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Performance Assessment of a Novel Gas-electric Hybrid System for Efficient Cooling Production

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ABSTRACT

Considering the hot weather annually and thus leading high cooling demands in Guangdong-Hong Kong-Macao Greater Bay Area (GBA) of China, a novel distributed cooling production system powered by gas-electric hybrid energy was proposed. The thermal, economic and environmental performances of this process were assessed. The conventional electric air conditioning cooling system was employed as a reference system to demonstrate the benefits of this proposed system. It was found that the total energy efficiency and energy saving rate of this newly proposed system were 201% and 27.8%, respectively, while the payback period was around 3 years. The CO2, SO2 and PM reduction ratios were found to be 54.8, 69.4 and 70.5%, respectively. Further discussion on the safety controlling methods has been included in order to reduce maintain operation cost and to achieve intelligence of this prototype.

Keywords: Gas-electric hybrid; cooling production; Energy analysis; Economic analysis; Environmental analysis; Experimental tests

1. INTRODUCTION

Distributed natural gas energy system refers to a new energy output scheme that employs natural gas as the main raw material to achieve energy supply aside the user side [1]. Due to its high energy utilization efficiency (>70%), low emissions, rapid response and high safety, researchers worldwide have built strong strength on its future application [2-4]. In recent years, the ongoing numbers as well as scale of natural gas distributed energy projects have been highlighted by both the government and the large-scale cooperation. However, the sad fact is up to now, the real projects under construction only account for 30% of the total number of projects that hava been beforehand planed in the 12th five-year plan [5] . The main reasons are as follows :(1) the key technology, especially the system integration technology, is not deeply researched, resulting in low energy efficiency of the system; (2) The low degree of localization of core equipment dominates the equipment investment cost, and the monopoly of natural gas price brings high operation cost; (3) The mismatch between energy supply and energy demand of a specific distributed energy system leads to frequent load changes of units, resulting in many restrictions on

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equipment stability and energy utilization efficiency [6, 7].

To address these facing problems, potential solutions have been aware by the engineers and researchers including :(1) focusing on core technologies and adopting an efficient single energy output integration scheme to improve the energy conversion efficiency; (2) using domestic equipment and integrating natural gas resources to reduce equipment investment costs and operating costs; (3) maintaining the maximum output load of the system and adopting the concept of multi-energy complementarity to improve the running time as well as matching degree of energy output demand [8].

Combined with the characteristics of hot weather and high cooling demand in GBA of China, this work proposes a high-efficiency, low-carbon, economic-interest idistributed cooling system fuelled by gas-electric hybrid energy, and analyses the process performances of this proposed process from three aspects, i.e., thermal, economic and environmental performances. The electric air conditioning cooling system is used as the reference system to compare with the newly proposed system. In addition, the practical application of the proposed process is addressed.

2. PROCESS DESCRIPTION

The gas-electric hybrid distributed cooling system is mainly composed by gas engine, electric chiller and waste heat absorption chiller, as shown in Figure 1. According to the current peak-valley-flat electricity price in GBA, the operation strategy of the proposed cooling system is divided into two periods: peak and flat period (07:00-23:00) and valley period (23:00-07:00). In the peak and flat stage, natural gas and air are compressed and then mixed into the internal combustion engine to generate electricity. The output electric energy drives the compressor in the electric chiller cycle to compress the refrigerant R134a. The high-temperature and high-pressure refrigerant goes through condenser, the circulatory mediator becomes low-temperature and high-pressure state. Then it passes through the valve and followed by evaporator, and the refrigerant vaporizes and the chilled water is subsequently obtained (Qc1). At the same time, the exhaust flue gas temperature of the internal combustion engine is about 450-550 oC, and the jacket water is about 80-90 oC. In order to recover this part of waste heat, the flue gas and hot water lithium bromide absorption chiller system are employed for refrigeration, and the output cooling capacity is Qc2. Therefore, in this stage, the total output cooling capacity is the sum of Qc1 and Qc2. In the second stage of valley period, considering the advantage of low electricity price, the system directly uses the municipal electricity to drive electric chiller, and to achieve the purpose of cooling output.

