Integration Research on Gas Turbine and Tunnel Kiln

Combined System

Shi Hefei, Ma Liangdong, Liu Mingsheng
Dalian University of Technology, China

Abstract. Through the integrated modeling of gas turbine and tunnel kiln combined system, a thermodynamic calculation method of combined system is put forward, and the combined system operation parameters are obtained. By this method, the optimization of the combined system is analyzed and the optimal configuration of the gas turbine is calculated. At the same time, the thermal efficiency of the combined system is analyzed, and the heat distribution and thermal efficiency of the system before and after the improvement are explained. Taking the 1500 kg/h ceramic production as an example, pointed out that if the tunnel kiln has a gas turbine with a power of 342 kw. The amount of electricity of the combined system that produced per unit volume of the fuel which consumes more than it used to will be 7.19 kwh, the system thermal efficiency will reach 57.49%, which higher than the individual gas turbine’s cycle thermal efficiency 20% at least.

1. Introduction

In the actual sintering process, ceramic products have strict requirements for temperature, and the burning temperature of the products is generally about 1200 °C [1]. In order to reduce the combustion temperature of natural gas, a large amount of excess air is needed. Therefore, the exhaust gas from the flue pipe contains a large amount of air have not involved in combustion reactions, the exhaust gas temperature is about 250 °C [1], this part of the gas is discharged into the atmosphere, which take away a lot of heat, lead to the reduction of kiln heat utilization rate and the waste of the fuel energy. In order to reduce the amount of oxygen content that has not been involved in the combustion process, a gas turbine model in a tunnel kiln has been built. In this technique, first burn natural gas and excess air [2], the combustion produces 1000 °C and over high temperature exhaust gas into the turbine, which for gas turbine electric power generation, and then put the medium temperature oxygen enriched steam that exhausted from the turbine into the kiln, burn with the supplementary natural gas and heat the ceramic products. Finally, the amount of oxygen in the exhaust gas that exhausted from the kiln is greatly reduced, the heat loss of exhaust gas is reduced, and the energy efficiency of the kiln is improved. Gas
turbine and tunnel kiln combined system transform natural gas energy into electrical energy firstly, and then for heat supply, thermal efficiency of combined cycle system can reach more than 55%.

2. Thermodynamic model of gas turbine tunnel kiln combined system

Figure 1 is the principle diagram of gas turbine tunnel kiln combined operation: a part of the fuel and excess compressed air mix and burn in the combustion chamber, high temperature exhaust gas produced (1200 °C–1400 °C), driven the gas turbine to generate electricity firstly, then the medium temperature oxygen enriched gas (about 500 °C–600 °C) was brought into the tunnel kiln, heat the material to the specified target process temperature together with the supplementary fuel.

![Thermodynamic Process Diagram](image.png)

**Figure 1.** Schematic diagram of combined operation of kiln and gas power generation.

The thermodynamic process of a gas turbine tunnel kiln combined system is shown in Figure 2: the operation of the combined system is 1-2-3-4-5-6-1. The compressor draws air from the atmosphere and compresses it. Then the high pressure air is sent to the combustion chamber, mixed with fuel and burned at constant pressure to produce high temperature gas. The combustion temperature reaches T3. The gas enters the gas turbine to expand, and then drives the impeller and output shaft power to exhaust the gas and the temperature of the exhaust gas is T4. The exhausted steam is fed into the kiln and mixed with fuel and burned, this process is a constant pressure process 4-5, heat transfer from burning gas to material, thermodynamic process is 5-6, it is a constant pressure process. After the heat transfer, the gas temperature drops to T6. Exhaust gas is discharged into the atmosphere from the flue. The process (6-1) is exothermic under constant pressure.

![Thermodynamic Process Diagram](image.png)

**Figure 2.** thermodynamic process diagram of combined system.
According to the formula of heat efficiency, the cycle thermal efficiency of gas turbine tunnel kiln combined system can be expressed as:

$$\eta = \frac{w_{0} - w_{1-2}}{q_{1}} = \frac{(h_{3} - h_{4}) - (h_{5} - h_{6})}{(h_{3} - h_{2}) + (h_{5} - h_{4}) - (h_{5} - h_{6})} \quad (1)$$

The specific heat capacity is taken as a fixed value, and the upper form can be rewritten as:

$$\eta = \frac{c_{p0}(T_{3} - T_{4}) - c_{p0}(T_{5} - T_{6})}{c_{p0}(T_{3} - T_{2}) + c_{p0}(T_{5} - T_{4}) - c_{p0}(T_{5} - T_{6})} = \frac{(T_{3} - T_{4}) - (T_{5} - T_{6})}{(T_{3} - T_{2}) - (T_{4} - T_{6})} \quad (2)$$

The cycle heat efficiency of an individual gas turbine is:

$$\eta' = \frac{T_{3} - T_{4}}{T_{3} - T_{2}} \quad [2]$$

3. Heat balance calculation of combined system

The heat balance calculation logic of the combined system is shown in Figure 3:

![Figure 3. Logic diagram of thermodynamic calculation of gas turbine tunnel kiln combined system](image)

3.1. Heat balance calculation of cooling zone

The heat income of the cooling zone is equal to the heat output, and the heat balance of the cooling zone is shown in figure 4.

