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Experimental study on an absorption heat pump prototype applied for rural residential heating

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Abstract

In order to replace the inefficient and polluting boilers, an ammonia-water absorption heat pump prototype is proposed for rural residential heating. The prototype can be driven by the combustion of biogas that is widely available in rural areas. Experimental investigations are carried out to analyze its performance under different working conditions. During the experiment, the prototype works with an electric oil heater which simulates the biogas burner in real applications, and uses conduction oil as the heating medium. Experimental results indicate that at the ambient temperature of -5 °C, the prototype can provide 25 kW heating capacity and the supply water temperature is 50 °C, with the coefficient of performance and primary energy efficiency of 1.37 and 1.14, respectively. By introducing the intermediate process, 2.39 kW exhaust heat is recovered, and the exhaust heat temperature is reduced to 41.3 °C. Moreover, the primary energy efficiency of the proposed system is still greater than 1 even when the ambient temperature is reduced to -10 °C, showing an obviously better performance than that of the conventional boiler.

Keywords: absorption heat pump; residential heating; biomass energy; exhaust heat recovery; experimental study.

1. Introduction

In China, buildings consume a large amount of energy, which occupies about 24% of the total energy consumption [1], and this number is expected to gain further enhancement considering the improving living standard [2], especially in rural areas where over 40% of the nation's whole population live in. Among the building energy consumption, residential heating systems account for over 20% [3]. At present, most of these heating systems are coal-fired boilers in rural areas of China, which produce a huge amount of aerosol and contaminant that is the main source of air pollution. Even worse, the primary energy efficiencies (PEEs) of the boilers are very low, ranging from 0.8 to 0.9. In order to meet the demand of energy conservation, emission reduction and environmental protection, more efficient and environmental friendly heating technologies haven been proposed to replace the boiler systems. Among these, absorption heat pump (AHP) is outstanding because of its higher primary energy efficiency. Conventional AHP systems use high-grade combustion heat of fossil fuels or waste heat of the industrial areas as the driving force, recover additional low-grade heat from the ambient (mainly including air and ground), and produce intermediate-grade heat for water heating, ranging from 40 °C to 100 °C.

The single-effect AHP systems applied for residential heating have been studied extensively. Some articles analyzed systems that are driven by the heat network, and a ground-source AHP [4] was analyzed for residential heating. The results showed that it was more efficient than the compression heat pump (CHP). Further studies [5] demonstrated that the AHP system has an energy efficiency that is 54% higher than that of the conventional

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heating systems based on boilers. Wu et al. [6] proposed a water-source AHP system to provide 45 °C water for district heating. Experimental study indicated that as the evaporation temperature is -10 °C, the COP is 1.2. Nitkiewicz et al. [7] compared the performance of a CHP, an AHP, and a gas-fired boiler. Results showed that the heating plant using ground-source AHP system had a much lower eco-indicator and environmental impact than those of the CHP and boiler. Li et al. [8] used an AHP to utilize heat from a heat network, and found that both the heating capacity and PEE were enhanced by recovering the low-grade renewable energy. Besides, the coal and power consumption was reduced significantly, and thus the operating cost became relatively lower. Other papers focused on directly gas-fired systems, and an AHP system that could provide hot water above 57 °C was proposed [9], and theoretical studies showed that the COP was 1.74 as the ambient temperature was about 20 °C. At the similar ambient temperature, an AHP prototype [10] could provide 45 °C hot water and the COP was 1.63. Baig et. al. [11] tested the performance of an AHP prototype. It was shown that when the ambient temperature was -5 °C, the PEE was above 1, which was higher than that of the conventional boiler. However, as the ambient temperature went down to -5 °C, the PEE decreased sharply below 1.

Although the traditional single effect AHP system is an efficient district heating method, its performance decreases obviously under low ambient temperature, which limits its application in cold areas [12]. Besides, no matter it is directly gas-fired or utilizes heat from the heating network based on gas boiler (combustor), there is no effective recovery method of flue gas waste heat.

