Optimization of Combustion Organization of Regenerative Reheating Furnace

Dong Sun, Shangchao Qi, Weibo Zheng, Riyi Lin, Xiuli Yang and Xiaofeng Hu

ABSTRACT

Regenerative reheating furnace is an important energy consuming equipment in petroleum industry. So it is very important to optimize the combustion organization of the heating furnace. In this paper, a gas consumption regenerative reheating furnace of oil field was taken as the research object. The impact of air excess ratio, preheating temperature of combustion-supporting air and the ratio of the primary air and secondary air on the generation of NO\textsubscript{x} in the radiant tube was analyzed by the combination of orthogonal test and numerical simulation. The conclusion was made that when the air excess ratio was 1.05, preheating temperature of combustion-supporting air was 900 °C, the ratio of primary air and secondary air was 20%: 80 %, the concentration of NO\textsubscript{x} in the radiant tube was only 1.1 ppm. The discharge quantity of NO\textsubscript{x} was reduced to the lowest limitation. And it is an ideal solution to reduce the NO\textsubscript{x} emissions.

INTRODUCTION

With the development of oil and gas fields, the water jacket furnace is widely used in transportation system. The main function of the furnace is to reduce the viscosity of the transport fluid by heating crude oil. So we can prevent the pipeline from being blocked due to excessive viscosity of fluid in the process of conveying. The amount of gas consumption of the furnace has an important influence on the energy saving and economic benefit of the whole oil field. [1] Traditional water jacket furnace has the following disadvantages, such as high emission of NO\textsubscript{x} and low efficiency of energy saving.

Dong Sun, Weibo Zheng, Xiuli Yang, Xiaofeng Hu. Shengli Oil Field Technology Inspection Center, 2# Jinan Street, Dongying, China
Shangchao Qi, Riyi Lin. China University of Petroleum, 66# Changjiang Sreet, Qingdao, China
High Temperature Air Combustion (HTAC) is a new combustion technology in the early 1880s. Its basic principle is that the fuel is burned in a high temperature and low oxygen concentration environment. [2] Because the fuel is burned in the low oxygen environment, the local high temperature region which often appear in the traditional combustion process will not appear in the process of combustion.

HTAC has many advantages such as efficient recovery of waste heat, high temperature preheating air, low pollution (NO\textsubscript{x}) discharge, and so on. In terms of energy conservation and environmental protection, it is very significant to focus on the NO\textsubscript{x} emissions. The actual operating parameters of the heating furnace such as air excess ratio, preheating temperature of combustion-supporting air and the ratio of the primary air and secondary air are the three important factors affecting the high temperature air combustion. So the optimal selection of these three parameters is very important.

Orthogonal experiment design is a design method studying multiple factors and multiple levels. [3] It is a method of using some representative test points instead of all test points. It has the advantages of high efficiency, fast and economical. The characteristic of orthogonal experiment design is to find out the best combination of the experimental factors after the analysis of the limited tests. Then it can make an assessment of the degree of importance of each factor and interaction. In traditional process of tests, the experiments are blindness, time-consuming and also heavy workload. But orthogonal experiment design can obviously avoid the disadvantages mentioned above. In this paper, orthogonal test method was employed, and the impact of air excess ratio, preheating temperature of combustion-supporting air and the ratio of the primary air and secondary air on the generation of NO\textsubscript{x} in the radiant tube was analyzed.

