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GAS-FIRED HEAT-DRIVEN DUPLEX STIRLING DOMESTIC COMBINED HEAT AND POWER SYSTEM

Yanlei Sun[1,2], Jianying Hu[1*], Ercang Luo[1*], Kaiqi Luo[1,2], Zhanghua Wu[1], Limin Zhang[1]

1 CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Beijing 100190, China

2 University of Chinese Academy of Sciences, Beijing 100190, China
* Corresponding author: Tel/Fax: +86 10 82543750; E-mail address: Ecluo@mail.ipc.ac.cn (EC Luo)
Tel/Fax: +86 10 82543733; E-mail address: jyhu@mail.ipc.ac.cn (JY Hu)

ABSTRACT

We designed, simulated, and analyzed a gas-fired heat-driven duplex Stirling domestic-combined heat and power system in order to alleviate the energy crisis and improve the efficiency of energy utilization. With the hot-end temperature of the Stirling engine fixed at 650℃ and the temperatures of the heat supply and the surroundings fixed at 60℃ and 0℃, respectively, the duplex Stirling machine can achieve an output heating power of 5115W and an output electrical power of 79.2W, corresponding to a relative Carnot efficiency of 44.53%. The output characteristics and efficiency of the system are greatly affected by the hot-end temperature, the surrounding temperature and the average pressure. In addition, our calculations show that optimal performance under different working conditions can be obtained by adjusting the electrical resistance.

Keywords: Duplex Stirling, Domestic-Combined Heat and Power, Efficiency, Electrical resistance

NOMENCLATURE

Abbreviations	
DHCP	Domestic-Combined Heat and Power generation
Symbols	
Q	Heat Power, W
W	Electrical power, W
T	Temperature, K
R	Electrical Resistance, Ω
Greek letters	
η	Efficiency
Subscripts	
0	Heating Supply End
d	Duplex Stirling Heat Pump
en	Stirling Engine
alt	Alternator
h	Hot-end
hp	Stirling Heat Pump
overall	Overall Performance Coefficient
r	Surrounding
RelCarnot	Relative Carnot Efficiency

1. INTRODUCTION

With the rapid development of the world economy, global carbon emissions are increasing, and energy shortages and environmental problems are becoming increasingly prominent. Sustainable economic development, resource utilization, and environmental management urgently require changes in the way power is produced and used. Cogeneration technology based on natural gas, biogas, and biomass promotes the comprehensive utilization of energy, alleviating the current shortage of fossil fuels and reducing environmental pollution. [1, 2]. A domestic combined heat and power generation (DCHP) unit is a low-power heat and electricity generation unit that can be installed in buildings to supply electricity, heat, and hot water for domestic use. It is fueled by natural gas and uses a micro-

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engine to drive a micro-generator that generates electricity. It provides between 0.5 and 10 kW of electrical power to the building while simultaneously providing 3 to 15 kW of heat power as required for space heating and domestic hot water. Advantages accrue both in terms of improved energy efficiency and reduced environmental impact provided that the systems operate in an energy-efficient manner, i.e., the supply and demand for electrical and thermal power can be made to match at a local level. [3-5]. DCHP devices can significantly save primary energy and improve energy efficiency. In addition, for some high-altitude or remote areas, DCHP technology also plays a vital role in ensuring the living standards of residents [6].

The most cited technologies in small-scale micro-cogeneration (less than 5 kWe) are fuel cells, internal combustion engines, and Stirling engines. [7] Stirling heat engines are closed-cycle reciprocating-piston external combustion engines. As well as being able to use a variety of fuels, Stirling engines offer the advantages of high conversion efficiency, stable operation, low noise, low pollution, and simple maintenance [8-9]. Stirling engines may be used as heat engines or prime movers, receiving heat at high temperature from an external source, converting some to mechanical work and rejecting the balance as waste heat at a lower temperature. Alternatively, they may be used as refrigerating machines or heat pumps that receive heat at a low temperature and deliver heat at a higher temperature. [10] Though many types of Stirling engines have been developed since their invention in 1816, the duplex Stirling engine is undoubtedly the most suitable design for domestic cogeneration, which involves generating both power and heat. [11]