In this paper, an ammonia-water absorption heat pump prototype is proposed for rural residential heating. The prototype can be driven by the combustion of biogas that is widely available in rural areas. Experimental investigations are carried out to analyse its performance under different working conditions. During the experiment, the prototype works with an electric oil heater which simulates the biomass burner in real applications, and uses conduction oil as the heating medium. Intermediate process is introduced, and the prototype can utilize both the low-grade ambient heat and waste heat from biomass combustion through the evaporator and intermediate evaporator, respectively.

2. System Structure

The rural residential heating network based on the proposed AHP system is shown in Fig. 1. The driving heat is generated by the combustion of biogas that comes from the biogas digester, and heat conduction oil is used as the heating medium to transform heat from the combustor to the generator. Return water from the heat consumer is heated in sequence through the rectifier, condenser and absorber, with its temperature increases gradually, and then the heated water is supplied to the heat consumer. A higher PEE is obtained because of the ambient heat, including air- and ground-source, recovered in the evaporator, and waste heat of exhaust gas recovered in the intermediate evaporator [13].

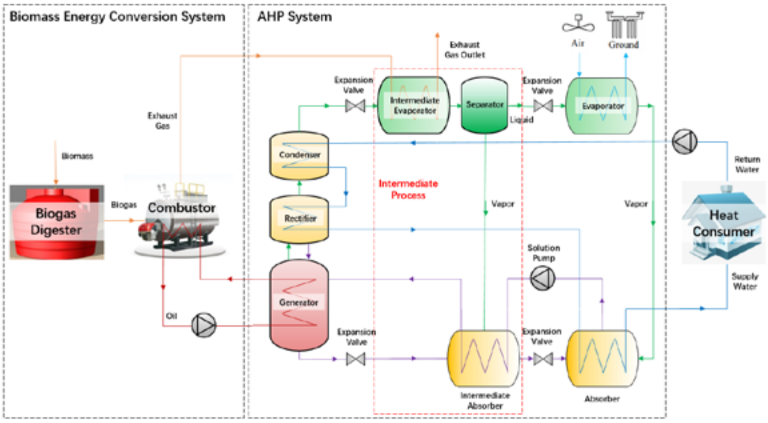
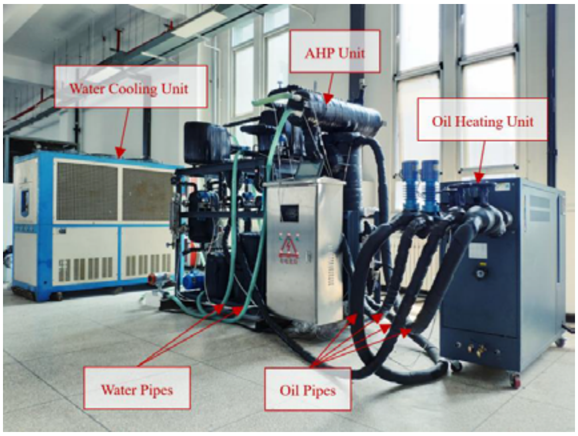


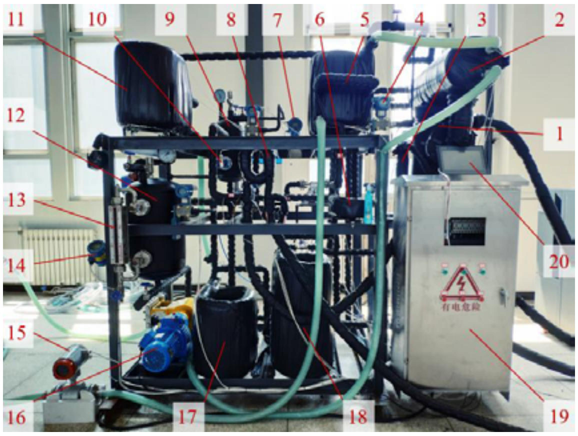
Fig. 1. Residential heating network based on AHP system.