**MODELING AND MESHING**

A regenerative-combustion heating furnace of oil field was considered as the physical model. The designed load rating of the furnace is 0.8 MW. The length of U-tube is 6.6 m. Inner diameter of U-tube is 600 mm. The burner of the furnace is reformed according to the regenerative combustion mode. And the physical structure of the burner is shown in Figure 1. Air staged combustion technology is adopted in this burner. The temperature of the primary air is room temperature. The secondary air is heated by regenerator before getting into the chamber of the furnace. Six nozzles of the primary air with diameter of 8.4 mm are evenly arranged along the circumference.
Seven nozzles of the secondary air are eccentrically arranged along the circumference. The diameter of the five big nozzles is 36 mm, and the diameter of the two small nozzles is 18 mm. The fuel channel with the diameter of 12 mm is arranged in the center of the burner. The relative height (h) of the secondary air vent and the fuel nozzle is 96 mm. And radial distance (L) is 130 mm. The angle of two secondary air nozzle (\( \alpha \)) is 29 degrees. In this paper, the regenerative combustion process was simulated by a commercial software-FLUENT. Computational domain consists of the U shaped radiant tube and regenerative burner. While meshing, hybrid structured grid was adopted in computational area. The area of nozzle and the combustion channel was refined. [4]

**SELECTION OF CALCULATION MODEL AND BOUNDARY CONDITIONS**

Considering the structure of the burner and the radiant tube, we should take several factors, such as turbulence, combustion, heat transfer and the formation of nitrogen oxides into account when we choose the right model. The \( k-\varepsilon \) two-equation model was employed for turbulence simulation, the PDF model for combustion simulation, DO model for radiative heat transfer. And the generating model of thermal and prompt NO\(_x\) model was also adopted. The NO\(_x\) generated during the combustion process is mainly NO, so the analysis of NO\(_x\) is mainly aimed at NO.

During the operational process of the regenerative-reheating furnace, the mass flow rate of fuel inlet was 0.019 kg/s, and its temperature was 293 K; The temperature of the primary air was 293 K. Constant temperature wall conditions were used in the area of U type radiant tube, and the temperature of it is 500 K. Constant pressure condition was adopted in the area of the outlet of flue gas, and the pressure value is -800Pa. The theoretical amount of air required for the complete combustion of the fuel gas can be calculated by the fuel component and mass flow rate. The calculated theoretical air mass flow rate is 0.277 kg/s. Components of fuel gas are shown in TABLE I.
SELECTION OF CALCULATION MODEL AND BOUNDARY CONDITIONS

The Concept and Principle of Orthogonal Experiment Design

Orthogonal experiment design is a method that is used to arrange and analyze multiple factors through orthogonal table. Its basic idea is to get the optimal combination of factors through limited representative tests instead of all possible tests.

Table I. Components of fuel gas.

| Fuel material | C₃H₈ | CO₂ | N₂ | C₂H₆ | CH₄ | C₃H₁₂ | C₄H₁₀ | O₂ |
|---------------|------|-----|----|------|-----|-------|-------|----|
| (%) (%) (%) (%) (%) (%) (%) (%) |
| Volume fraction | 2.23% | 3.42% | 4.21% | 1.93% | 81.85% | 3.00% | 2.64% | 0.72% |

Table II. Test schemes of three factors and three levels.

| A₁B₁C₁ | A₂B₁C₂ | A₃B₁C₃ |
|--------|--------|--------|
| A₁B₂C₂ | A₂B₂C₃ | A₃B₂C₁ |
| A₁B₃C₃ | A₂B₃C₁ | A₃B₃C₂ |

Nine representative points with the test label are selected from the 27 test points by the use of orthogonal table L₉(3⁴). Details of the experimental programs are shown in TABLE II. The 9 experimental points were chosen to replace all 27 experimental points in order to get the optimal combination of the factor A, B and C.

Application of Orthogonal Experimental Design in Optimization of Combustion Organization

According to the theory of combustion, the intensity of primary combustion mostly depends on the classification of the primary and secondary air. When the oxygen content is low, the combustion rate and combustion temperature of the primary fuel enrichment zone will decrease. So the production of thermal NOₓ will also be reduced. At the same time, the NO generated before will react with intermediate product HCN, NH₃ generated by the combustion of fuel to form N₂. So, the classification of the primary and secondary air has a greater impact on the generation and emission of NO. The other two factors which have relatively large effects on high temperature combustion respectively are the preheating temperature of combustion air and excess air coefficient.

