Combustion Optimization Test of “W” Flame Furnace Based on Orthogonal Experimental Design

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Abstract. This paper focuses on the selection ideas, test methods, test results and analysis of a “W” type flame furnace combustion test program. Under the electrical load of 300MW, 250MW, 200MW and 150MW, the orthogonal test method is adopted to change the “furnace outlet oxygen amount”, “secondary wind and grading wind distribution mode”, “burning air opening degree”, “secondary damper combination method” and “heat load distribution” of the boiler so as to make clear about the impact of various operating conditions on boiler efficiency and NOx emission level, and summarize the optimal operation mode of the boiler. The combustion adjustment can improve the economic and environmental protection of the boiler under different working conditions, which provides data support for equipment safety, environmental protection and economic operation, and provides reference for boiler combustion optimization test research and combustion optimization of the same type of furnace.

1. Introduction
The No. 2 boiler of a power plant has been put into production for many years, the boiler efficiency is low, and the NOx emission level is relatively high. In face of increasingly severe environmental protection pressure, the combustion adjustment is prepared to improve boiler efficiency and reduce NOx emissions. In order to systematically understand the operating conditions of the boiler, master the boiler economy level, and find out the impact level of each operating condition on various boiler indexes, a comprehensive and systematic combustion optimization adjustment test was carried out. This paper introduces in detail the selection of test schemes and test results, effectively summarizes the optimal operation mode (combination) of boilers, and improves the economic and environmental protection of boilers under different working conditions, providing data support for equipment safety, environmental protection and economic operation. It also provides a reference for the study of boiler combustion optimization test and the same type of furnace combustion optimization.

2. Boiler Overview
The No. 2 boiler of the plant is the HG-1025/17.3-WM18 furnace produced by the Harbin Boiler Plant, which is produced by the British Mitsui Babcock technology. The boiler is subcritical, and has the characteristics of double arch single furnace, balanced ventilation, tail double flue, flue gas baffle temperature regulation, solid slag discharge, open air layout, all steel frame suspended steam drum furnace, with anthracite as its main coal. The combustion system is a positive pressure direct blow type, the flue gas system is balanced ventilation, the combustion mode is “W” type, burners are
respectively arranged on the front and rear arches of the furnace, and a 370 m² refractory belt is laid
around the lower furnace. The boiler is equipped with 4 sets of BBD-4060 double-inlet and double-out
steel ball coal mills.

3. Test Plan Design

3.1 Design Idea
The test plan is designed according to the principle of objective, practical and high efficiency. Under
the electrical load of 300MW, 250MW, 200MW and 150MW, the “furnace outlet oxygen”,
“secondary wind and grading wind distribution” and “burning” of the boiler Various factors such as
hurricane opening degree, “secondary damper combination method”, “powder system application
method”, and “heat load distribution” were changed to study changes in boiler efficiency and NOx
emissions[1,2].

In this test, the experimental scheme was designed by orthogonal method, and an appropriate
amount of the preferred confirmatory test was organized according to the orthogonal test results. The
orthogonal test is a test method for studying multi-factor and multi-level test conditions, and has the
characteristics of “uniform dispersion and uniformity”[3,4].

3.2 Influence Factor Selection
Carrying out tests on the control parameters such as “furnace outlet oxygen amount”, “secondary air
and grading wind distribution method”, “burning damper opening degree”, “secondary damper
combination method”, “heat load distribution method” and “polishing system”[1]. Restricted by the
market and controlled by the load dispatching, the two uncontrollable factors of coal combustion and
unit load are independent and parallel test factors in this test, which are excluded in the orthogonal
table[2]. The horizontal test factor level table under the conditions of 300MW, 250MW, 200MW and
150MW is as follows[5]:

| Table 3-1 300MW Orthogonal Test Factor Level |
|---------------------------------------------|
| Factor Level |
| A | B | C | D |
| Furnace Outlet Oxygen | Second/Third Wind Ratio | Air Distribution | Burnout Wind Opening |
|---|---|---|---|
| 1 | 2.6 | 60/70 | Waist Drum | 10 |
| 2 | 3.0 | 50/60 | Constricted | 20 |
| 3 | 3.4 | 50/65 | Equal | 25 |
| 4 | 3.8 | 50/70 | / | 30 |