The duplex Stirling machine is an efficient and compact double-Stirling structure based on the free-piston Stirling engine. In a duplex Stirling machine, a Stirling engine drives a Stirling-cycle heat pump or refrigerator. The two free-piston Stirling-cycle machines in the duplex Stirling are in a back-to-back configuration with a common piston coupling them. There are no major mechanical links guiding the piston or displacers, which are controlled by springs (gas or mechanical) and gas forces. [11] The heat engine part uses helium as a working fluid and an externally combusted fuel such as natural gas to produce power to operate the refrigerator or heat pump part. Compared with other Stirling heat engines, the duplex Stirling unit is characterized by high efficiency, compactness, and low operating cost.

Based on this, a gas-fired heat-driven duplex Stirling DHCP system was proposed that uses a light-load linear alternator instead of a conventional mechanical resonator. The system was analyzed using the SAGE software package. We examined the performance of the system under different working conditions and discussed how the temperature can be controlled by adjusting the electrical resistance of the alternator. These results are helpful for understanding the thermodynamic performance of duplex Stirling systems.

2. SYSTEM MODEL

The gas-fired heat-driven duplex Stirling domestic combined heat and power system consists of a free-piston Stirling engine, a light-load linear alternator, a free-piston Stirling heat pump, a burner, a heater, and a hot-water tank, as shown in Fig 1. The light-load linear alternator is located between the free piston Stirling engine and the free piston Stirling heat pump to match the acoustic fields on the two side of the linear alternator.

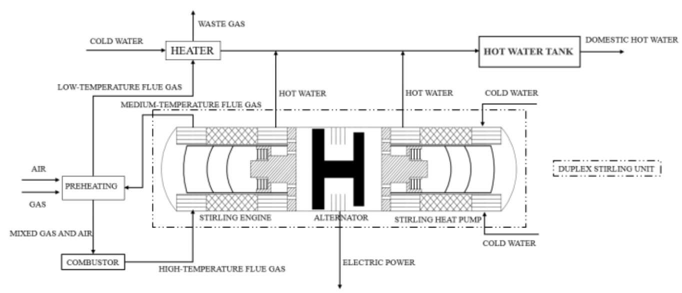

Fig 1 Schematic of gas-fired heat-driven duplex stirling domestic-combined heat and power system

2.1 Working Process

High-temperature flue gas is produced when natural gas and air are burned in the combustor. The temperature of the flue gas decreases after passing through the hot-end heat exchanger of the free piston Stirling engine. Air and gas are mixed in the preheating chamber and heated by the medium-temperature flue gas. The air/gas mixture from the preheating chamber flows into the combustor for combustion, while the temperature of the flue gas decreases still further in the preheating chamber. The low-temperature flue gas exiting the preheating chamber then enters the heater. In the heater, cold water is heated by the low-temperature flue gas and then stored for domestic use in the hot water tank, while the waste gas is discharged after treatment. The Stirling engine continuously converts high-grade heat from natural gas combustion into acoustic power that is used to drive the Stirling heat pump, which extracts heat from the environment to warm the circulating water. The light-load linear alternator, located between the free-piston Stirling engine and the free-piston Stirling heat pump, consumes a portion of the acoustic power to generate electricity. The heat released by the Stirling engine at room temperature can also be used for domestic hot water, further improving the performance coefficient of the whole system. This cogeneration system simultaneously outputs electricity and heat during operation. Since the main purpose of the system is heating, the output heating power of the system is much greater than the output electrical power.

2.2 System design conditions

Table 1 System-design conditions

Operating Frequency	Working Medium	Average Pressure	Hot-End Temperature	Heating Supply Temperature	Surrounding Temperature	Electrical Resistance
50Hz	He	4MPa	650°C	60°C	0°C	100Ω

The operating conditions of the system design are shown in Table 1.