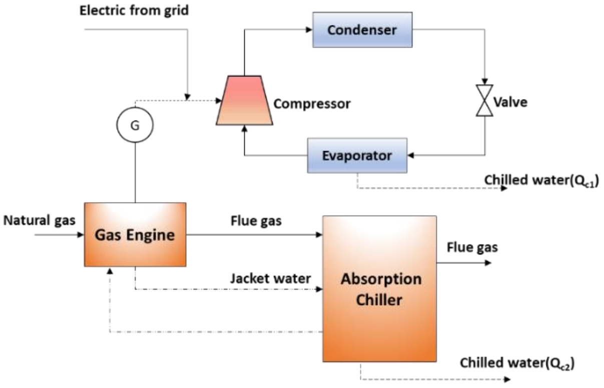

Figure 1 Diagram of gas-electric hybrid cooling system

In the calculation, natural gas flow is 25.56 m^3 /h, pressure is 0.2 MPa, flue gas exhaust temperature is 100 ^{o}C, while condensering cooling water inlet/outlet temperature is 32/37 ^{o}C, chilled water outlet/inlet temperature is 7/12 ^{o}C, flow rate is 84 m^3 /h.

3. EVALUATION INDICATORS

3.1 *Thermodynamic efficiencies*

Energy efficiency is a performance index to evaluate the degree of energy utilization, and its calculation formula is as follows:

$$\eta_{total} = \frac{Q_{c1} + Q_{c2} + Q_e}{F_{NG} LHV_{NG}}$$

Where, Q_{c1} and Q_{c2} denote the cooling capacities from electric chiller and absorption chiller. Q_e represents the equivalent cooling capacity. F_{NG} and LHV_{NG} depict the flow rate and lower heating value of the feeding natural gas of the system.

The primary energy saving rate (PESR) reflects the saving capacity of the system on primary energy consumption, and its calculation formula is as follows:

$$\mathrm{PESR} = 1 - \frac{F_{NG} LHV_{NG}}{\frac{W_e}{\eta_{ref,e}} + \frac{Q_c}{\eta_{ref,th}}}$$

Where W_e is the excess electricity power in the system, Q_c is the total cooling capacity which is the sum of Q_{c1} and Q_{c2}. $\eta_{ref,e}$ and $\eta_{ref,th}$ are the referred power efficiency and cooling efficiency, their values are31.3% and 1.44, respectively.

3.2 *Economic evaluation*

As mentioned above, the system is driven by natural gas for refrigeration from 7:00 to 23:00 daily, and is driven by electricity for refrigeration from 23:00 to 7:00 for the remaining time. Therefore, the calculation formula of total operating cost C of this process is as follows:

$$\mathrm{C} = C_1 + C_2 + C_{op}$$

Where C_1, C_2 and C_{op} are the natural gas cost, electricity cost and the maintenance cost, respectively.

This novel system will replace the user's original electric refrigeration unit to provide cooling, so the profit margin is the difference between the cooling cost of the user's original electric refrigeration equipment and the cooling cost of this novel system (with the same cooling amount). The profit margin can be obtained by combining the coefficient of concession, and the formula is as follows:

$$\mathrm{W} = (C_0 - C) * \left(1 - \eta_{pro}\right)$$

Where C is the total capital cost of the proposed system, while C_0 is the total capital cost of the original cooling system of the user. η_{pro} is the benefit coefficient that give to the consumer.

Theoretically, the net income of this process system remains constantly annually, and the calculation formula of static payback period is as follows：

$$\sum_{t=0}^{t} (CI - CO)_t = 0$$

where $(CI - CO)_t$ is the net cash flow at year t.