Note: in this paper waist drum type distribution wind is referred to as Waist drum; constricted air distribution
mode is referred to as Constricted; equal distribution wind is referred to as Equal.

| Table 3-2 250MW Orthogonal Test Factor Level |
|---------------------------------------------|
| Factor Level |
| A | B | C | D |
| Furnace Outlet Oxygen | Second/Third Wind Ratio | Air Distribution | Burnout Wind Opening |
|---|---|---|---|
| 1 | 3.2 | 45/65 | Waist Drum | 10 |
| 2 | 3.4 | 50/60 | Constricted | 20 |
| 3 | 3.8 | 50/70 | Equal | 30 |
| 4 | 4.2 | 60/50 | / | 40 |
### Table 3-3 200MW Orthogonal Test Factor Level

| Factor Level | Furnace Outlet Oxygen | Second/Third Wind Ratio | Air Distribution | Burnout Wind Opening | Heat Load Distribution |
|--------------|-----------------------|--------------------------|------------------|----------------------|-----------------------|
| 1            | 4.1                   | 35/50                    | Waist Drum       | 0                    | Full Mill             |
| 2            | 4.4                   | 40/60                    | Constricted      | 10                   | A Stopped             |
| 3            | 4.7                   | 55/60                    | Equal            | 20                   | B Stopped             |
| 4            | 5.0                   | 45/70                    | /                | 30                   | /                     |

### Table 3-4 150MW Orthogonal Test Factor Level

| Factor Level | Furnace Outlet Oxygen | Second/Third Wind Ratio | Burnout Wind Opening |
|--------------|-----------------------|--------------------------|----------------------|
| 1            | 3.2                   | 40/70                    | 10                   |
| 2            | 4.3                   | 45/65                    | 20                   |
| 3            | 5.1                   | 50/60                    | 30                   |

### 4. Orthogonal Test Results

#### 4.1 300MW Working Condition Test Results

Twelve tests were carried out under 300 MW working conditions, and the factors were changed according to the orthogonal test factor level table designed in Table 3-1. The test and analysis results are as follows:

#### Table 4-1 Summary of Working Conditions of 300MW Load Section

| Project Working Condition | Furnace Outlet Oxygen | Secondary Air Distribution | Burnout Wind | Heat Load Distribution | Boiler Efficiency | NOx Value |
|---------------------------|-----------------------|-----------------------------|--------------|------------------------|------------------|-----------|
|                           | %                     | %                           | %            | %                      |                  | mg/m³     |

| 1            | 2.61 | 4.43 | 60/70 | Waist Drum | 25       | Full Mill | 89.93 | 697  |
| 2            | 2.79 | 3.71 | 60/70 | Constricted| 10       | Full Mill | 89.01 | 729  |
| 3            | 2.39 | 3.40 | 50/60 | Waist Drum | 30       | Full Mill | 87.50 | 615  |
| 4            | 2.21 | 3.08 | 50/60 | Waist Drum | 10       | Full Mill | 88.14 | 624  |
| 5            | 3.34 | 3.12 | 50/65 | Equal      | 25       | Full Mill | 88.87 | 633  |
| 6            | 2.75 | 3.00 | 50/65 | Equal      | 30       | Full Mill | 87.78 | 613  |
| 7            | 2.25 | 2.20 | 60/70 | Constricted| 25       | Full Mill | 87.66 | 608  |
| 8            | 2.38 | 2.70 | 50/65 | Equal      | 20       | Full Mill | 86.96 | 637  |
| 9            | 3.32 | 3.14 | 50/65 | Equal      | 20       | Full Mill | 87.12 | 635  |
| 10           | 2.01 | 2.28 | 50/70 | Waist Drum | 20       | Full Mill | 84.45 | 541  |
| 11           | 2.28 | 2.13 | 50/70 | Waist Drum | 30       | Full Mill | 85.19 | 552  |
| 12           | 2.06 | 1.97 | 50/70 | Waist Drum | 10       | Full Mill | 86.32 | 573  |

The oxygen factor (A), the second/third air ratio (B), the secondary air distribution method (C) and the burnout wind opening (D) were selected to analyze the factors of boiler efficiency and their influences on NOx.