![Figure 4. Schematic diagram of heat balance of cooling zone](image)

The heat balance formula of cooling zone is \([2]\):

$$Q_{a} + Q_{b} = Q_{c} + Q_{d} + Q_{e} + Q_{f} \quad (3)$$

According to the formula of heat balance, the cold air volume can be obtained by solving the equation. In the same way, a balance equation between the preheating zone and the firing zone can be obtained according to the equilibrium equation of heat budget. Thus the consumption of natural gas is calculated.
4. Combined system energy evaluation index

4.1. Cyclic thermal efficiency of combined system
The thermodynamic cycle of the combined system shows that the cycle thermal efficiency of the gas turbine tunnel kiln system is obviously higher than that of the single gas turbine when the gas turbine tunnel kiln combined system is be use\textsuperscript{[4]}d, from the above calculation we can see that

\[ \eta = \frac{(T_3 - T_4)(T_5 - T_6)}{(T_1 - T_2)(T_4 - T_6)} \]  

(4)

The higher the cycle thermal efficiency of the combined system, the less energy wasted and the more energy saved, so cycle thermal efficiency of the system is an important indicator of the evaluation of the integrated system.

4.2. The amount of electricity that produced per unit volume of the fuel which consumes more than it used to of the combined system
The generating capacity of the individual gas turbine is 3 kwh/m\textsuperscript{3}~4 kwh/m\textsuperscript{3}\textsuperscript{[5]}, After the integration of gas turbine and tunnel kiln, the natural gas consumption has increased by $\Delta V$, The electrical energy produced is $W_e$. Therefore, from the point of view of the combined system. The amount of electricity that produced per unit volume of the fuel which consumes more than it used to can be calculated by the next formula:

\[ e = \frac{W_e}{\Delta V} \]  

(5)

The higher the amount of electricity that produced per unit volume of the fuel which consumes more than it used to, the higher efficiency of the high-grade energy will be produced by the combined system, so the amount of electricity that produced per unit volume of the fuel which consumes more than it used to be an important indicator of the evaluation of the integrated system.

5. Analysis of calculation results
Taking the weight of 1500 kg into the kiln per unit time as an example, the thermodynamic performance can be obtained before and after the integration:

| items                                | before integrating | after integrating |
|--------------------------------------|--------------------|------------------|
| Material inlet quality/kg            | 1500               | 1500             |
| Material moisture Content            | 2%                 | 2%               |
| High temperature coefficient of kiln | 0.85               | 0.85             |
| The temperature of natural gas entering the kiln/\degree C | 20                 | 20               |
| Compressor outlet pressure/MPa       | —                  | 20               |
| Excess air coefficient               | 1.63               | 2.43             |
The temperature of the material entering the kiln/℃ 20 20
The temperature of material entering the firing zone/℃ 1043 1049
Sintering temperature of material/℃ 1200 1200
Material output temperature/℃ 80 80
Exhaust gas temperature/℃ 250 250
Hot air temperature/℃ 200 200
Fuel combustion temperature/℃ 1413 1413
Total consumption of natural gas/m³ 144.9 192.57
The consumption of natural gas in gas turbine/m³ — 99.34
The consumption of natural gas in kiln/m³ 144.9 93.23
Low heating value of the natural gas/kJ/m³ 36,000 36,000
A total amount of consumed heat/kJ 5,220,862.92 6,938,445.45
The heat consumption of gas turbine/kJ — 3,579,299.67
The heat consumption of kiln/kJ 5,220,862.92 3,359,145.78
Fume Exhaust Volume/m³ 9.92 9.39
8
Heat loss due to exhaust gas 67.18% 53.31%
The amount of electricity that produced per unit volume of the fuel which consumes more than it used to /kwh/m³ — 7.19
Cycle thermal efficiency — 57.49%
The price of natural gas/RMB/m³ 2.8 2.8
The total price of natural gas/RMB 405.72 539.20
generated energy/kwh — 342.65
electricity price/RMB/kwh 0.8 0.8
Electricity generation income/RMB — 274.12

Table 2. Gas turbine operating parameters (pressure ratio is 20)

| Compressor inlet temperature/℃ | Compressor outlet temperature/℃ | Compressor efficiency | Combustion chamber efficiency | Turbine efficiency | Turbine inlet initial temperature/℃ | Exhausted temperature/℃ |
|--------------------------------|---------------------------------|-----------------------|-------------------------------|-------------------|-----------------------------------|-------------------------|
| 20                             | 300                             | 0.85                  | 0.99                          | 0.88              | 1226                              | 635                     |

Compared with the amount of the natural gas consumption of kiln, the gas turbine kiln tunnel combined system increased 47.67 m³. But it also increased 342.65 kwh of electricity, equivalent to 1 m³ of natural gas made 7.19 kwh of electricity. When the gas turbine operates alone, 1 m³ natural gas only generate 3.45 kwh of power. After integration, the efficiency of gas generation is equivalent to 2.08 times of that before integration. Based on the load of the kiln, thermal efficiency of combined cycle system reached 57.49%, 23.03% higher than the cycle thermal efficiency of individual gas turbine, efficiency of the
combined system is improved greatly, the energy utilization improved, energy saving effect is remarkable.

6. Conclusion
An energy saving technology by putting gas turbine in front of tunnel kiln is put forward. A calculation model of heat balance of gas turbine tunnel kiln is built. By this method, the operating parameters of the combined system that can satisfy the firing temperature of the kiln are calculated, including gas turbine operating parameters and kiln operation parameters.

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7. Reference
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