

Design and Study on Low Concentration Gas Catalytic Oxidation Power Generation System

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Abstract: Aiming at the present difficult situation of direct utilization of low concentration gas in coal mine and the slow development of industrial application of catalytic oxidation technology, it is necessary to explore a new utilization mode about low concentration gas which the methane concentration with 1.0% in coal mines directly used in catalytic oxidation gas turbine power generation. Based on the design and development of a 30kW low concentration gas catalytic oxidation gas turbine power generation system, the design process of key devices such as catalytic oxidation combustor, low temperature and low pressure turbine and flow-reversal regenerator is introduced. This work will carry forward the industrial application of the technology.

1. Introduction

Coal mine gas is an unconventional natural gas. It's a clean, efficient and high-quality energy that has risen in recent years [1]. Among them, the low concentration gas with methane concentration less than 10% is difficult to utilize because of its large gas volume, low concentration and fluctuation [2]. While wasting energy resources, it also affects the overall utilization rate of coal mine gas in China. At present, the low concentration gas is usually mixed with mine ventilation air or air for oxidation. The catalytic flow-reversal reactor (CFRR) and thermal flow-reversal reactor (TFRR) are two mainstream technologies for the utilization of low concentration gas in coal mines [3]. In view of the current development status, the industrial application of TFRR technology is more promising [4]. However, catalytic oxidation technology benefits from the application of catalysts. When treating low concentration gas, its oxidation temperature is lower, the space occupied by equipment is smaller, and it has technical characteristics that can not be ignored [5]. Therefore, it is urgent to strengthen technical research, explore new ways of catalytic oxidation of low concentration gas, and promote the industrialization process of this technology. This paper describes in detail the design and development of a 30 kW low concentration gas catalytic oxidation gas turbine power generation system, focusing on the development of catalytic oxidation combustion chamber, low temperature and low pressure turbine and flow-reversal regenerator and other key devices, to explore and research on catalytic oxidation gas turbine power generation technology of low concentration gas in coal mine which the methane concentration with 1.0% [6].

2. Technological process of low concentration gas catalytic oxidation power generation system

The low concentration gas catalytic oxidation power generation system (technological process is shown in Figure 1) is mainly composed of mixing device, centrifugal compressor, flow-reversal regenerator, catalytic combustion chamber (including ignition device), runoff turbine, gearbox and generator, etc. The operating principle of the system is that the low concentration gas is mixed into a relatively stable concentration of feed gas in the mixing device, which is compressed into a certain pressure in the compressor, and then compressed gas enters the flow-reversal regenerator. The

waste heat from the exhaust of the turbine is heated to about 400°C in the regenerator.[7] A honeycomb catalyst is placed in the catalytic combustion chamber, and the catalytic oxidation combustion of low concentration gas at the outlet of the regenerator occurs on the surface of the catalyst. The temperature of the catalytic combustion can be raised to about 700 ~ 800°C. High-temperature and high-pressure flue gas expands in the turbine to do work to drive the generator to generate electricity. The turbine is connected to the generator through the gearbox, and the temperature drops to about 500°C. Then the exhaust gas is returned to the regenerator to heat the new low concentration gas feed gas. In this way, the chemical energy of low concentration gas catalytic combustion can be transformed into electric energy.

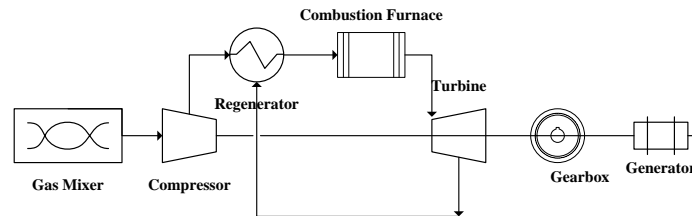


Fig.1. Technological process of low concentration gas catalytic oxidation power generation system

