Case study: gas engine heat pump (GEHP) as a water heater applied in bathroom

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Abstract. This paper investigates the suitability of sewage source gas engine heat pump (SSGEHP) as a retrofit application for a public shower facility. The system performance is evaluated by primary energy ratio (PER) based on a practical example. The performance analysis indicates that the PER of SSGEHP varied in the range of 1.4 to 1.9, showing good potential in primary energy saving (as high as 69%) and emissions reduction compared to gas boiler system. It only needs 1.6 years to recover the initial investment by using the SSGEHP water heating system to reform existing the gas boiler. Therefore, the SSGEHP may be a promising retrofit scheme for the existing gas boilers.

1. Introduction
The rapid development of the economy and the improvement of people's living standards are based on a lot of energy consumption at present. Energy and environment are the world's two significant social problems [1]. In China, there are a lot of large-scale public shower facilities which are now facing retrofit due to their low energy efficiency as well as serious air pollution. Most bathrooms are open during fixed time periods, so the heat use and heat rejection are relatively concentrated. Considering that a great deal of heat is contained in the bathing wastewater, it will contribute a lot to energy conservation and environmental protection to recycle the exhaust heat [2]. Investigations on the potential of shower water heat recovery indicated that more than 50% of the shower wastewater heat can be recycled by a high-performance heat recovery device [3].

Heat pump technologies are widely utilized for the heating field due to the outstanding performance [4]. In recent years, the gas engine heat pump (GEHP) attracts increasing attention owing to its advantage of high efficiency [5]. Lazzarin and Noro [6] compared the efficiencies and total CO2 emissions between the GEHP system and gas boiler, and the results revealed that the annual overall efficiency of the GEHP system was about 1.75, much higher than 1.1 of the gas boiler. The total CO2 emissions of the GEHP system decreased by 54% and 39% when working in two heating circuits (40/30 °C, 60/40 °C heating circuit) than the gas boiler, respectively. Similarly, Yang et al. [7] presented the simulation and experiment of GEHP water heating using R134a as the refrigerant and indicated that GEHP reduced the operation cost and emission by 30-37% compared to the gas boiler.

In this study, a novel water heating system, sewage source gas engine heat pump (SSGEHP), is proposed to combine the advantages of high primary energy efficiency of gas-engine heat pump and the energy-saving potential of sewage heat recovery. The system configuration and control methods are presented in detail. Meanwhile, the performance of the SSGEHP under different conditions is simulated in this paper. In addition, the proposed SSGEHP system is compared with the conventional technologies
in order to evaluate the potential of energy-saving and environmental protection in public shower facilities.

2. System description

The schematic diagram of the SSGEHP water heating system is illustrated in Fig. 1. The system consists of three sections: the gas engine, the heat pump and the heat recovery system. In addition, a gas burner is included in the exhaust gas heat exchanger to heat tap water for the first user, and maintain hot water temperature in the heat storage tank (HST). Moreover, a filtering device is necessary between the sewage storage tank (SST) and the sewage heat exchanger (HE) due to a lot of impurities in the sewage [8].

At the operation period of the SSGHP, the sewage is pumped to the sewage HE for preheating the tap water. Then, the sewage flows from the sewage HE into the evaporator to release heat. Finally, sewage is discharged at low temperatures. In this condition, the tap water is heated in the sewage HE firstly, then it successively enters the heat pump unit condenser, gas engine unit jacket water HE and exhaust gas HE before entering the HST. In the process of heating water, tap water is heated with once heating mode.

3. Methodology

3.1. Basic information

A public bathroom in Tianjin area is analyzed in this study, which consists of 50 shower nozzles in total, with a flow rate of 0.067 L/s for each nozzle. The bathroom opening hour is from 13:40 to 21:00, and the maximum daily bathwater (45 °C) demand is 64 tons. The shower temperature in winter is between 41 and 44 °C, while that in summer is in the range of 38-42 °C. The temperature of waste drainage is 30-32 °C all year round, and the temperature of tap water is designed at 12 °C.

