Performance Testing and Case Studies of Rural Household Biogas Micro-CHP Systems

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Abstract. Against the backdrop of clean rural heating and dual carbon targets, this paper investigates and develops a household combined heat and power (CHP) unit. The performance of the unit under natural gas operating conditions was tested and evaluated in the laboratory. The test results show that at rated operating conditions the unit has an electrical efficiency of 29% and an overall efficiency of 96%. The micro-CHP was then tested in a civil building in a demonstration site in Xuzhou, Jiangsu province, for trial operation under biogas working conditions. The test results show that when the unit in biogas working condition is heating the room, the unit has a rated working condition power generation of 3.2 KW and still has an average electrical efficiency of about 26.8% and a thermal efficiency of 65.6%, which remains at a high level. And the room temperature data shows that the heat supply meets the heating demand. Finally, this paper compares the performance with micro-CHP units available in the European and American markets. The results show that the performance of this unit is superior to many micro-CHP units available overseas. This paper demonstrates through test results that rural micro-CHP system can meet the daily energy needs of farmers, improve energy use efficiency and reduce carbon emissions.

1 Introduction

Chinese government committed that the carbon emission in China would reach the peak before 2030, and then different measures would be taken to neutralize all carbon emission before 2060. Among all kinds of energy consumption, the household energy consumption in rural area is becoming a nonnegligible part. The electricity consumption was growing fast, which rose from 2.62 kwh/m2 to 18.82 kwh /m2[1]. The growing need for electricity consumption reveals the unreasonable side of energy consumption structure in Chinese rural areas, which leads to the underuse of other kinds of energy, including biomass energy. It is a rich resource in rural areas and should be explored more sufficiently[2,3].

China has abundant biomass resources. Among all kinds of biomass energy, biogas has developed rapidly in rural area during recent decades and government has been introducing several policies in order to guarantee the development of related industries[4-7]. As for biogas power generation, China is still in the initial stage of using biogas to generate electricity, with an installed capacity of 500 million kilowatts of biogas grid-connected power generation[8]. With the above potential of biogas power generation in China reaching 196.32 billion kWh[9], the potential of biogas power generation is huge.

The combined heating and power(CHP) system reuse the waste heat when generating electricity so that both electricity and heat demand can be met. The CHP generators lower than 50KW are called micro-CHP generators. The household micro-CHP generators have been marketized and popularized in Europe and America. But in China, they lack of market and related research. Micro-CHP devices use biogas to meet the resident's need of electricity and thermal comfort. They can not only realize the energy cascade utilization, but also help solve the problems faced by the transmission-line system of electric power in rural areas[10-12]. More importantly, biogas will play a driving role in the target of carbon peaking and carbon neutralization.

So we develop the household biogas micro-CHP system. The electricity can meet the daily life need and the superfluous part can be sold to power grid company. The heat it produces can meet the basic heating and hot water demand. In this paper we first introduce a new type of micro-CHP unit. Then we will introduce the test result both in laboratory and on site of Jiangsu Xuzhou and compare it with the existing micro-CHP generators in foreign country.

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2 Materials and Methods

2.1 Introduction of micro-CHP unit

For the whole system, the micro-CHP unit is the core, and the grid and water tank are used as the auxiliary to provide electricity and heat to users. The system composition is as follows

Figure 1 The structure of micro-CHP

The unit is in front and rear compartment form. The front compartment is the electronic control part and the external operating console, as is shown in figure 1,2. The rear compartment is the main equipment of the unit, and the end of unit is the grid connection port and external signal access port. There is air inlets on the side of shell, where the air flows through the front compartment and then enters the rear cabin suction port. The unit uses fully enclosed structure, only the operating console of front compartment is open to users.

Figure 2 indicates how the unit is connected to the water tank and the location of each sensor arrangement during the laboratory test. The circulating water enters the unit and passes through the gas heat exchanger first, and then enters the plate heat exchanger for heat exchange with the antifreeze coolant. In this way the latent heat of vaporization of water in the flue gas can be recovered, which will maximize the thermal efficiency. The main component of the micro-CHP unit is shown in table 1.