3. EVALUATION OF SYSTEM PERFORMANCE

We calculated the overall performance coefficient ($\eta_{overall}$) of the duplex Stirling, the output heating power, and the overall relative Carnot efficiency to evaluate the system's performance. Since the medium-temperature flue gas and low-temperature flue gas can also provide parts of the heat, the actual efficiency of the system will be higher than the overall efficiency defined below.

The overall performance coefficient ($\eta_{overall}$) of the duplex Stirling is defined as

$$Q_d = Q_{d,hp} + Q_{d,en} \quad (1)$$

$$\eta_{overall} = (Q_d + W_{alt}) / Q_h \quad (2)$$

where Q_d, $Q_{d,hp}$, $Q_{d.en}$, W_{alt}, and Q_h are the output heating power of the duplex Stirling, the output heating power of the Stirling heat pump, the output heating power of the Stirling engine, the output electrical power of the duplex Stirling, and the input heating power to the hot end of the Stirling engine in W, respectively.

The overall relative Carnot efficiency ($\eta_{RelCarnot}$) of the system is given by:

$$\eta_{RelCarnot} = \left[W_{alt} + Q_d \left(1 - T_0 / T_r\right) \right] / \left[Q_h \left(1 - T_0 / T_h\right) \right] \quad (3)$$

where T_h, T_r, and T_0 are the hot-end temperature of the Stirling engine, the heating supply temperature, and the surrounding temperature in °C, respectively.

4. SIMULATION RESULTS AND DISCUSSION

4.1 System calculation results

The commercially available software SAGE (version 10) was used to simulate the system. With the electrical resistance and working frequency of the system fixed at 100Ω and 50 Hz, respectively, we found that the input and output heating power are 3191 W and 5115 W, respectively. The overall performance coefficient of the duplex Stirling reached 1.628, corresponding to a relative Carnot efficiency of 44.53%. The calculation results are shown in Table 2.

Table 2 System calculation results

Input Heating Power /W	Output Heating Power /W	Output Electrical power /W	$\eta_{overall}$	$\eta_{RelCarnot}$
3191	5115	79.2	1.628	44.53%

4.2 Influence of hot-end temperature

Figures 2 and 3 show the system performance curve as a function of the hot-end temperature of the Stirling engine. Fig. 2 shows that when the electrical resistance is constant, the output heating power and the output electrical power of the system increase substantially as a function of the hot-end temperature. As the hot-end temperature increases, the influence of the electrical resistance on the system increases significantly. Fig 3 illustrates that at constant electrical resistance the overall performance coefficient increases smoothly with the hot-end temperature and gradually reaches an asymptotic value. The effect of electrical resistance on performance is most pronounced at lower hot-end temperatures. The overall relative Carnot efficiency gradually decreases with increasing hot-end temperature at constant electrical resistance. This trend becomes more pronounced as the electrical resistance increases. As the hot-end temperature increases, the unit provides less output electrical power at higher electrical resistance, and the ratio of output electrical power to output heating power also gradually diminishes. Fig. 3 shows that when the hot-end temperature is 500℃, the corresponding relative Carnot efficiency is higher because the electrical resistance is higher. By contrast, the corresponding relative Carnot efficiency is higher when the electrical resistance is smaller at a hot-end temperature of 800℃. Unlike the relationship between heating and electrical power, electrical resistance has a lesser effect on efficiency as the hot-end temperature increases. Selecting a larger electrical resistance at hot-end temperatures between 600°C and 700°C will therefore yield the best performance in terms of cost.

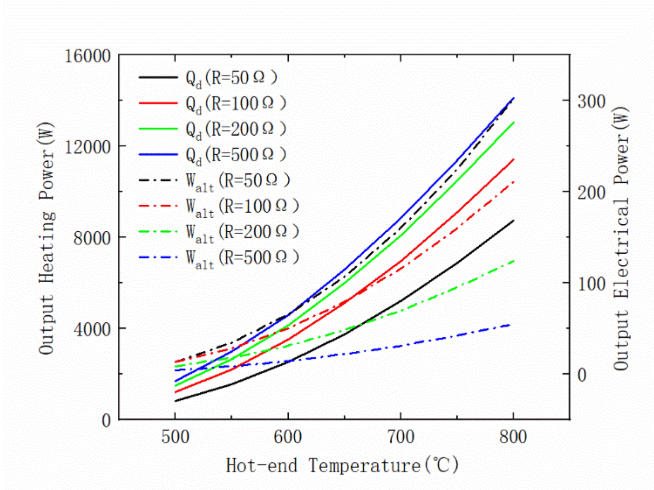

Fig 2 The influence of hot-end temperature on output power at different values of electrical resistance