The above three evaluation indexes are objective and to avoid the chaotic cooling price on the market at present. The basic parameters for economic analysis is shown in Table 1.

Table 1 Main assumptions for economic evaluation

Item	**Value**	**Unit**
Electricity peak price	1.01	yuan/kWh
Electricity flat price	0.66	yuan /kWh
Electricity valley price	0.21	yuan /kWh
Peak period	09:00-11:30;14:00-16:30;19:00-21:00	
Flat period	07:00-09:00;11:30-14:00;16:30-19:00;21:00-23:00	
Valley period	23:00-07:00	
Cooling price	0.2	yuan /kWh cooling capacity
Gas price	2.5	yuan /Nm^3
Total capital cost	600000	yuan

Natural gas flow	25.56	Nm^3/h

3.3 Environmental analysis

For the environmental benefits of the system, the emission reduction ratio of CO_2, SO_2 and particulate matter (PM) compared with that of electric cooling based on coal-derived power generation are investigated. According to life cycle analysis method (LCA) and taking the 1kWh cooling capacity as the calculation benchmark, the emission reduction ratio of each substance can be calculated as follows:

$$RE_j = \frac{E_{j,N} - E_{j,E}}{E_{j,E}} \times 100\%$$

Where, $E_{i,N}$ and $E_{i,E}$ represent the pollutant emission of this novel process and the electric refrigeration process supplied by coal-based power, respectively. j stands for the type of pollutant, namely CO_2, SO_2 and PM.

4. RESULTS AND DISCUSSION

4.1 Energy analysis

According to the law of energy balance and the performance parameters, the energy input, output and energy efficiency of the process and the three main units are calculated and summarized in Table 2.

As indicated, the comprehensive energy efficiency of the process system is 201%, and the energy saving rate is 27.8%. The power generation efficiency of the generator set is 32.1%, the COP of the electric refrigerator is 5.93, and the comprehensive COP of the absorption chiller is 1.06. Due to the energy cascade utilization, the waste heat in the jacket water and medium cold water is transferred to the cooling water in the chiller unit, leading to a higher energy efficiency. Meanwhile, the two-stage pump frequency conversion theory is applied to this process. Hence, the total energy consumption is reduced.

Table 2 Energy balance of the proposed system

Item	**Value**	**Unit**
Energy balance of the process		
Total energy input	280.44	kW
Total output cooling capacity	490.6	kW
The output power	15	kW
Heat loss	49.64	kW
Energy refrigeration efficiency	201	%
PESR	27.8	%
Energy balance of the gas engine		
Total energy input	280.44	kW

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Total generating capacity	90	kW
Jacket water heat	58	kW
Medium cold water heat	10.2	kW
Exhaust heat	82.8	kW
Other heat loss	39.44	kW
Power generation efficiency	32.1	%
Energy balance of the gas engine		
Energy input	59.3	kW
Output cooling capacity	351.6	kW
COP	5.93	
Energy balance of the absorption chiller		
Energy input	131.1	kW
Output cooling capacity	139	kW
COP	1.06	

4.2 *Economic evaluation*

Based on the calculation formula of economic evaluation, the annual gas consumption, annual profit and static payback period of the process system are calculated, which is showed in Table 3. It is noted that the result is presented at the benefit coefficient of 0.1. Clearly, the daily cost of the proposed system is 1805.91 yuan, which is 10% lower than that of the original cooling system. This is mainly attributed to the cheaper natural gas cost than the electricity, especially at the peak and flat period. Besides, the higher energy efficiency of the proposed system also contributes to the cost savings. As a result, the payback period can be realized to be within 3 years, which shows a good profitability.