The SSGEHP water heating system is proposed as a retrofit scheme. All components of the SSGEHP water heating system, such as the gas engine, compressor, heat exchanger, etc., have been selected based on the heating demand. In addition, two conventional EHP water heating systems, “EHP+ electric heater” and “EHP+gas boiler” are studied for comparison. The initial design parameters of the public shower facility are shown in Table 1 and Table 2.
Table 1. Initial design parameters of public shower.

| Parameters | Value      | Remarks                                      |
|------------|------------|----------------------------------------------|
| \(m_f\)   | 3.35 L/s   | Designed for the maximum drainage volume    |
| \(m_p\)   | 3.35 L/s   | Designed for the maximum drainage volume    |
| \(t_f\)   | 45°C       |                                              |
| \(V_{HST}\)| 3 m³       |                                              |
| \(V_{SST}\)| 3 m³       |                                              |

Table 2. Initial design parameters of the SSGEHP system.

| Tap water Parameter | Sewage Parameter |
|---------------------|------------------|
| \(t_{f1}\)          | \(t_{p1}\)       |
| 12°C                | 30°C             |
| \(t_{f2}\)          | \(t_{p2}\)       |
| 25°C                | 17°C             |
| \(t_{f3}\)          | \(t_{p3}\)       |
| To be confirmed     | 5°C              |
| \(t_{f4}\)          |                  |
| 45°C                |                  |

The natural gas consumption rate was estimated using a typical natural gas heat value (34 MJ/m³). The natural gas price (2.8 yuan/m³) and electricity price (0.88 yuan/kWh) are chosen from the data of Tianjin province, China.

3.2. Model of the SSGEHP

An open-type screw compressor is used according to heat load. A simple and practical static characteristics model is obtained by fitting these experimental data of input power and refrigerant mass flow rate [9].

\[
P_{com} = E \cdot \sum_{i=0, j=0}^{3} c_{ij} \cdot t_e^i \cdot t_c^j
\]  

(1)

The temperature difference between evaporating temperature and the sewage temperature of evaporator outlet.

The temperature of the sewage side can be determined by energy equation in evaporator:

\[
Q_e = m_p \rho c_p (t_{p2} - m_{p3})
\]  

(2)

The temperature of the tap water side can be determined by energy equation in condenser:

\[
Q_c = m_f \rho c_p (t_{f2} - m_{f3})
\]  

(3)

Assuming that the input fuel energy to the gas engine is considered as 100%, and the heat recovery efficiency \(\theta_r\), engine efficiency \(\theta_m\) and losses \(\theta_i\) are balanced based on their percentage share for the engine at a given point, which is 30%, 55%, 15% respectively [10]:

\[
\theta_m + \theta_r + \theta_i = 1
\]  

(4)

The efficiency of gas engine is related by:

\[
Q_{gas} = P_{com}/\theta_m
\]  

(5)

The total heat output includes the condenser heat of heat pump \(Q_c\), the heat recovered from the gas engine \(Q_r\) and the heat recovered by the sewage HE \(Q_s\):

\[
Q_{total} = Q_c + Q_r + Q_s
\]  

(6)

The primary energy ratio is calculated as:

\[
PER = (Q_c + Q_r)/Q_{gas}
\]  

(7)

According to Equations (7) to (10), the power of natural gas consumption \(Q_{gas}\) is 152 kW. The heat
capacity of gas engine exhaust heat $Q_t$ and SSGEHP system $Q_{total}$ are 83.6 kW and 479.6 kW respectively. Consequently, the outlet temperature of the tap water from the exhaust gas HE is 46.2 °C, and the PER of the SSGEHP water heating system can be as high as 1.9.

4. Energy performance analysis of the SSGEHP

4.1. Effect of the sewage flow rate

In the operation process of the SSGEHP water heating system, the sewage flow rate is changeable. The sewage drainage temperatures ($t_{f3}$) is 5 °C, and the tap water flow rate ($m_{f}$) is identical with the sewage flow rate ($m_{p}$). In order to study the influence of sewage flow rate on performance, PER of the SSGEHP at different sewage flow rate is simulated.

Fig. 2 indicates the influence of sewage flow rate on PER of the SSGEHP system. The PER of simulation increases by 36% when the sewage flow rate increase from 2.0 to 3.5 L/s. When the water flow rate is lower than the design flow rate (3.5 L/s), the load of the compressor is lower than the rated value. The efficiency of the compressor is reduced at a lower load. Therefore, when the heat pump system operates at partial load using, the engine should be adjusted by variable speed to keep the compressor at a higher efficiency.

Fig. 2. Performance of the SSGEHP water heating system versus sewage flow rate.

