$

3) Heat absorption of the system is the sum of heat absorption of three evaporators:

$$ Q_o = m_{gas}(h_{gas, in} - h_{gas, out}) $$

4) Thermal efficiency of the system. According to the heat efficiency definition formula

$$ \eta = \frac{W}{Q} $$

the final thermal efficiency formula can be obtained:

$$ \eta_{sys-z} = \frac{W_{net-z}}{Q_{e-z}} $$

When the heat absorption Q (waste heat recycled by the system is $Q_{e-z}$) is fixed, the thermal efficiency directly reflects the work capacity of the system.

In allusion to the special condition of the bathroom, the following assumptions are made:

1) Assume that the refrigerant pressure drop in the evaporator and condenser is constant.
2) The evaporation temperature is 80 °C.
3) The evaporator and other mechanical efficiency were selected as 0.7 and the working medium pump efficiency as 0.8.

Then substitute the corresponding working medium R245ea, R600a and R600 into the system, and the net output work of the system is 1219-3048.75 $kJ/kg$, and the heat absorption of the system is 4878-12195 $kJ/kg$. It is found that the maximum utilization rate of thermal energy of the system can
be increased to 25%, and the thermal efficiency of the system will be higher when the working medium is mixed.

4. Conclusions
Considering the current situation that the flow of bath wastewater is quite large, the existing energy system can be reformed to achieve the optimization of energy saving and consumption reduction as well as the cascade utilization of residual heat energy. Using one of R123, R600a and R600 or any proportion of two or more of them as working mediums, a multistage utilization system of wastewater thermal energy based on Rankine’s cycle is designed to fit in the special environment (temperature, flowrate, etc.) of bathrooms, as is shown in Fig. 1 and 2. Under the temperature between 30°C and 60°C, ORC system has significantly increased the recovery and utilization of wastewater thermal energy (heat utilization of hypothermal wastewater), which is energy-saving, economic and environment-friendly. Its maximum utilization rate of lost heat can be increased to 25%, which can effectively improve people's quality of life and transform urban wastewater into resource.

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