3. Design of low concentration gas catalytic oxidation power generation system

3.1 Catalytic combustion chamber

3.1.1 Structure design of catalytic combustion chamber

The catalytic combustion chamber of low concentration gas is filled with catalysts in multiple stages, the ignition device is heated by resistance wire, and the hot air is circulated in the closed system of the combustion chamber by high temperature blower, and the catalyst is heated to the lowest ignition temperature required for the catalytic reaction of methane. The multi-stage loading of catalysts in combustor is easy to load and disassemble the catalysts. More importantly, the catalysts loaded in each stage have different functions according to the catalytic combustion reaction. The first stage is filled with the whole catalyst with noble metal as the active component which has lower ignition temperature and better activity for methane catalytic combustion and the second stage is filled with less noble metal. The third stage is hexaaluminate monolithic catalyst which is difficult to deactivate at high temperature. The conversion of methane in the catalytic combustion chamber is over 99% and the catalyst life is greatly improved by loading three different types of catalysts.

3.1.2 Size calculation of catalytic combustion chamber

1)Volume of catalyst

The optimum space velocity of the low concentration gas in the catalyst which is obtained through the small scale experiment of methane catalytic oxidation is directly related to the size of the catalyst and the catalytic combustion chamber. The calorific value of the mixture gas whose methane concentration with 1.0% is 355 kJ/Nm³. So the gas flow rate with 1% methane concentration is needed for the reaction can be calculated through the calculation results of the thermal cycle of the system that 30 kW low concentration gas catalytic oxidation power generation system, and then the volume of the catalyst is obtained. In order to achieve the best coating effect of the active component of the catalyst, the diameter of the support should not exceed 330 mm. Therefore, the length of the catalyst is determined.

2)Thickness of combustion chamber insulation layer

The temperature rise of the combustion chamber is designed less than 35°C. The parameters such as the outer wall temperature (T_2) of the insulation layer, the catalyst temperature (T_1) of the inner wall, the thermal conductivity (λ) of the insulation material and the diameter (r_1) of the reaction tube are selected and the heat loss per meter of the combustion chamber (Q/L) is below 500 W/m. The external diameter (r_2) can be obtained by the heat conduction rate equation from cylinder wall.

$$\ln r_2 = \frac{2\pi\lambda L}{Q}(T_1 - T_2) + \ln r_1 \quad (1)$$

The thickness of insulation layer is the difference between r_2 and r_1 .

3)power of ignition device

Based on the volume of the metal supported monolithic catalyst (V) and the specific heat capacity of the catalyst (C_{p1}), the heat required to heat the catalyst from 20°C to 450°C can be obtained.

$$Q_1 = VC_{p1} \Delta t \quad (2)$$

Choosing the constant pressure heat capacity (C_{p2}), diameter, wall thickness, length, density and other parameters of stainless steel reaction tube, the mass of stainless steel reaction tube (m_1) is calculated. Choosing the diameter, wall thickness, length and density of branch pipe of circulating fan, and the branch pipe mass (m_2) is calculated. The heat required to heat the stainless steel reaction tube and the branch pipe of circulating fan from 20°C to 450°C can be obtained.

$$Q_2 = (m_1 + m_2)C_{p2} \Delta t \quad (3)$$

The total heat required for ignition $Q = Q_1 + Q_2$

Assuming the regenerative efficiency of the catalyst in the catalytic combustion chamber is η , the actual heat required is Q/η .

3.2 Design of low temperature and low pressure turbine

Because of the low methane content in low concentration gas of coal mine, the compressor and turbine have the characteristics of low inlet temperature, low pressure and large flow capacity, so the thermodynamic calculation of turbine and compressor need to be calculated according to the given parameters. [8] According to the results, the design parameters of the compressor and turbine are selected. The aerodynamic design, rotor dynamics design and structural strength design of the compressor and turbine are calculated as follows.