The proposed AHP system has the intermediate process. Exhaust gas from the biomass combustor enters the intermediate evaporator and the waste heat is recovered in the intermediate evaporator, where partial ammonia evaporation happens. The ammonia two-phase flow enters the separator, and the liquid and vapour flows to the evaporator and intermediate absorber, respectively. The vapour is absorbed by the weak solution from the generator, and the heat from the intermediate absorption process is recovered by the pressurized strong solution. The above process occurs at the intermediate pressure between the system high pressure and low pressure. The additional intermediate pressure can reduce the degradation of system performance due to the large pressure difference at the low ambient temperature. In addition, the introduction of intermediate processes has two additional benefits: lower waste heat discharge temperature and improved internal heat recovery.

Based on the previous simulation studies [40], an experimental prototype system of residential heating is designed and built, as is shown in Fig. 2(a). The system contains three units: the oil heating unit, the water cooling unit and the AHP unit. The oil heating unit is an electric oil heater (simulating the biogas combustor), which heats the oil to the target temperature and delivers it to the generator of the AHP unit through the oil pipes; the water cooling unit is a water chiller (simulating the heat consumer), which cools the supply water down to the target return water temperature and delivers it to the AHP unit through the water pipes. The structure of the AHP unit is shown in Fig. 2(b).



(a) Three units of the experimental prototype system.



(b) Structure of the AHP unit.

1-Generator, 2-Rectifier, 3-Solution preheater, 4-Pressure transmitter, 5-Condenser, 6-Subcooler, 7-Mass flowmeter, 8-Intermediate evaporator, 9-Separater, 10-Temperature transmitter, 11-Evaporator, 12-Solution tank, 13-Content gauge, 14-Concentration meter, 15-Volume flowmeter, 16-Solution pump, 17-Absorber, 18-Intermediate absorber, 19- Electric control cabinet, 20-Display panel.

Fig. 2. Experimental prototype system of residential heating.

3. Calculation Method

3.1. Calculation of the generation heat Q_G

The generation heat Q_G is defined as the enthalpy difference between heat conduction oil inlet and outlet of the generator. It is calculated based on Eq. (1):

$$Q_G = m_{OG} \cdot c_{p,O} \cdot \Delta T_{OG} = \rho_O \cdot V_{OG} \cdot c_{p,O} \cdot \left(T_{OG,in} - T_{OG,out}\right) \tag{1}$$

where m_{OG} and V_{OG} are the mass and volume flow rates of the heat conduction oil through the generator; ρ_O and $c_{p,O}$ are the linear mean values of its density and specific heat, considering that they both change with temperature.

3.2. Calculation of the recovered exhaust heat Q_{WH}

The recovered exhaust heat Q_{EH} consists of two parts: waste heat recovered in the solution preheater Q_{SP} and waste heat recovered in the intermediate evaporator Q_{IE}. They are calculated based on Eqs. (2) ~ (4):

$$Q_{SP} = m_{OIE} \cdot c_{p,O} \cdot \Delta T_{OSP} = \rho_O \cdot V_{OIE} \cdot c_{p,O} \cdot \left(T_{OSP,in} - T_{OSP,out}\right) \tag{2}$$

$$Q_{IE} = m_{OIE} \cdot c_{p,O} \cdot \Delta T_{OIE} = \rho_O \cdot V_{OIE} \cdot c_{p,O} \cdot \left(T_{OIE,in} - T_{OIE,out}\right) \tag{3}$$

$$Q_{EH} = Q_{SP} + Q_{IE} = \rho_O \cdot V_{OIE} \cdot c_{p,O} \cdot \left(T_{WH,in} - T_{WH,out}\right) \tag{4}$$

where m_{OIE} and V_{OIE} are the mass and volume flow rates of the heat conduction oil through the intermediate evaporator; $T_{OSP,in}$ and $T_{OSP,out}$ are the oil inlet and outlet temperatures of the solution preheater, and $T_{OSP,in}$ is equal to $T_{WH,in}$; $T_{OIE,in}$ and $T_{OIE,out}$ are the oil inlet and outlet temperatures of the intermediate evaporator, and $T_{OIE,out}$ is equal to $T_{WH,out}$.