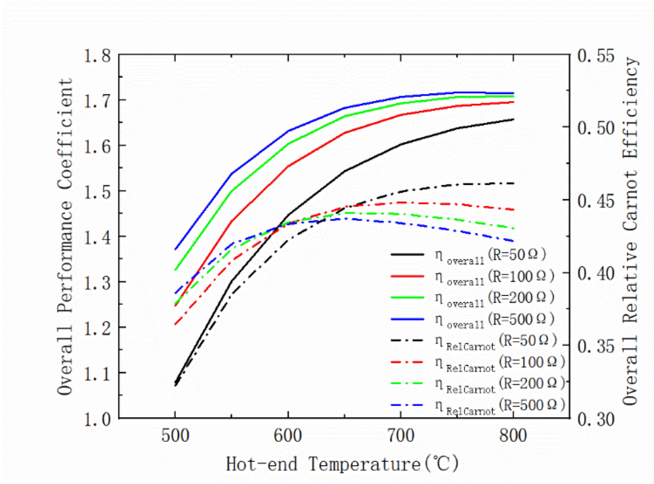

Fig 3 The influence of hot-end temperature on the efficiency at different values of electrical resistance

4.3 Influence of temperature of surroundings

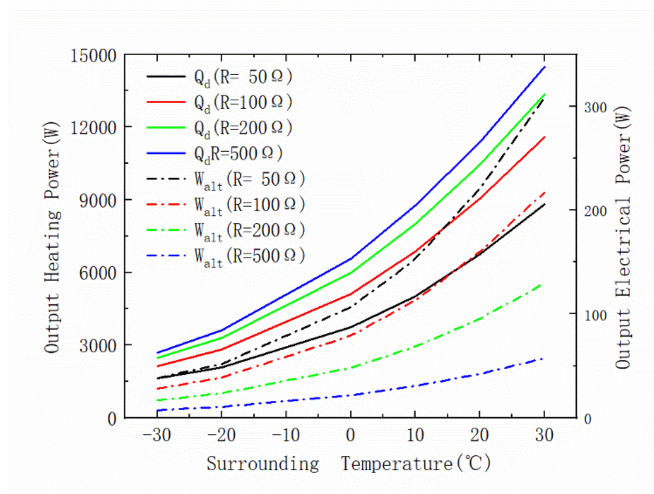

Fig 4 The influence of the surrounding temperature on the output power at different electrical resistance values

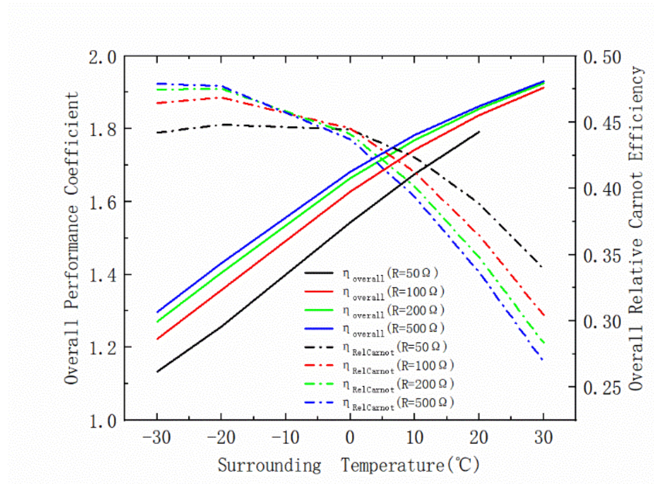

Fig 5 The influence of temperature of the surroundings on the efficiency at different electrical resistance values