4.2. The comparison of different retrofit schemes

The SSGEHP performance has been compared with the conventional technologies such as gas boiler, “electrical heat pump (EHP)+gas boiler” and “EHP+electric heater”. The supplied hot water temperature is set as 45 °C and condensing temperature is designed as 45 °C. In the three schemes, the design parameters of the heat pump unit are the same. The difference between the three systems is the heating method for tap water from the outlet of the condenser to HST, using an electric heater, gas boiler, and the gas engine exhaust heat respectively. The thermal efficiency of the gas boiler and is taken as 90%. The operating time every year of the public shower facility is taken as 300 days.

| Energy          | Gas boiler | EHP+ electrical heater | EHP+ gas boiler | SSGEHP |
|-----------------|------------|------------------------|----------------|--------|
| Electricity     | -          | 214,606                | 72,960         | -      |
| Natural gas     | 87,108     | -                      | 16,664         | 27,104 |
| Primary energy (natural gas) | 87,108     | 45,446                 | 32,115         | 27,104 |
| Primary energy saving (%) | -          | 48                     | 63             | 69     |

Note: the units of electricity and natural gas are kWh and m³, respectively.

Table 3 shows the energy consumption per year of each system. It can be seen that the “EHP+electric heater” consumes 214,606 kWh electricity. Assuming that the power generation
efficiency is 50% for gas power plant, it needs natural gas of 45,446 m³ totally. The scheme of the “EHP+gas boiler” requires 72,960 kWh electricity and 16,664 m³ natural gas, which amounts to natural gas of 32,115 m³. All these three schemes show good potential in terms of 48%, 63%, 69% primary energy saving respectively.

5. Economic and emission comparison

5.1. Economic analysis

The initial cost and operating cost are compared in this study. Combining the equipment investment and installation cost, the initial cost for the three schemes is demonstrated in Fig. 3. With the same amount of hot water provided, the ranking of the initial cost is: “EHP+electric heater” < “EHP+gas boiler” < SSGEHP. Due to the extra equipment is necessary for SSGEHP, such as gas engine, engine cylinder heat exchanger and gas burner, the initial cost of the SSGEHP system is slightly higher than that of EHP systems.

![Fig. 3. Comparison of initial costs of the three schemes](image)

Fig. 3. Comparison of initial costs of the three schemes

Fig. 4 shows the operating cost for the estimated 10 years of service of these systems (initial cost + operating cost × 10). It should be noticed that the total cost of the gas boiler is the highest whereas that of the SSGEHP is the lowest. Although the initial cost of the “EHP+ electric heater” system is lower than the other two retrofit schemes, its total cost increment is faster. The reason is that the price of electricity, which is high-grade energy, is much higher than the price of natural gas when considering the heating costs. Additionally, for the SSGEHP water heating system used to reform the existing gas boiler, the payback period is estimated to be 1.6 years. In conclusion, the SSGEHP is more financially advantageous over other conventional water heating methods, due to its low overall operating cost and significant energy-saving performance.

![Fig. 4. Comparison of total cost in the estimated years.](image)
5.2. Emission reduction analysis
Carbon emissions are calculated according to the natural gas carbon emission factors released by the Chinese Academy of Engineering, which is 0.41 kg(c)/kg (tce) [11]. In addition, the number of pollutant emissions, such as soot, SOx and NOx, can be calculated respectively according to Ref. [12]. Table 4 shows the annual emission amounts of various pollutants. All these three retrofit schemes are able to save operating costs and reduce pollutant emissions. It is worth noticing that the SSGEHP has the greatest reduction of pollutant emissions due to its high PER. It can be concluded that the SSGEHP is the most environmentally friendly scheme with the minimum consumption of natural gas, as well as the least emission of CO2 and pollutants.

| Systems          | Annual energy input (m³) | Soot (kg) | SOx (kg) | NOx (kg) | CO₂ (kg) | Emission saving (%) |
|------------------|--------------------------|-----------|----------|----------|----------|---------------------|
| Gas boiler       | 87,108                   | 20.9      | 8.7      | 54.9     | 152.2    | -                   |
| EHP+electric heater | 45,446                  | 10.9      | 4.5      | 28.6     | 79.4     | 48                  |
| EHP+gas boiler   | 32,115                   | 7.7       | 3.2      | 20.2     | 56.1     | 63                  |
| SSGEHP           | 27,104                   | 6.5       | 2.7      | 17.1     | 47.3     | 69                  |

6. Conclusions
In this paper, a sewage source gas engine heat pump (SSGEHP) water heating system is designed and analyzed as a retrofit scheme for a public shower facility. The primary energy-saving and emission-saving of the EHP+electric heater, EHP+gas boiler and SSGEHP have been analyzed. Compared to the existing gas boiler, all these three retrofit schemes show good potential in terms of 48%, 63%, 69% primary energy-saving respectively. The SSGEHP is able to save annual operating costs by 55–64%. It only needs 1.6 years to recover the initial investment by using the SSGEHP water heating system. Therefore, the SSGEHP may be a promising retrofit scheme for the existing gas boilers.

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