Table 3 Economic performance of the proposed system

Item	**Value**	**Unit**
Cost of the original cooling system	1992.58	yuan/day
Cost of the proposed cooling system	1805.91	yuan/day
Cost savings per day	186.68	yuan/day
Cost savings per month	5600.28	yuan/month
Annual net revenue	188040.99	yuan/year
Payback period	3.19	year

4.3 *Environmental evaluation*

In this study, LCA-based environmental analysis was carried out to track the CO_2, SO_2 and PM reduction between the proposed cooling system and the traditional electric chiller under the same cooling capacity. The result is showed in Table 4.

It is apparent that the proposed cooling system have lower environmental impacts than the electric chiller powered by electricity from coal fired plant. Specifically, The CO_2, SO_2 and PM achieve reductions of 54.8, 69.4 and 70.5%, respectively.

Table 4 Environmental behaviors of the proposed system compared with the electric chiller under the same cooling capacity.

Item	**Value**	**Unit**
CO_2 emission reduction		
CO_2 emissions from coal-fired power plant	860	g CO_2/kwh
CO_2 emissions from natural gas-fired power plant	412	g CO_2/kwh
CO_2 emissions under the desired cooling capacity based on coal-derived power	2.61	t/day
CO_2 emissions under the same cooling capacity based on this proposed system	1.18	t/day
CO_2 reduction ratio	54.8	%
SO_2 emission reduction		
SO_2 emissions from coal-fired power plants	0.26	g SO_2/kwh
CO_2 emissions from natural gas-fired power plants	0.027	g SO_2/kwh
SO_2 emissions under the desired cooling capacity based on coal-derived power	782.8	g/day
SO_2 emissions under the same cooling capacity based on this proposed system	239.4	g/day
SO_2 reduction ratio	69.4	%
PM emission reduction		
PM emissions from coal-fired power plants	0.44	g SO_2/kwh
PM emissions from natural gas-fired power plants	0.036	g SO_2/kwh
PM emissions under the desired cooling capacity based on coal-derived power	1344.3	g/day
PM emissions under the same cooling capacity based on this proposed system	396.4	g/day
PM reduction ratio	70.5	%

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4.4 Practical application of the novel system

Based on the above evaluations of this novel hybrid process, to make it inclined to intelligent and flexible equipment, the following technological functions need to be inserted:

- Control technology: developing the independent control system, mainly to achieve two aims: (1) the whole machine frequency conversion function. When the cooling demand of the user changes, the novel equipment can adaptively adjust the cooling output to meet the energy demand of the user in real time. (2) Early warning and automatic repair. A chain of safety management algorithm consisting of perception, intelligent analysis and adaptive regulation should be built. When the data is collected by sensors, then it is deeply analyzed by the internal neural network learning model. If the equipment is in unsafe state, then it can be automatic repair according to adaptive control algorithm so as to realize unattended operation.
- Skid mounted design: the whole equipment is designed in one skid-mounted mode that the main units, control devices, power units and flue-gas treatment units. In this way, this novel equipment is easy to disassemble and move, and compared with the plane layout of each equipment, the overall skid-mounting layout can reduce the floor area by 40%. In addition, the noise level and temperature inside the box can be controlled in 75 dB and 40 °C.
- Multiple digital technologies integration. The establishment of a digital smart energy ecosystem including the physical equipment, energy control platform and mobile APP. The energy control platform currently has four major functions, namely, monitoring of unit operation parameters, economic performance analysis, safety performance analysis and environmental performance analysis. The control platform can summarize and analyze the energy consumption characteristics of user side from statistical data. Then, personalized and differentiated energy value-added services can be provided to the user side through mobile APP.

5. CONCLUSIONS

In this study, it was found that total energy efficiency of the system could reach to 201% and the energy saving rate could reach to 27.8% when the system was operated under the design condition. When benefit coefficient is 0.1, the payback period of investment was realized to be near 3 years, the daily cost of the proposed system is 10% lower than that of the original electric chiller. In addition, the CO_2, SO_2 and PM reduction ratios were found to be 54.8, 69.4 and 70.5%, respectively. Further practical application of the novel system was discussed.

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