Technology for Optimizing Flue Gas Pollutant Emission Reduction in Oil Field Heating Furnace Combustion

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Abstract. The energy consumption of the heating furnace is an important part of the energy consumption of the oilfield gathering and transportation system. The low energy efficiency of the heating furnace will directly lead to the increase of oilfield production costs. In response to the national energy-saving and emission-reduction policy, the oilfield has implemented energy-saving practices in heating furnace load adjustment, efficient combustion, excess air coefficient control, flue gas waste heat utilization, and furnace modification. It is clear that the energy efficiency of oilfield heating furnaces is still lower than foreign advanced levels. There is an urgent need for further energy conservation and efficiency enhancement. MVR low-temperature flue gas heat recovery technology, flame shape matching technology, nanofluid heat transfer enhancement technology, solar auxiliary heating technology and other new technologies that can be used for energy saving and consumption reduction of oilfield heating furnaces provide a reference for oilfield heating furnaces to tap the potential and increase efficiency.

Key words. Oil field heating furnace, combustion optimization, pollution control, energy saving and emission reduction.

1. Introduction
Oil field heating furnace is one of the indispensable equipment of oil field transfer station and joint station. It is mainly used for heating processes such as hot washing, water mixing, heating, and crude oil transportation. Conventional heating furnaces generally adopt the heat transfer process of "flame and high-temperature flue gas transfer heat to the heat exchange surface, and the heat is transferred from the heat exchange surface to the medium". In production and operation, fouling on the heat exchange surface is inevitable, leading to increased operating costs such as reduced operating thermal efficiency, increased fuel consumption, and scaling. As far as the current burner is concerned, the load ratio is only 1:2.7, which is far from meeting the requirements of load regulation, and the combustion effect is lower at low load [1]. This not only causes waste of fuel, but also some unburnt materials in convection the deposition on the heated surface seriously affects the heat transfer effect and reduces the efficiency of the boiler. Therefore, in order to improve the efficiency of the heating furnace, reduce
fuel waste, and develop a large turndown ratio, high-efficiency natural gas burners have important practical significance.

2. Direct heat transfer mechanism research

2.1. Formation and flow of high-temperature flue gas

Natural gas is the main fuel consumed by the heating furnace in use in the oil field, and natural gas is the research object in the research process of this article. The high-temperature flue gas here refers to the product of the combustion of natural gas and air. Since the heat released during combustion is carried by it, these products have a high temperature and exist in a gaseous state, so they are called high-temperature flue gas.

2.1.1. The formation of high temperature flue gas. Since the exit temperature of the furnace hearth far exceeds the condensation temperature of water vapor, the calculation of high temperature flue gas adopts low calorific value. Regarding high-temperature flue gas, the main parameters include theoretical air volume, flue gas volume, and flue enthalpy [2]. The combustible substances in natural gas include H2, CO, H2S, and C1-C7 hydrocarbon gases, and their composition is generally expressed in volume fraction. All parameters of high temperature flue gas can be calculated according to the volume fraction of each component and the properties of each component. The theoretical air volume can be obtained by the following formula:

\[ V^c = 0.0476 \left[ 0.5CO + 0.5H_2 + 1.5H_2S + \sum (m + n/4)C_nH_n - O_2 \right] \]  

(1)

The actual flue gas quality can be obtained by the following formula:

\[ G_v = 0.01 \frac{[1.96CO + 1.52H_2S + 1.25N_2 + 1.43O_2 + 1.25CO + 0.0899H_2 + \Sigma (0.536m + 0.045n)C_nH_n]}{1000} + \frac{d_w}{1000} + 1.306aV^c \]  

(2)

The flue gas enthalpy can be obtained by the following formula:

\[ I_g = V_{g} = V_{CO}_2 \left( C^c \right)_{CO}_2 + V_{N_2} \left( C^c \right)_{N_2} + V_{H_2O} \left( C^c \right)_{H_2O} + (a - 1)V^c \left( C^a \right) \]  

(3)

In the formula: \( V^c \) is the theoretical air volume, m³/ m³; \( m \) is the number of carbon elements; \( n \) is the number of hydrogen elements; \( G_v \) is the actual flue gas mass, kg/ m³; \( d_w \) is the water content of the gas fuel, g/ m³; \( I_g \) is the enthalpy of flue gas, kJ/ m³; \( V_{g} \) is the volume of triatomic gas, m³/ m³; \( V_{N_2} \) is the theoretical volume of nitrogen, m³/ m³; \( V^c \) is the theoretical volume of water vapor, m³/ m³; \( \left( C^c \right)_{CO}_2 \), \( \left( C^c \right)_{N_2} \), \( \left( C^c \right)_{H_2O} \), \( \left( C^a \right) \) is 1 m³ at a certain temperature The flue gas enthalpy of the fuel; \( a \) is the air coefficient.