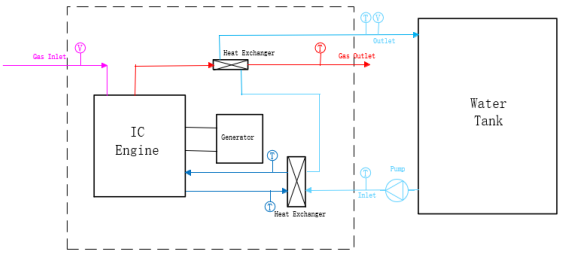

Figure 2 Diagram of the connection between micro-CHP unit and tank

Table 1 The testing instruments

Component	Brand	Type	Number
IC Engine	Chery	SQR272	1
Generator	Dingge	Air-cooling,5kW	1
Three-way catalyst	Custom	/	1
Tubular heat exchanger	Custom	/	1
Plate heat exchanger	Baode	2308704 BL14-16D	1

2.2 Introduction of laboratory test

The main focus of this paper is on power generation, heat recovery and total efficiency. Therefore, the main tests are as follows: the power generation of the micro cogeneration machine, the inlet and outlet water temperature of the machine, the inlet and outlet temperature of the plate exchanger, the exhaust temperature, the input gas flow rate, the inlet and outlet water flow rate of the machine, and the ambient temperature and humidity. The testing instruments are shown in table 2.

Table 2 The testing instruments

Test content	Instruments	Precision
Temperature	Pt100 Temperature sensors, Thermocouple temperature sensors	0.30+0.005
Gas flow rate	IVC-FA Intelligent Volume Corrector	0.1; ±0.5%
Water flow rate	LDG-SUP Electromagnetic heat meters	0.001; ±0.5%R
Power generation	100/5 Current transformers	/
Ambient temperature and humidity	Ximo PD-WDJ-04	0.1(℃); 1%(RH)

In order to better test the performance of the unit, the test is proposed to be conducted in two parts. The first part is Testing unit performance during islanded operation and the micro-CHP unit runs at 2.8kW, 3.1kW,3.5kW. The second part is testing unit performance during grid-connected operation and the unit runs at 2.8kW, 3.1kW,3.5kW. The unit runs at each load in three conditions, of which the outlet water temperature is 50, 60, 70℃. Three sets of data are recorded for each condition, and all of them need to be recorded after the micro-CHP unit maintains stable.

First, turn the key knob to the running gear, and then press Start to start the unit with the ignition. The unit is first in a 30S standby state, then enters a 30S high-speed warm-up state, and then enters normal operation. The outlet water temperature is adjusted by adjusting the inlet and outlet bypass valves, and the relevant data is recorded after the temperature is stabilized.

2.3 Introduction of on-site test

The site chosen for this demonstration is a office building in a biogas station in Tongshan District, Xuzhou City, Jiangsu Province. It is a centralized gas supply station in the Tongshan District. The methane content of the produced biogas is 50.854% and the outlet pressure of the biogas is 3kpa.

The ambient temperature for this test was approximately between 0-12 ℃ and the humidity was between 35% and 65%. The atmospheric pressure was approximately 100kPa. The equipment is placed on the first floor of the building, the water tank is placed on the second floor of the building, which are connected by vertical water pipes. The pumps on both sides are placed on the second floor return pipes and wall mounted radiators are placed in each room.

The micro-CHP system consists of the unit, water tank, desulphurization tank, dewatering tank, cache tank, water pump and end radiator. The unit, desulphurization and dewatering and cache tanks are located on the first floor of the building. The biogas passes through a dehydrator, desulphurization tank and gas skin meter before entering the cache tank, which is connected to the micro-CHP unit. The water inlet and outlet of the unit is connected to the water tank through a pp pipe and the pump is installed on the outlet side of the water tank. The water tank is placed on the first floor. The connection form of system is shown in figure 3. Radiators installed in each room, each radiator connected in parallel. Hydraulic balancing through the valve of return water ensures sufficient hot water flow on the least favorable loop. Major equipment is shown in table 3.

Table 3 The components of micro-CHP system

Equipment	Type	Precisions/Notes
Gas meter	RSC-W (NB-IoT) Membrane gas meters	0.001
Water meter	LXSG-20E AMICO hot water meter	0.0001
Thermometer in pipes	Pt100 Temperature sensors	/
Indoor Hygrometer	TR-76Ui-S High accuracy thermohydrometer	0.1(℃); 0.1%(RH)
Outdoor Hygrometer	TESTO625 High precision thermohydrometer	0.5(℃); 2.5%(RH)

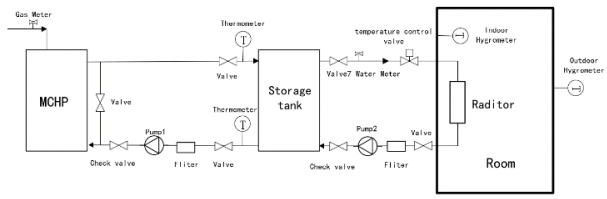

Figure 3 The connection of micro-CHP system

The test is divided into 2 main parts. The first part focuses on the electrical power and thermal efficiency of the unit under biogas conditions. The second part focuses on the unit's ability of continuous working, running according to established control logic and meeting indoor heat load.