Table III. The contents of each factors and levels.

| levels | A Ratio of the primary air and secondary air | B Preheating temperature of combustion-supporting air (°C) | C Air excess ratio |
|--------|---------------------------------------------|----------------------------------------------------------|------------------|
| 1      | 10%:90%                                     | 800                                                      | 1.00             |
| 2      | 20%:80%                                     | 850                                                      | 1.05             |
| 3      | 30%:70%                                     | 900                                                      | 1.10             |
Table IV. Orthogonal table of 3 factors and 3 levels.

| Levels | A   | B    | C   | Index |
|--------|-----|------|-----|-------|
| 1      | A₁  | B₁   | C₁  |       |
| 2      | A₁  | B₂   | C₂  |       |
| 3      | A₁  | B₃   | C₃  |       |
| 4      | A₂  | B₁   | C₂  |       |
| 5      | A₂  | B₂   | C₃  |       |
| 6      | A₂  | B₃   | C₁  |       |
| 7      | A₃  | B₁   | C₃  |       |
| 8      | A₃  | B₂   | C₁  |       |
| 9      | A₃  | B₃   | C₂  |       |

Three influencing factors were expressed by A, B and C respectively. The contents of each factor and level are shown in TABLE III. Considering numbers of factors and levels L₉(3⁴) orthogonal table was selected for analysis. Details of the orthogonal table are shown in TABLE IV. Mass flow of the theoretical air calculated by boundary conditions is 0.277 kg/s. The concentration of NO was obtained by simulation. The specific test data and results are listed in TABLE V.

Table V. Schedule of test data and results.

| Levels | A     | B  | C    | NO emission |
|--------|-------|----|------|-------------|
| 1      | 0.0277:0.2493 | 800 | 1.0  | 3.7         |
| 2      | 0.029085:0.26176 | 850 | 1.05 | 2.0         |
| 3      | 0.03047:0.27423 | 900 | 1.1  | 2.1         |
| 4      | 0.05817:0.23268 | 800 | 1.05 | 1.4         |
| 5      | 0.06094:0.24376 | 850 | 1.1  | 3.0         |
| 6      | 0.0554:0.2216   | 900 | 1.0  | 1.9         |
| 7      | 0.09141:0.21329 | 800 | 1.1  | 3.2         |
| 8      | 0.0831:0.1939   | 850 | 1.0  | 2.6         |
| 9      | 0.087255:0.203595 | 900 | 1.05 | 3.3         |

ANALYSIS OF ORTHOGONAL TEST RESULTS

Range Analysis of Experimental Data

Comparing the data in TABLE V we can know that the number 4 scheme is the best choice. Emission concentration of NO is only 1.4 ppm. And the optimal scheme is A₂B₁C₂. Only 9 experiments were carried out in the above process. But there are 81 kinds of test schemes according to the orthogonal table. The optimal combination of each factor may be not included in the 9 combinations mentioned above. In order to solve the problem further analyses are needed. For the convenience of analysis, the result of combination of j factor and i level is represented by Kji. The test results of each factor were divided into 3 groups represented by Kj1, Kj2, Kj3 respectively. All test results which have the same factor and level were summed up. The calculation procedure of level 1 and factor A is KA₁ = 3.7 + 2.0 + 2.1 = 7.8. And we can get the calculation results of Kji. In order to reflect the problem more directly, we should
calculate the arithmetic mean of each group. The calculation results of the average value are expressed by \( k_{ji} \). And calculation results of \( k_{ji} \) are listed in TABLE VI.

| levels | Factors |  \( \degree \text{C} \) |  \( \degree \text{C} \) |  \( \degree \text{C} \) |
|--------|---------|-----------------|-----------------|-----------------|
| 1      | A 2.60  | B 2.77          | C 2.73          |
| 2      | A 2.10  | B 2.53          | C 2.23          |
| 3      | A 3.03  | B 2.43          | C 2.77          |