2.1.2. Flow of high temperature flue gas. In order to realize the direct heat exchange between the flue gas and the liquid medium, the fuel combustion chemical reactions are all carried out in the furnace, and all heat exchange is carried out in the heat exchange chamber. Therefore, the mixture of natural gas and air in the furnace should be as good as possible. The speed of natural gas flow and the relative speed between natural gas and air determine the strength of the mixture. When the air flow is in a laminar state, the mixing speed has nothing to do with the flow velocity [3]. The greater the flow rate,
the longer the flame; in the turbulent state, the mixing is very strong, and the increase in the flow velocity will shorten the flame length; the greater the relative velocity of the gas and the gas, the longer the flame. In order to shorten the time required for mixing, reduce the size of the furnace, and reduce the steel consumption of the furnace, it is best to split the large stream of natural gas into multiple small air streams and spray them into the air stream.

2.2. Flow of cryogenic liquid

The direct heat exchange between flue gas and liquid medium is mainly the heat exchange between high-temperature flue gas and low-temperature liquid. The calculation formula of the heat exchange is as follows:

$$ Q = A \cdot h \cdot \Delta t $$

(4)

In the formula: A is the heat transfer area, which here refers to the surface area of the cryogenic liquid; h is the heat transfer coefficient, and its size is related to many factors in the heat transfer process, and not only depends on the physical properties of the fluid (λ, μ, ρ, c etc.) and heat transfer the shape, size and layout of the surface are also closely related to the flow rate. Here, the physical properties and other factors are already fixed values, so they mainly depend on the flow rate; \( \Delta t \) is the temperature difference. During the entire heat exchange process, the high temperature flue gas and the low temperature liquid the temperature changes continuously with the progress of heat exchange, so the temperature difference also changes, taking the logarithmic average temperature difference

$$ \Delta t_w = \frac{(\Delta T_{max} - \Delta T_{min})}{\ln(\Delta T_{max} / \Delta T_{min})} $$

(5)

From the above analysis, it can be seen that the surface area and flow rate of the cryogenic liquid have the greatest impact on heat transfer. Therefore, from the perspective of enhancing heat transfer, it is decided to adopt the form of spraying (Figure 1). Under the premise that the pressure of the liquid circulation system allows, the surface area and flow rate of the cryogenic liquid should be increased as much as possible, that is, the cryogenic liquid enters the heat exchange chamber in the form of spray, and relies on its own initial velocity and gravity to exchange heat flows downward in the hot chamber, contacts and exchanges heat with the high-temperature flue gas flowing upward during the flow process, and then falls into the buffer tank.
Figure 1. Schematic diagram of spray structure

3. Design of thermoacoustic coupled pulsation combustion system

3.1. Overall structure design
The overall structure of the thermoacoustic coupled pulsation combustion oil field heating furnace is shown in Figure 2. The front part is the pulsation combustion device. Because there is a certain modal sound field in the pulsating combustion, the pressure amplitude in the combustion chamber is about 170dB, so both the flue gas outlet and the air inlet are designed with silencer devices [4]. The main components of the pulse burner are as follows.

Figure 2. Overall structure of 0.29MW pulsating combustion two-in-one heating furnace

3.1.1. Combustion chamber. The task of the combustion chamber is to fully mix, burn, and release heat energy between air and fuel. The combustion chamber is also a Helmholtz resonant cavity. Its volume and slenderness ratio directly affect the frequency and sound loss of the pulsation. The combustion chamber of the 0.29MW pulse combustion device is cylindrical, with a flat head at the front and an elliptical head at the rear, with a volume of 36L. A spark plug is installed in the centre of
the flat head, and three air inlets and three fuel nozzles are alternately installed on the flat head to form a vertical mutual impact type mixing structure.

