Energy Consumption Analysis Model of Typical Cogeneration Systems

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Abstract. At present, China's urban heating system consumes a lot of energy and is seriously polluted. Our government is working hard to develop urban natural gas regional heating systems to replace traditional coal-fired heating to reduce the serious impact of coal combustion emissions on the urban atmospheric environment during the heating season. On this basis, the characteristics of traditional energy efficiency comparison methods and the problems encountered by these traditional methods in the energy efficiency analysis and application of distributed energy cold, hot and power multigeneration systems in China are analyzed, and the comparable performance efficiency analysis methods suitable for the application of cold, hot and hot power multiple production applications of distributed energy are studied.

1. Introduction
Due to its proximity to the energy demand load center, distributed energy systems can reduce energy transmission distances, promote efficient energy use and reduce environmental impacts. Distributed energy systems can not only provide electricity to surrounding users and avoid long-distance transmission losses, but also use low-grade energy after power generation, such as flue gas waste heat, for low-grade energy requirements such as low heat source temperature required by building heating. Steam and hot water are generated by using flue gas waste heat, which are widely used in refrigeration, heating, dehumidification and drying. In terms of systems, distributed energy systems can merge the power generation, heating and cooling systems that were originally separated from each other to form a cold, hot and power multi-generation system. Cogeneration is an energy production mode that uses primary energy such as natural gas and coal to generate electricity according to the principle of energy cascade utilization, and then uses the residual heat after power generation for heating. Cogeneration technology is an important development direction of world energy technology. It has the characteristics of high energy utilization efficiency, small environmental impact, reliable supply and good economic benefits [1].

The main forms of cogeneration are boiler-heated steam turbine cogeneration system, gas turbine cogeneration system, internal combustion engine cogeneration system and fuel cell system [2]. The gas cogeneration system has the characteristics of high comprehensive thermal efficiency, so it is gradually applied to the power supply system. The application of this system can not only effectively use clean energy, but also form a complementarity between seasonal peaks and valleys of gas and power loads, and alleviate the tension of electricity consumption [3]. Cogeneration systems can effectively use part of the waste heat for power generation or heating, and produce power and heat energy at the same time, so as to increase the utilization rate of energy to more than 80%[4].

The distributed energy cold and hot power multi-generation system combines a variety of systems such as power generation, transmission and distribution, heat grid, building heating and cooling, etc., and the system complexity is high. The change laws of cold, hot and electric loads vary from region to region.
region and different building type, and the grade and energy consumption of various energy products are very different. The difficulty and complexity of energy efficiency evaluation of distributed energy cold, heat and power multigeneration systems are significantly higher than that of traditional production distribution systems.

2. Energy Consumption Analysis Model

2.1 Energy Consumption Analysis Model of Coal-fired Unit System

The multi-energy complementary system based on coal-fired cogeneration uses the heating and steam pumping of the thermal power unit for heating, and at the same time drives the absorption refrigeration unit for refrigeration, so as to realize the triple supply of cold, hot and electricity, optimize the matching of the three loads of cold and hot power, and realize the cascade utilization of energy, which is the key to energy conservation of the system.

For the convenience of analysis, the user side cold load of the system is set as $Q_{rc}$, the heat load is $Q_{rh}$, the electric load is $P_{re}$, the power generation load of the cogeneration unit is $P$, the pumping load is $Q$, and the pumping load $\lambda Q$ is used for absorption refrigeration units. The insufficient cold and electric load is supplemented by the electric refrigerator and the external power grid, and there is generally no need to configure a peak adjustment boiler.

By introducing the thermoelectric ratio $K = \frac{Q}{P}$, it can be calculated that the heat consumption of the system is:

$$Q_c = P^*(K + 1)\eta_{tg} + \frac{P_{re} - P}{\eta_p} + \frac{Q_{rh} - (1 - \lambda)K P}{\eta_b} + \frac{Q_{rc} - \lambda K PCOP_a}{COP_a \eta_p} \quad (1)$$

In the formula: $COP_p$ is the performance coefficient of the electric refrigeration unit; $COP_a$ is the performance coefficient of the absorption unit; $\eta_b$ is the efficiency of the peak regulating boiler (%), $\eta_p$ is the thermal efficiency of the condensed steam unit (%), and $\eta_{tg}$ is the fuel utilization coefficient of the cogeneration unit (%).