3.3. Calculation of the heating capacity Q_{HC}

In the experimental prototype, the return water passes through the condenser, rectifier and absorber, and are heated to the target temperature. Therefore, the heating capacity Q_{HC} consists of three parts: condensation heat Q_C, rectification heat Q_R and absorption heat Q_A. They are calculated based on Eqs. (5) ~ (8) [14]:

$$Q_C = m_W \cdot c_{p,W} \cdot \Delta T_{WC} = \rho_W \cdot V_W \cdot c_{p,W} \cdot \left(T_{WC,out} - T_{WC,in}\right) \tag{5}$$

$$Q_R = m_W \cdot c_{p,W} \cdot \Delta T_{WR} = \rho_W \cdot V_W \cdot c_{p,W} \cdot \left(T_{WR,out} - T_{WR,in}\right) \tag{6}$$

$$Q_A = m_W \cdot c_{p,W} \cdot \Delta T_{WA} = \rho_W \cdot V_W \cdot c_{p,W} \cdot \left(T_{WA,out} - T_{WA,in}\right) \tag{7}$$

$$Q_{HC} = Q_C + Q_R + Q_A = \rho_W \cdot V_W \cdot c_{p,W} \cdot \left(T_{SW} - T_{RW}\right) \tag{8}$$

where m_W and V_W are the mass and volume flow rates of the circulating water; ρ_W and $c_{p,W}$ are its density and specific heat; $T_{WC,in}$ and $T_{WC,out}$ are the water inlet and outlet temperatures of the condenser; $T_{WR,in}$ and $T_{WR,out}$ are the water inlet and outlet temperatures of the rectifier; $T_{WA,in}$ and $T_{WA,out}$ are the water inlet and outlet temperatures of the absorber; T_{SW} and T_{RW} are the supply water and return water temperatures, T_{SW} is equal to $T_{WA,out}$, and T_{RW} is equal to $T_{WC,in}$.

3.4. Calculation of the heating efficiency COP and PEE

The experimental prototype has two heating efficiency indexes: the coefficient of performance COP and the primary energy efficiency PEE, which are calculated based on Eq. (9) and (10):

$$\mathrm{COP} = \frac{Q_{HC}}{Q_G + W_P} \tag{9}$$

$$\mathrm{PEE} = \frac{Q_{HC}}{Q_G / \eta_C + W_P / \eta_E} \approx \frac{Q_{HC}}{Q_G + Q_{EH} + W_P / \eta_E} \tag{10}$$

where W_P is the pump work; η_C is the efficiency of the combustor; η_E is the efficiency of electricity generation, which is around 33% [2]; Q_G / η_C is the calorific value of the natural gas, and is approximately equal to the combustion heat plus flue gas waste heat: $Q_G / \eta_C \approx Q_G + Q_{EH}$ [13].

4. Results and Discussion

4.1. Performance under basic working condition

The performance of the experimental prototype system is studied under the basic working condition: the ambient temperature is about -5 °C, the oil inlet temperature is 180 °C, and the return water temperatures is 35 °C. Summary of experimental performance under the basic working condition is shown in Table 1. In the basic working condition, the return water passes in sequence through the condenser, rectifier and absorber, and its temperature increases to 40.0, 46.2 and 50.6 °C, respectively, when the flow rate is kept at 1.4 m^3/h. It is also shown that by introducing the intermediate process, 2.39 kW exhaust heat is recovered, and the exhaust heat temperature is reduced to 41.3 °C, which is lower than the dew point of the exhaust gas, indicating that the exhaust heat recovery is improved. Besides, the pressurized strong solution of 46.5 °C is first heated to 127.6 °C by recovering the intermediate absorption heat, and then it is further heated in the solution preheater into the two-phase flow, indicating that the internal heat recovery is improved. Moreover, the energy input and output of the AHP unit are 26.59 and 25.43 kW, respectively. Therefore, the heat loss is about 1.16 kW that is only 4.4% of the total energy input, indicating that the experimental prototype is in good energy balance. It is shown that when the evaporation temperature is -5 °C, the experimental prototype system can provide 25 kW heating capacity to heat the water from 35 °C to above 50 °C, and the COP and PEE are 1.37 and 1.14, respectively.