We performed simulations with the electrical resistance set to constant values of 50 Ω, 100 Ω, 200 Ω, and 500 Ω to determine how the surrounding temperature affects the performance of the system. The results are shown in Fig. 4 and Fig. 5. Fig. 4 shows that when the electrical resistance is constant, the output heating power and output electrical power of the system increase significantly with the surrounding temperature. As the surrounding temperature increases, so does the effect of the electrical resistance on the system. The overall performance coefficient and the overall relative Carnot efficiency show opposing trends: when the electrical resistance is constant, the overall performance coefficient initially increases steeply and then more gradually as the surrounding temperature increases (Fig. 5), while the influence of the resistance on the overall performance coefficient gradually decreases as the surrounding temperature increases. At high values of electrical resistance, the overall relative Carnot efficiency curve of the unit decreases more sharply as the surrounding temperature increases. Therefore we recommend that when the surrounding temperature is low, a higher resistance should be selected to obtain a higher efficiency, and a higher electrical resistance should be selected to achieve a higher output heating power whether the surrounding temperature is high or low.

4.4 Influence of average pressure

We also investigated the influence of average pressure on the system performance at different electrical resistances (Fig 6 and Fig 7). Fig 6 shows that at constant electrical resistance the output heating power and electrical power first increase and then decrease as the average pressure increases. The maximum values of the output heating power and electrical power vary with the electrical resistance of the system. In order to obtain a higher maximum value of the output heating power, a larger electrical resistance can be selected at average pressures between 3.6MPa and 3.9MPa. However, a lower electrical resistance should be selected to obtain a higher maximum value of the output electrical power. Fig 7 shows that the overall performance coefficient and the overall relative Carnot efficiency similarly first increase and then decrease as the average pressure increases and that the maximum value is obtained at around 3.9 MPa. Therefore, in order to obtain higher output power and efficiency, the average pressure of the system should be kept near 3.9 MPa.

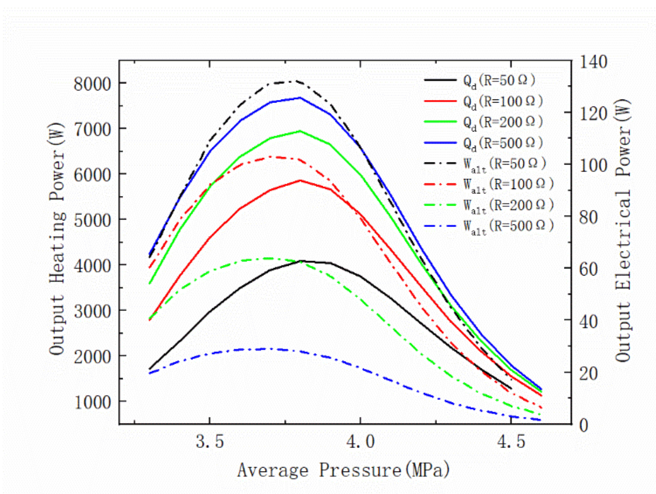

Fig 6 The influence of average pressure on the output power at different values of electrical resistance

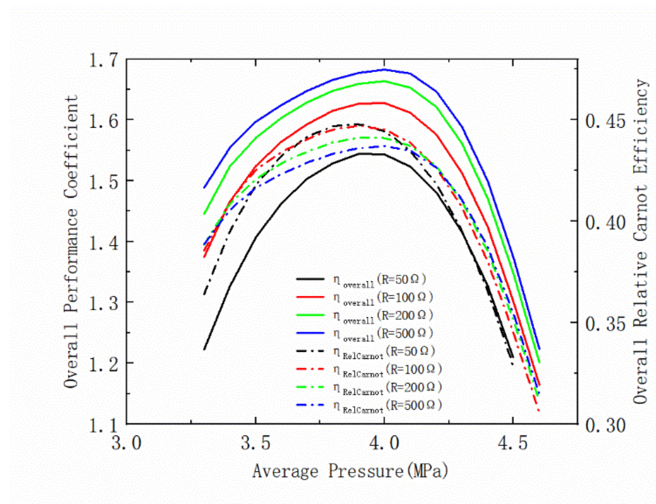

Fig 7 The influence of average pressure on the efficiency at different values of electrical resistance