If it is in the form of cold, hot and electrical supply, the heat consumption of the system is:

$$Q_s = \frac{P_{re}}{\eta_p} + \frac{Q_{rh}}{\eta_b} + \frac{Q_{rc}}{COP_a \eta_p} \quad (2)$$

Compared with the distribution system, the difference in heat consumption between the multi-energy complementary system is:

$$\frac{Q_s - Q_c}{Q_s} = 1 - \frac{P^*(K + 1)}{\eta_{tg}} + \frac{P_{re} - P}{\eta_p} + \frac{Q_{rh} - (1 - \lambda)K P}{\eta_b} + \frac{Q_{rc} - \lambda K PCOP_a}{COP_a \eta_p}$$

$$= \frac{P + (1 - \lambda)K P + \lambda K PCOP_a - P^*(K + 1)}{\eta_p + \frac{Q_{rh}}{COP_a \eta_p} + \frac{Q_{rc}}{\eta_{tg}} \quad (3)$$

It can be seen from formula (3) that when the cold and heat power load on the user side continues to increase, the energy saving generated by the multi-energy complementary system gradually decreases. When the load of the peak adjustment equipment of the multi-energy complementary system is zero, the energy-saving potential of the system is the greatest, and then the critical energy-saving conditions of the multi-energy complementary system can be obtained as follows:
2.2 Energy Consumption Analysis Model of Gas Unit System

The multi-energy complementary system based on the triple supply of natural gas, unlike cogeneration units, which can adjust the cold, hot and electric load through the adjustment of steam turbine pumps, its operation mode mainly adopts two types: thermal fixation (FTL) and electric fixation (FEL), among which the thermal fixation mode is also known as the thermal follow mode. That is, during the operation of the system, gas turbines and supporting waste heat boilers give priority to meeting the heat needs of the system and generate electrical energy at the same time. If the electricity can meet the demand, buy electricity from the grid. The electric heating mode, also known as the electric follow-up mode, is contrary to the thermal heating mode. Gas turbines give priority to meeting the needs of the system electrical load. When the system heat load is large, the insufficient heat is provided by the peak-adjusting boiler to burn natural gas. Optimization of this type of system mainly compares the differences between thermoelectric (FTL) and electrothermal (FEL) [10-11].

In the operation mode of thermal fixed electricity, when the heat required by the system is greater than the steam provided by the system waste heat boiler, it is necessary to start the peak-adjusting boiler to replenish the heat. The natural gas consumption and outsourced power of the system are shown in Type (5):

\[
1 - \frac{(K + 1)/\eta_g}{\frac{1}{\eta_p} + \frac{(1 - \lambda)K + \lambda K\eta_p}{\eta_b + \frac{\lambda K\eta_p}{COP_c\eta_p}}} \geq 0
\]

\[
(4)
\]

\[
2.2 \text{ Energy Consumption Analysis Model of Gas Unit System}
\]

In the operation mode of thermal fixed electricity, when the heat required by the system is greater than the steam provided by the system waste heat boiler, it is necessary to start the peak-adjusting boiler to replenish the heat. The natural gas consumption and outsourced power of the system are shown in Type (5):

\[
F_S = \frac{(1 - \omega)Q_{rec} + Q_{rh}}{\eta_{rec}COP_e} - \frac{\rho_{max}(1 - \eta_{GT})^*\eta_{rec}}{\eta_{GT}} + F_{max}
\]

\[
P_{buy} = P_{rec} + \frac{\rho_{max}(1 - \eta_{GT})^*\eta_{rec}}{\eta_{GT}}
\]

When the heat required by the system is less than the steam provided by the waste heat boiler, there is no need to start the gas boiler. The natural gas consumption and outsourced power of the system are as follows:

\[
F_S = \frac{(1 - \omega)Q_{rec} + Q_{rh}}{\eta_{rec}COP_e}
\]

\[
P_{buy} = P_{rec} + \frac{\rho_{max}(1 - \eta_{GT})^*\eta_{rec}}{\eta_{GT}}
\]

In the formula: \( F_S \) is the natural gas consumption of the system, \( P_{buy} \) is the outsourced power of the system, \( \omega \) is the cooling share of the electric refrigeration unit, \( F_{max} \) is the natural gas consumption under the maximum operating conditions of the gas turbine, \( \eta_{GT} \) is the power generation efficiency of the gas turbine, and \( \eta_{rec} \) is the thermal efficiency of the waste heat boiler.