Table 1. Summary of experimental performance under basic working condition

	Components	Energy input (kW)		Energy output (kW)	
		Value	Uncertainty	Value	Uncertainty
Energy Transfer	Generator	18.13	±0.41	/	/
	Rectifier	/	/	6.45	±0.31
	Condenser	/	/	10.14	±0.47
	Evaporator	5.57	±0.35	/	/
	Intermediate Evaporator	1.54	±0.21	/	/
	Absorber	/	/	8.84	±0.42
	Solution Preheater	0.85	±0.05	/	/
	Solution Pump	0.50	±0.03	/	/
	Total	26.59	±0.57	25.43	±0.69
Performance Parameters	Parameters	Value		Uncertainty	
	Heating Capacity	25.43 kW		±0.69 kW	
	Recovered Exhaust Heat	2.39 kW		±0.07 kW	
	Supply Water Temperature	50.6 °C		±0.3	
	Exhaust Heat Temperature	41.3 °C		±0.3	
	COP	1.37		±0.05	
	PEE	1.14		±0.03	

4.2. Influence of the oil inlet temperature

The oil inlet temperature T_{OI} is an important working condition parameter of the absorption heat pump system, because of its effects on the generation process and system performance. Low T_{OI} cannot provide sufficient driving force for system operation, while high T_{OI} will cause huge exergy destruction in the heat transfer process. Some research shows that there is an optimal T_{OI}, and when the value continue goes up, the system performance will not improve or even degrade. This is also observed in this study, as is shown in Fig. 3. When T_{OI} increases from 165 to 186 °C, both COP and PEE increase rapidly at first till reach 1.61 and 1.32, respectively, and then remain nearly constant. The turning point happens when T_{OI} is about 175 °C.

For the exhaust heat temperature, it raises along with T_{OI}, but basically keeps between 39 and 42 °C. Moreover, the supply water temperature increases linearly from 54 to 59 °C when T_{OI} increases from 165 to 186 °C, and is expected to continue to raise when T_G further increases. Therefore, in order to obtain the target supply water temperature, the oil inlet temperature can be appropriately increased above the optimal value, at the cost of slightly reducing the COP.

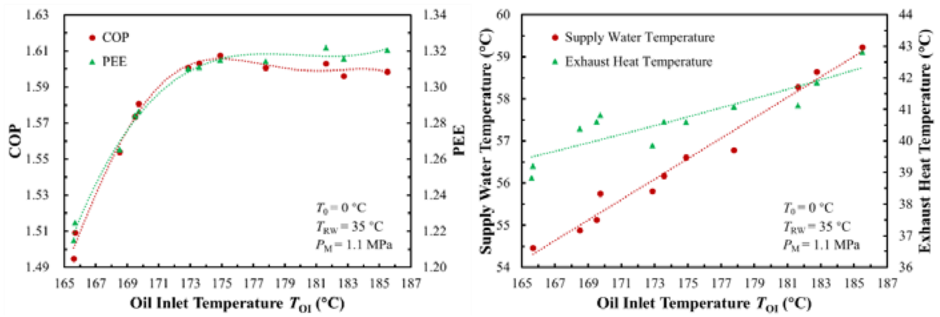


Fig. 3. Influence of the oil inlet temperature on the system performance

4.3. Influence of the ambient temperature

The ambient temperature T_0 has a huge influence on the evaporation process and thus the system performance. It is shown in Fig. 4 that as T_0 decreases from 5 °C to -10 °C, the heating capacity reduces from 30 kW to 22 kW, and the COP decreases from 1.60 to 1.25. The proposed system has a much higher primary energy efficiency than that of the conventional boiler, and it is higher than 1 even when the ambient temperature T_0 is reduced to -10 °C.