3.1.2. Tail pipe and exhaust decoupler. The tail pipe is the main component of the pulsation combustor. Its length and cross-sectional area determine the pulsation frequency and exit acoustic impedance of the combustor. At the same time, the tail pipe is the main heat exchange surface (80% of the heat exchange occurs in the tail pipe). The shape of the tail pipe can be straight or curved, one end is connected with the combustion chamber, and the other end is connected with the exhaust decoupler. The decoupler is also a heat transfer surface. Its main body adopts a cylindrical shell and the two ends are sealed by elliptical heads [5]. It has the function of a certain volume decoupler, which is mainly to isolate the burner from other accessories acoustically. To ensure its acoustic boundary conditions.

3.2. Key technology

3.2.1. Maintain the normal pulsation of combustion. The period of pressure pulsation depends on the geometric parameters of the combustor and the speed of sound in the combustor, and the speed of sound is determined by the structure of the fuel delivery system and the distribution of vortexes generated upstream of the combustor. In addition, the length of the tail pipe must ensure the necessary acoustic impedance so as to achieve the required amplitude [6]. This is another basic condition to maintain the normal operation of the pulse burner.

3.2.2. Fully automatic control system. The pulsation burner is closed, the flame is not visible, and the danger of gaseous fuel is greater, so a reliable automatic control system must be provided. In addition, the high degree of automation can reduce the labour intensity of on-site operators, so the pulsating combustion heating furnace adopts an industrial PLC furnace front control system. The system has three main functions: one is automatic ignition start and shutdown program control; the other is temperature control system, which automatically maintains the outlet water temperature; the third is flameout protection [7]. The control program of the pulsating combustion heating furnace is shown in Figure 3.

![Figure 3](image-url) Schematic diagram of the control program of the pulsating combustion heating furnace

4. Field test results
In order to confirm the technological advancement of the 0.29MW pulsating combustion two-in-one heating furnace. Field tests were carried out at the design institute test base, and various design performance and technical indicators were measured [8]. The relative performance parameters of the
new and old two-in-one heating furnace are shown in Table 1. Preliminary comparison calculations show that the following considerable benefits can be seen:

(1) The combustion intensity is increased from the current 170kW/\(m^3\) to 9000kW/\(m^3\), which means that the furnace volume can be reduced from 1.7 \(m^3\) to 0.035 \(m^3\). (2) The heat exchange area has dropped from the current 26\(m^2\) to about 6 \(m^2\). (3) The heat transfer intensity is increased from 11.2kW/\(m^2\) to 50kW/\(m^2\). (4) The total weight of the burner part of the original two-in-one heating furnace (including smoke, fire tube and chimney) is 3247kg (not considering delivery and connection parts), which can be reduced to less than 550kg after changing to a pulse burner. In this way, the total furnace body can be reduced from 7200kg to 3700kg. The total weight will be reduced by 3500kg. (5) The cost can be reduced from RMB 120,000 to RMB 95,000. (6) From manual ignition monitoring to fully automatic control. (7) Cancel the facilities in front of the furnace and the fire room.

Table 1. Comparison of relevant parameters of new and old 0.29MW heating furnace

| Benefit Analysis                  | Conclusion |
|----------------------------------|------------|
| Good economy                     |            |
| 77% reduction                    |            |
| 7.5 times higher                 |            |
| Decrease 125°C                   |            |
| 16% increase                     |            |
| -1.1%                            |            |
| 92% reduction                    |            |
| Reduce 3.5t                      |            |
| 16m reduction                    |            |
| Easy to operate                  |            |
| Reduced 25,000 yuan              |            |
| 25% reduction                    |            |

5. Conclusion
How to use and manage heating furnaces well has become an important link in oilfield energy-saving management and even the level of production technology. Based on the energy-saving monitoring results of heating furnaces in Oilfield, and based on the characteristics of heating furnaces in different production sites, a series of measures are proposed to reduce air leakage, modify burners, monitor flue gas, remove ash and scale, eliminate high energy-consuming equipment, and improve operation management. Provide a reference for other similar oilfield heating records to improve efficiency.

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