In the mode of electrothermal operation, when the power required by the system is greater than the maximum power provided by the triple supply unit, it is necessary to buy electricity from the grid. The natural gas consumption and outsourced power of the system are respectively:
When the power required by the system is less than that provided by the triple supply unit, the natural gas consumption and outsourced power consumed by the system are:

\[
F_S = \frac{(1-\omega)Q_{re} + Q_{th} - F_{\max}(1-\eta_{GT})*\eta_{rec}}{\eta_{b}} + F_{\max}
\]

\[
P_{buy} = P_{re} + \frac{\omega Q_{re}}{\eta_{GT}} - F_{\max}\eta_{GT}
\]

2.3 Optimization Guidelines for Operation of Cogeneration Systems

For the convenience of analysis, the ratio of flue gas heat output to power generation power of gas turbine is defined as \( \frac{Q_{gt}}{P_{gt}} \). When the ratio of the equivalent heat load (including cold and heat) to electric load of the system is \( \frac{Q_{eq}}{P_{eq}} \), the natural gas consumption and outsourced power of the system are:

\[
F_S = \frac{Q_{r}}{(1-\eta_{GT})*\eta_{rec}}
\]

\[
P_{buy} = P_{re} - \frac{Q_{r}}{Y}
\]

The energy consumption difference of the system in the two ways is:

\[
\Delta E = \frac{Q_{r}}{(1-\eta_{GT})*\eta_{rec}} - \frac{P_{re}}{\eta_{GT}} + \frac{P_{re} - \frac{Q_{r}}{Y}}{P_{re}}
\]

\[
= (\frac{Q_{r}}{Y} + P_{re})*\frac{1}{\eta_{GT}}/(1-\eta_{GT})
\]

\[
> 0
\]

At this time, the system adopts a thermo-determined operation mode better than electro-determined mode. When the ratio of the system’s equivalent thermal load (including cold and heat) to electrical load is \( \frac{Q_{eq}}{P_{eq}} \), the natural gas consumption and outsourced power of the system are determined by thermal power:

\[
F_S = \frac{Q_{r}}{(1-\eta_{GT})*\eta_{rec}}
\]

\[
P_{buy} = 0
\]

Natural gas consumption and outsourced power of the system in the form of electrified heating:
\[ F_s = \frac{P_{re}}{\eta_{GT}} + \frac{Q_s - P_{re} \times (1 - \eta_{GT}) \eta_{rec}}{\eta_b} \]

The energy consumption difference of the system in the two ways is:

\[ \Delta E = \frac{Q_r}{Y \times \eta_{GT}} - \frac{P_{re}}{\eta_{GT}} - \frac{Q_s}{\eta_b} + \frac{P_{re} Y}{\eta_b} \]

\[ = (Q_r - Y \times P_{re}) \times \frac{1}{\eta_b} - \frac{Y \times \eta_{GT}}{1} \]

\[ = (Q_r - Y P_{re}) \times \frac{(1 - \eta_{GT}) \times \eta_{rec} - \eta_b}{\eta_b \times (1 - \eta_{GT}) \times \eta_{rec}} \]

Generally speaking, as \((1 - \eta_{GT}) \times \eta_{rec} - \eta_b < 0\), \(\Delta E < 0\) it is better to run in an electrothermal manner at this time than in a thermothermal manner. Through the above analysis, the basic criteria for the operation optimization of the multi-energy complementary system based on the triple supply of natural gas cold, heat and electricity can be obtained. When the ratio of the equivalent heat load (including cold and heat) to electric load of the system is less than the ratio of flue gas output heat to power generation power of the gas turbine, the system should operate in the form of thermal fixed electricity, and vice versa.

3. Conclusions

This paper mainly analyzes the advantages of cogeneration of cold, heat and power generation, and analyzes in detail the energy efficiency of cogeneration of gas systems and cogeneration of steam systems. Distributed cogeneration system is a multigeneration total energy system that integrates cold, heat, electricity and other energy sources. Its biggest feature is multi-level utilization of energy of different qualities, which has the characteristics of energy conservation and environmental protection, and has been widely valued worldwide. Thermal energy with low temperature can be used for heating or refrigeration, and heat energy with higher temperature can be used for power generation. Under the guidance of the principle of cascade utilization, co-supply not only improves the utilization rate of energy but also reduces the emission of harmful gases.

4. References

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