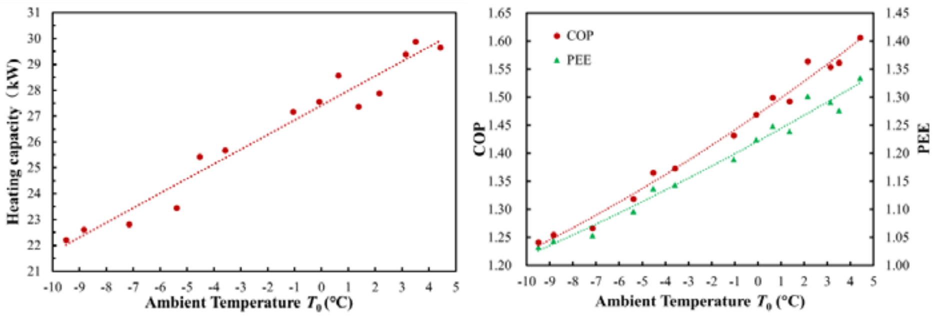


Fig. 4. Influence of the ambient temperature on the system performance

4.4. Influence of the return water temperature and water flow rate

The return water temperature T_{RW} has effects on almost all the processes of the AHP system, including the condensation, rectification, generation and absorption processes. If T_{RW} is high, the ammonia vapour becomes difficult to condense in the condenser and rectifier, and the system high pressure will increase, which has a negative effect on the generation process. Even worse, it also obstructs the absorption process since the absorption heat is hard to carry away. In the previous analysis, T_{RW} is fixed at 35 °C, which is a common return water temperature for most residential heating systems. However, it changes as the working condition deviates from the set state, such as the ambient temperature suddenly drops. Fig. 5 indicates that the system is quite sensitive to the return water temperature when the water flow rate V_W is fixed. It is shown that the COP drops linearly from 1.57 to 1.27, as T_{RW} increases from 30 to 40 °C. At the same time the supply water temperature T_{SW} raises from 46.6 to 52.3 °C. On the other hand, if the return water temperature T_{RW} is fixed, the COP will increase and the supply water temperature T_{SW} will decrease, as the water flow rate V_W raises, as is shown in Fig. 6. Therefore, if T_{RW} deviates from the set value, V_W can be adjusted accordingly to stabilize the system performance. More specifically, enlarge V_W if T_{RW} increases, and reduce V_W if T_{RW} decreases.