3 Results & Discussion

3.1 Results pf laboratory test

The electrical efficiency, thermal efficiency and total efficiency of the unit will be the main evaluation criteria in the test results. The calculation is as follows:

$$\eta_e = \frac{Q}{qv} \tag{1}$$

In the formula, η_e is the electric efficiency, Q is the electric power of engine, q is calorific value of gas and v is flow rate of gas.

$$\eta_q = \frac{cm(t_1 - t_2)}{qv} \tag{2}$$

In the formula, η_q is the heat efficiency, c is the specific heat capacity of water, m is the mass flow rate of water,t1 and t2 is the temperature of outlet and inlet water, q is calorific value of gas and v is flow rate of gas.

The micro-CHP unit is running at a constant speed of 1500 rpm, and the data are shown in Table 4. From the table below, we can see that the electrical efficiency is basically stable between 23% and 25%, and the total efficiency is basically higher than 80%. The thermal efficiency is highly sensitive to the inlet water temperature. Taking the 3KW operating condition as an example, the thermal efficiency is close to 60% when the outlet water temperature is maintained near 50℃, while the thermal efficiency is only 52% when the outlet water temperature rises to near 70℃.

Table 4 The isolated network operation data

Power	Outlet temperature	Heat efficiency	Electric efficiency	Total efficiency
2.8kw	50	0.61	0.24	0.85
	60	0.59	0.24	0.83
	70	0.65	0.23	0.88
3kw	50	0.58	0.25	0.83
	60	0.57	0.25	0.82
	70	0.52	0.25	0.77
3.5kw	50	0.66	0.25	0.92
	60	0.60	0.26	0.85
	70	0.53	0.26	0.79

This is due to the fact that water and flue gas transfer heat first, so high water temperature is not conducive to the recovery of latent heat of gasification from vapor, and then the heat transfer effect will be greatly reduced. If the load and discharge water temperature are both high, it is difficult for the unit to reach a thermally stable condition. At this point the engine temperature rises rapidly, and the water temperature also soars rapidly, until the engine reaches 100 ℃ and is shutdown under protection. Therefore, the power generation and water temperature should be controlled moderately.

When the islanding test is completed, the grid-connected test is conducted. The total efficiency is the similar with the island operation, and is affected by the temperature of the inlet water. But the temperature difference between the inlet and outlet water temperatures has increased compared to the island operation mode, mainly because the temperature on the day of the grid connection test was lower than on the day of the island test. The higher heat load results in an increase in heat exchange between the hot water and the environment.

Based on the above data, the outlet temperature of the unit can be set at 60 degrees Celsius, at this time, the corresponding thermal, electrical and total efficiencies under grid-connected conditions are shown in Figure 4. The overall generation efficiency of the unit at rated operating conditions is at 29% and the overall efficiency is at 96%.

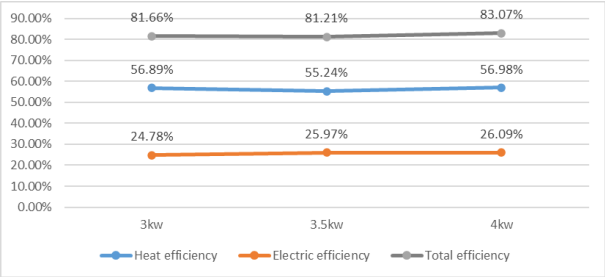

Figure 4 The thermal, electrical and total efficiencies under grid-connected conditions

3.2 Results of on-site test

To test the performance of the unit, the Micro-CHP power was set to 3.24kW. We started the machine and after idling at start-up and warming up at high speed, the unit maintained 1500 rpm. After 30mins in this state, the unit enters thermal equilibrium, at which point data recording begins. The low calorific value of biogas is 18.374 MJ/m3. When the outlet water temperature is maintained near 50°C, there is an electrical efficiency of 27%, a thermal efficiency of 68% and an overall efficiency of 95%. Exhaust temperatures are all around 50°C at this point. It was also found that the thermal efficiency was more sensitive to the humidity of the air. The higher humidity also leads to the higher thermal efficiency

When testing the operational stability of the unit, the inlet water temperature was set at around 60°C based on the results of laboratory tests. We turned the machine on and recorded a set of performance data after the system was stabilized. It run overnight after recording another set of performance data half an hour later. The next day at 8am a set of performance data and load side water meter data was recorded. The total supply and return water temperature on the load side was recorded at 59.8°C and 56.8°C at this time. Under the condition of 60°C discharge temperature and continuous operation, the efficiency of the unit still has an average electrical efficiency of 23% and an average total efficiency of 82%, which remains at a high level.