For the further analysis of the data range analysis should be carried out. The so-called range \( R_j \) refers to the difference between the maximum and minimum values of the \( k_{ji} \) of each factor. The range calculation for factor A is \( R_A = 3.03 - 2.10 = 0.93 \). In the same way we can get the value of \( R_B \) and \( R_C \). The value of \( R_B \) is 0.34. And the value of \( R_C \) is 0.54. According to the theory of range analysis, the greater the range value of the factor is, the greater impact of the factor has on the result. Therefore, the primary and secondary order of the influence that factors have on the result should be: \( A > C > B \).

In order to make the process of analysis more intuitive, \( k_{ji} \) was taken as the horizontal coordinate and the vertical coordinate is the average value of the index. So we can get Figure 2.

It can be clearly seen from the above, the best scheme should be \( A_2B_3C_2 \). But the best scheme selected by orthogonal test is \( A_2B_1C_2 \). It is obvious that \( A_2B_3C_2 \) is not included in the 9 tests of the orthogonal table. And whether it is the best scheme, further analyses are needed.

**Validation of the Optimal Scheme**

The combustion process was simulated by FLUENT software under the condition of the optimal scheme \( A_2B_3C_2 \). We can get that the emission concentration of NO was just 1.1ppm. And it is lower than the emission concentration of NO of the optimal scheme we have obtained before. And the conclusion we obtained from analyses above verifies the correctness of the method of orthogonal test analysis. The concentration distribution of NO along the center axis of the burner is shown in Figure 3.
As can be seen from Figure 3, the concentration of NO reached a peak near 2.2 m region. And there is a small peak in the 1 m, which confirmed the existence of primary combustion zone. However, due to the slow combustion, a large amount of NO will not be generated during the combustion process. When the distance is greater than 3 m, the concentration of NO tends to be stable with about 1.1 ppm. The optimal scheme A₂B₃C₂ is in accordance with the orthogonal analysis and it is an ideal solution to reduce the NOₓ emissions.

CONCLUSION

The combination of orthogonal test and numerical simulation was applied in the optimization of combustion organization of regenerative-reheating furnace. The method of orthogonal test is based on the analysis of some representative test points instead of all the test points. It can obviously avoid the blindness of the tests and the waste of funds. And the experimental workload could be reduced vastly due to the application of this method.

Considering the main factors that have important influences on the combustion organization L₉(3⁴) orthogonal table is selected in the process of optimization. The best scheme A₂B₃C₂ was obtained by orthogonal test. The conclusion was made that when the air excess ratio was 1.05, preheating temperature of combustion-supporting air was 900 °C, the ratio of primary air and secondary air was 20% : 80%, the concentration of NOₓ in the radiant tube was only 1.1 ppm. The discharge quantity of NOₓ was reduced to the lowest limitation. And it is an ideal solution to reduce the NOₓ emissions.

Based on the range analysis of the experimental results, the primary and secondary order of the influence of the three factors have on the NO emission is obtained: The ratio of the primary air and secondary air > the air excess ratio > the preheating temperature of combustion-supporting air.
REFERENCES

1. Q.F. Li, G.Z. Zhang, J. Zhang, et al. 2007. Optimal structural design of oilfield bathed heater. *Journal of China University of Petroleum (Natural Science)* 31(3): 114-118.

2. Z Wen & C.H. Dai. 2002. Research status and application prospect of high temperature air combustion technology with regeneration. *Henan Metallurgy* (6): 3-8, 37.

3. Z.G. Xu et al. 2002. Brief Introduction to the Orthogonal Test Design. *Tech Information Development & Economy* 12(5): 148-150.

4. Šarlej M. & Petr P., Hájek J. 2007. Computational support in experimental burner design optimization. *Applied Thermal Engineering* 27(16): 2727-2731.