3.2.1 Aerodynamic design of compressor

The flow rate, pressure ratio, inlet temperature and inlet pressure of the compressor are determined according to the compressor operating conditions and thermodynamic calculation results. Compressor simulation design is carried out through the turbomachinery design software named NREC. Firstly, the compressor is designed in one-dimensional by Compal module. After the one-dimensional meets the requirement, then import into the Acent module for two-dimensional analysis, and the parameters of the impeller are adjusted and optimized.

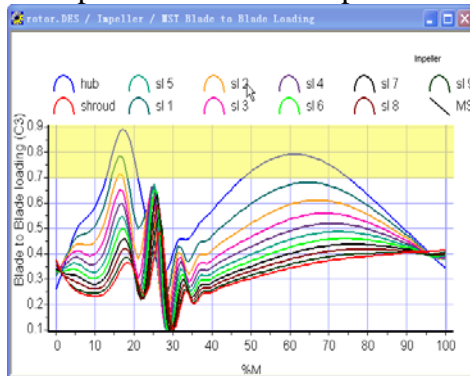


Fig.2. Load distribution of compressor impeller blades

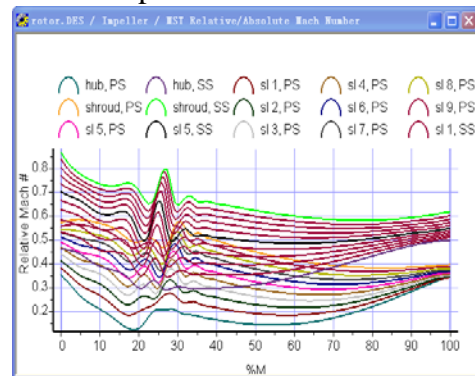


Fig.3. Relative Maher number distribution in compressor impeller

After the above two-dimensional analysis, the full three-dimensional flow simulation module is imported to calculate the three-dimensional flow in the compressor. As shown in Figure 4.

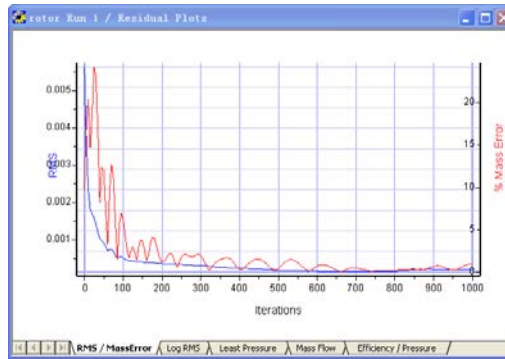


Fig.4. Residual convergence curves of three dimensional simulation analysis

From the above three-dimensional analysis results, it can be seen that the relative Mach number distribution inside the impeller is more uniform, there is no supersonic flow area, and the tail part is smaller. The main parameters of the compressor are determined.

3.2.2 Aerodynamic design of turbine

Similar to the aerodynamic design of compressor, according to the turbine operating conditions and thermal calculation results, through one-dimensional design and two-dimensional optimization, the three-dimensional module is imported to carry out full three-dimensional flow simulation analysis, and the turbine flow characteristics under the design speed are obtained.