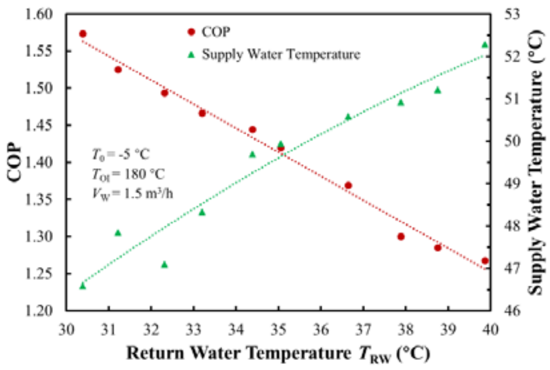


Fig. 5. Influence of the return water temperature on the system performance

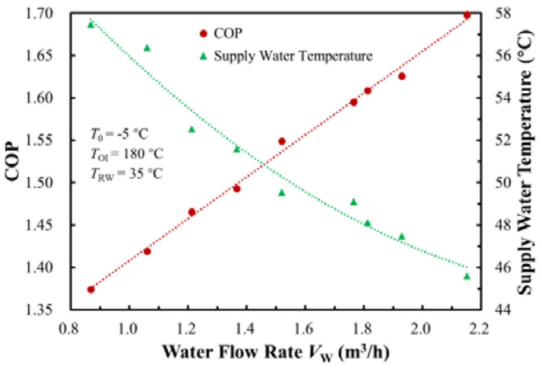


Fig. 6. Influence of the water flow rate on the system performance

4.5. Influence of the return water temperature and water flow rate

The intermediate pressure P_M is a key parameter of the proposed system, and its value influences both the waste heat recovery of the intermediate evaporator and the solution heat recovery of the intermediate absorber. Fig. 7 shows that as the intermediate pressure increases, the waste heat outlet temperature raises from 39 °C to 45 °C, indicating that the waste heat recovery is limited. It is probably because the enhanced intermediate pressure raises the intermediate evaporation temperature and thus increases the waste heat outlet temperature. On the other hand, a higher intermediate pressure causes a higher solution heat recovery outlet temperature of the intermediate absorber, indicating that the internal heat recovery is improved.

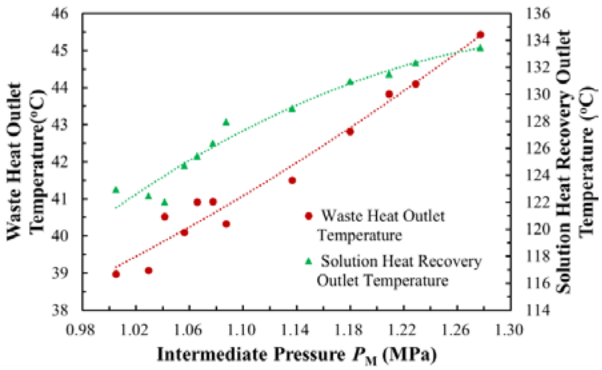


Fig. 7. Influence of the intermediate pressure on the system performance

5. Conclusions

In order to replace the inefficient and polluting boilers, an ammonia-water absorption heat pump prototype is proposed for rural residential heating. The prototype can be driven by the combustion of biogas that is widely available in rural areas. Experimental investigations are carried out to analyse its performance under different working conditions. During the experiment, the prototype works with an electric oil heater which simulates the biomass burner in real applications, and uses conduction oil as the heating medium. Several conclusions are drawn as following.

- When the ambient temperature is -5 °C and the oil inlet temperature is 180 °C, the experimental prototype system can provide 25 kW heating capacity to heat the water from 35 °C to above 50 °C, and the COP and PEE are 1.37 and 1.14, respectively.
- By introducing the intermediate process, 2.39 kW exhaust heat is recovered, and the exhaust heat temperature is reduced to 41.3 °C, which is lower than the dew point of the exhaust gas, indicating that the exhaust heat recovery is improved.
- When the oil inlet temperature increases, both COP and PEE increase rapidly at first, and then remain nearly constant. The turning point happens when the oil inlet temperature is about 175 °C.
- As the ambient temperature decreases from 5 °C to -10 °C, the heating capacity reduces from 30 kW to 22 kW, and the COP decreases from 1.60 to 1.25. The proposed system has a much higher primary energy efficiency PEE than the conventional boilers, and it is higher than 1 even when the ambient temperature is reduced to -10 °C.
- The COP drops and the supply water temperature raises as the return water temperature increases. On the other hand, the COP increases and the supply water temperature decreases as the water flow rate raises. Therefore, if the return water temperature deviates from the set value, the water flow rate can be adjusted accordingly to stabilize the system performance.
- As the intermediate pressure increases, the waste heat outlet temperature raises from 39 °C to 45 °C, indicating that the waste heat recovery is limited. On the other hand, a higher intermediate pressure causes a higher solution heat recovery outlet temperature of the intermediate absorber, indicating that the internal heat recovery is improved.

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