At this point the temperature load in the room reaches the heating requirement, as shown in figure 5. Temperatures in typical rooms were roughly above 14°C and all met the heating requirements. The bedroom temperature fluctuated around 14°C with an average of 14.4°C. The average temperature in the living room, on the other hand, was 13.6°C, probably due to the large window-to-wall ratio in the living room. For the average farmhouse, the window-to-wall ratio will be much smaller, and the thermal load on the building will be less. So the heat supply from the unit is sufficient.

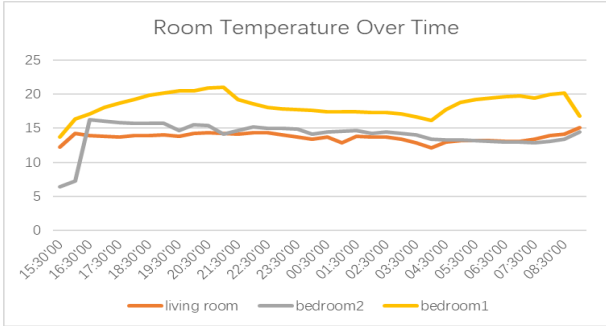

Figure 5 Room temperature over time

3.3 Comparison with similar unit

Bernd Thomas[13,14] evaluate the performance of existing Micro-CHP units at Reutlingen University. The result shows that electrical efficiency of the generators are all around 25% and the overall efficiency differ from 84% to 99%. The electrical efficiency at full power is around 31% and the total efficiency is around 94%, according to DIN4709 test standard. Zachary Taie[15,16] conducted performance test on Honda Ecowill and Marathon Ecopower. The electrical efficiency of Honda Ecowill was about 23.5% and the overall efficiency was about 74.5%. The Marathon Ecopower was tested at different electricity output ranges, which differed from 1 to 4.5 Kwe. The electrical efficiency of Marathon Ecopower was about 24.4% and the overall efficiency was about 94.5% when the outlet water temperature was about 70 ℃. Antonio Rosato[17] have carried out several experimental tests on an AISIN SEIKI (model GECC60A2) natural gas fueled reciprocating internal combustion engine. The electrical efficiency of GECC60A2 (NR-P） was about 28.8% and the overall efficiency was about 85%.

From the point of view of electrical efficiency, the micro-CHP unit is only inferior to the SenerTec "Dachs" GECC60A2 (NR-P) in the kilowatt class, and the difference is not significant. The efficiency of the various units is therefore compared uniformly when converted to an average temperature of 40-45°C and operating at full load. The electric efficiency is shown in figure 6. The red indicates the device of this paper, all others are foreign comparison devices.

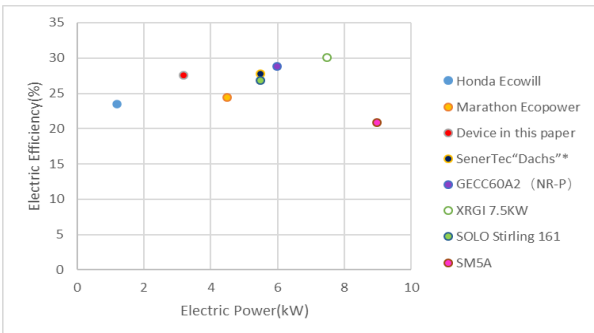

Figure 6 Scatter plot of electric efficiency of each unit

Overall, it can be seen that the performance of this thesis unit is superior to that of many foreign micro-CHP

units, and the overall efficiency of this unit is among the highest for the same level in the kW class.

4 Conclusions

This paper conducts laboratory tests and on-site tests on natural gas and biogas conditions respectively. The laboratory results show that the electrical efficiency remains stable under different conditions. The thermal efficiency is more sensitive to the inlet water temperature. For the on-site tests, the results show a maximum electrical power of 3.2kW, an electrical efficiency of 26.8% and an overall efficiency of 92.4% when in the field. And it can meet the user's heat demand during long and stable operation. When compared with existing micro-CHP units from abroad, the overall efficiency of the unit in this paper also ranks among the best.

In summary, the devices in this paper can meet rural heating needs and provide a new approach to clean rural heating.

Acknowledgement

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