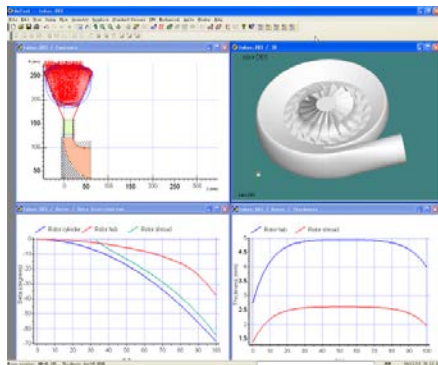


Fig.5. optimized turbine in Acent

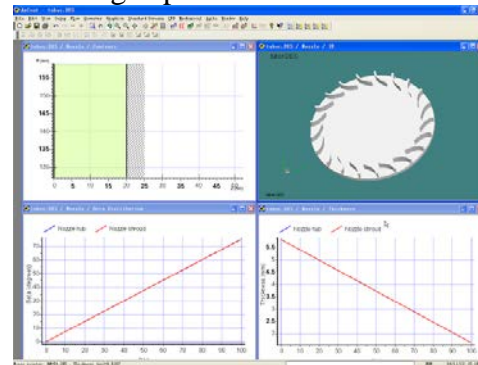


Fig.6. optimized nozzle ring in Acent

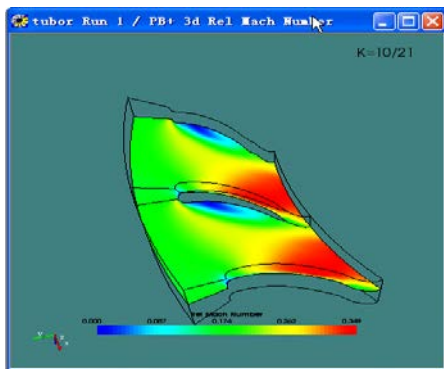


Fig.7. Relative Mach number distribution of nozzle ring

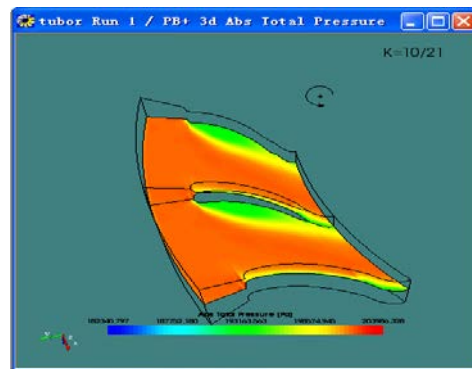


Fig.8. Total pressure distribution in nozzle ring

According to the above three-dimensional simulation results, it can be seen that in the turbine design, the flow distribution is more uniform, no obvious separation, impact loss is small and turbine efficiency is higher. The main parameters of turbine are determined.

3.2.3 Dynamic design of rotor

The software named Dyrobes is used to analyze the bearing performance and rotor dynamic performance, and the rotor modeling of whole machine as shown in Figure 9. The system performance is analyzed while the static and dynamic characteristics of bearing are calculated and

the critical speed of turbine, high speed shaft and the whole machine are calculated. The calculation results are shown in Figure 10-12.

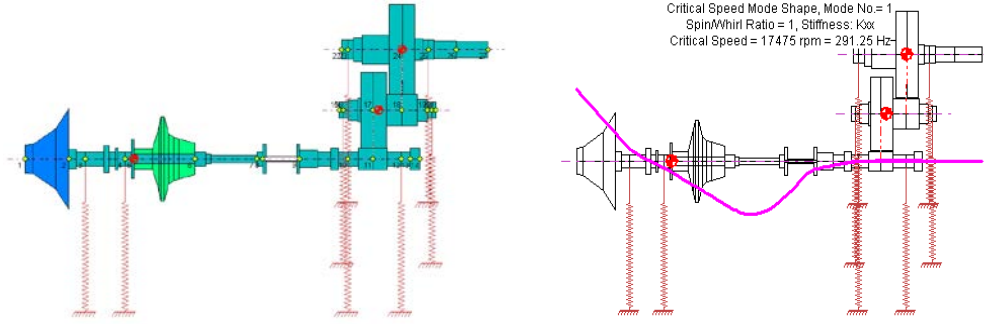


Fig.9. Rotor modeling of whole machine Fig.10. the first critical speed of the whole machine