5. CONCLUSIONS

In order to reduce environmental pollution and improve energy efficiency in buildings, we proposed a gas-fired heat-driven duplex Stirling domestic combined heat and power system. The main elements of this system are a free-piston Stirling engine, a light-load linear alternator, and a free-piston Stirling heat pump. The system is more compact and efficient than conventional cogeneration units and is suitable for use in single houses. Our analysis was based on simulations conducted using the SAGE software package for numerical simulation and analysis. We found that with the hot-end temperature of the Stirling engine fixed at 650℃, the temperature of the heating supply at 60℃, the surrounding temperature at 0℃, the frequency of the system at 50Hz, and the electrical resistance at 100Ω, the duplex Stirling system achieved an overall performance coefficient of 1.628 and a relative Carnot efficiency of 44.53%. We also analyzed the effects of the heating temperature, the surrounding temperature, and the average pressure on the performance of the system. When the heating temperature and the surrounding temperature increase, the output heating power and electrical power of the system and the overall performance coefficient increase significantly. The overall relative Carnot efficiency first increases and then decreases as the heating temperature increases. The overall relative Carnot efficiency decreases sharply as the surrounding temperature increases. The electrical resistance affects the shape of the overall relative Carnot efficiency curve. The output power and efficiency of the system first increase and then decrease with increasing pressure. Our calculations show that the best output performance under different working conditions can be obtained by adjusting the electrical resistance of the system. We plan to confirm these findings experimentally in the near future.

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REFERENCE

[1] LIN A-biao CHEN Hong-wei FANG Yue-lan. Feasibility Analysis of Combined Supply of Cool, Heat and Power System Based on Stirling Engine[J]. APPLIED ENERGY TECHNOLOGY, 2007(7):1-4.

[2] Li T, Tang D W, Li Z, et al. Development and test of a Stirling engine driven by waste gases for the micro-CHP system[J]. Applied Thermal Engineering, 2012, 33-34(none):119-123.

[3] Malliotakis E, Founti M. Energy management and primary energy optimization of a thermally interconnected semi-autonomous commercial district via optimized μ-CHP dispatch strategy[J]. Sustainable Cities and Society, 2017, 32:160-170.

[4] Burrel I G, Ballois S L, Monmasson E, et al. Energy Performance of a New Stirling Micro Cogenerator[J]. EPE Journal, 2008, 17(4):20-28.

[5] Alanne K, Paatero J, Beausoleil-Morrison I. Performance assessment of a Stirling engine plant for local micro-cogeneration[J]. International Journal of Energy Research, 2012, 36(2):218-230.

[6] YANG Min-lin DING Jing YANG Xiao-xi. Application of Stirling Engine in Distributed Energy System[J]. GAS & HEAT, 2006, 26(9):48-53

[7] Alanne K, SoDerholm N, Kai Sirén, et al. Techno-economic assessment and optimization of Stirling engine micro-cogeneration systems in residential buildings[J]. Energy Conversion and Management, 2010, 51(12):2635-2646.

[8] Boucher J, Lanzetta F, Nika P. Optimization of a dual free piston Stirling engine[J]. Applied Thermal Engineering, 2007, 27(4):802-811.

[9] REN Tian-yu CHEN Xi ZHANG Hua FENG Li-na WANG Jian-zhong. Analysis of Trigeneration System Based on Stirling Engine[J]. Fluid Machinery,2012, Fluid Machinery, 40(11):71-74.)

[10] Walker G, Fauvel R, Gustafson R, et al. Stirling engine heat pumps [J]. International Journal of Refrigeration, 1982, 5(2):91-97.

[11] Erbay L B , Ozturk M M , DogAn B . Overall performance of the duplex Stirling refrigerator[J]. Energy Conversion and Management, 2017, 133:196-203.

[12] L.B. Penswick, I. Urieli.Duplex Stirling machines[C]//19th annual intersociety energy conversion engineering conference San Francisco, California (1984), pp. 1823-1828