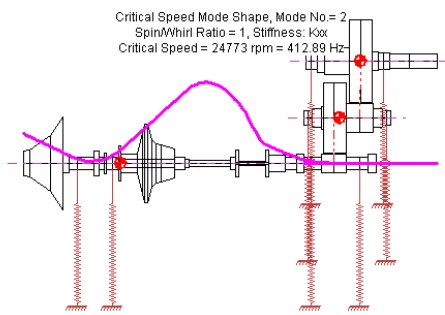


Fig.11. the second critical speed of the whole machine

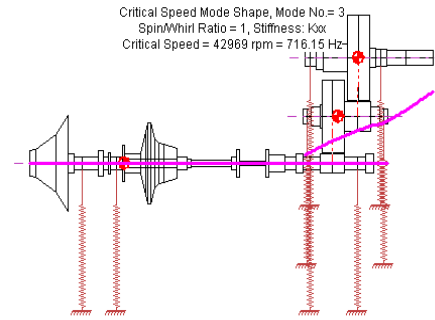


Fig.12. the third critical speed of the whole machine

According to the above calculation, the main rated speed of the system is between the second and third critical speed, and it should be avoided to run near the first and second critical speed in the course of use. The rotor-bearing system meets the design requirements at 3600 rpm.

3.2.4 Design of flow-reversal regenerator

Regenerator is an essential component of low concentration gas catalytic oxidation power generation system. It preheats the high temperature flue gas from the turbine outlet into the gas before the catalytic oxidation reaction chamber, and promotes the temperature of raw material to the ignition temperature of catalyst to realize catalytic combustion, so as to improve the thermal efficiency, reduce the energy consumption of the system and save energy. The regenerator of the system is designed in the form of main surface heat exchanger which has advantages in heat efficiency, compactness and heat flux density.

3.2.5 Area of regenerator

According to the inlet and outlet temperature of the system, the logarithmic mean temperature difference (Δt_m) can be calculated and the heat quantity that to heat the feed gas from 125°C to 500°C of regenerator.

$$Q = mC_p \Delta t = m_{Air} C_{pAir}^{500-125} + m_{ch_4} C_{pch_4}^{500-125} \Delta t \quad (4)$$

The total heat transfer coefficient (K) of regenerator is 50[W/(m²·K)] refer to relevant literatures and the heat transfer area required for regenerator can be obtained.

$$A = \frac{Q}{K \Delta t_m} \quad (5)$$

3.2.6 Inlet and outlet diameters of feed gas and high temperature flue gas

According to the volume flow rate (G_1) of the regenerator inlet, the feed gas temperature (T_1) of regenerator inlet, the feed gas temperature (T_2) of regenerator outlet, the high temperature flue gas temperature (T_3) of regenerator inlet, the high temperature flue gas temperature (T_4) of regenerator

outlet and pressure ratio of the compressor, the inlet and outlet pressure of the air inlet and outlet in the regenerator are calculated. The inlet and outlet pressure of high temperature gas in the regenerator is set at 101kPa atmospheric pressure and the flow velocity of high temperature gas and air in the pipeline is generally 20 to 30m/s. According to the standard nominal diameters commonly used and calculation results in pressure pipeline design, DN200 is selected for diameter (D_1) of feed gas of regenerator inlet, DN250 is selected for diameter (D_2) of feed gas of regenerator outlet, DN400 is selected for diameter (D_3) of high temperature flue gas of regenerator inlet and DN300 is selected for diameter (D_4) of high temperature flue gas of regenerator outlet.

4. Conclusions

1) The technology of low concentration gas catalytic oxidation power generation in coal mine opens up a new way of direct utilization of low-concentration gas which is more difficult to use. It can reduce environmental pollution by oxidizing the low-concentration gas, and at the same time directly generate electricity and create economic benefits.

2) Through the structural design and dimension calculation of catalytic combustion chamber, the aerodynamic design of compressor and turbine and the design of regenerator, the key design difficulties of a set of 30KW low concentration gas catalytic oxidation power generation system are solved.

3) Low concentration gas catalytic oxidation power generation system has compact structure and small floor area, and can be flexibly arranged. However, at present, the scale of single generation is small and the unit investment is large. There is still room for improvement in the scale and efficiency of power generation and needs further study.

Acknowledgement

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