It can be seen from the analysis of the test results: as for the boiler efficiency, the range of the second/third wind ratio (item B) is the largest, so the second/third air ratio has the greatest influence on the boiler efficiency. The optimal combination of boiler efficiency is B1D3C2A4. As for the NOx value, the range of second/third air ratio (item B) is the largest, so the item B has the largest influence...
on the NOx value. As for the control of NOx emissions, the optimal combination of conditions is B4C1D4A3. Please see Table 4-2 and Table 4-3 for details.

Table 4-2 Orthogonal Test Analysis on 300MW Boiler Efficiency

|   | A   | B   | C   | D   |
|---|-----|-----|-----|-----|
| 1 | 87.21 | 88.87 | 87.07 | 87.82 |
| 2 | 87.28 | 87.82 | 88.34 | 87.25 |
| 3 | 87.23 | 87.68 | 87.68 | 88.82 |
| 4 | 88.27 | 85.32 | 87.19 | 87.19 |
| Range | 1.04 | 3.55 | 1.27 | 1.63 |

Table 4-3 Orthogonal Test Analysis on 300MW NOx Emission

|   | A   | B   | C   | D   |
|---|-----|-----|-----|-----|
| 1 | 622.40 | 678.09 | 617.81 | 642.11 |
| 2 | 632.28 | 619.71 | 668.68 | 626.75 |
| 3 | 598.71 | 629.52 | 629.52 | 646.15 |
| 4 | 620.77 | 555.31 | 0.00  | 600.08 |
| Range | 33.57 | 122.78 | 50.86 | 46.07 |

4.2 250MW Working Condition Test Results

Eleven tests were carried out under 250 MW working conditions, and the factors were changed according to the orthogonal test factor level table designed in Table 3-2. The test and analysis results are as follows:

Table 4-4 Summary of Working Conditions of 250MW Load

| Project Working Condition | Furnace Outlet Oxygen | Secondary/Third Wind | Secondary Air Distribution | Burnout Wind | Heat Load Distribution | Boiler Efficiency | NOx Value |
|--------------------------|-----------------------|----------------------|----------------------------|--------------|-----------------------|-------------------|-----------|
|                          | Left: % | Right: % | % | % | % | % | % | % | mg/m³ |
| 1 | 3.15 | 3.65 | 50/60 | Waist Drum | 20 | Full Mill | 88.00 | 805 |
| 2 | 3.10 | 4.00 | 50/60 | Constricted | 10 | Full Mill | 88.36 | 657 |
| 3 | 3.50 | 4.50 | 60/50 | Equal | 10 | Full Mill | 89.33 | 730 |
| 4 | 2.88 | 2.43 | 40/65 | Waist Drum | 30 | Full Mill | 87.22 | 460 |
| 5 | 4.05 | 4.82 | 50/60 | Waist Drum | 40 | Full Mill | 87.45 | 637 |
| 6 | 3.43 | 4.31 | 50/55 | Waist Drum | 20 | Full Mill | 87.59 | 631 |
| 7 | 3.30 | 3.96 | 45/65 | Equal | 20 | Full Mill | 89.30 | 564 |
| 8 | 2.75 | 3.41 | 45/65 | Waist Drum | 10 | Full Mill | 87.66 | 529 |
| 9 | 2.76 | 2.69 | 50/60 | Constricted | 30 | Full Mill | 87.38 | 542 |
| 10 | 3.00 | 3.09 | 60/50 | Waist Drum | 30 | Full Mill | 88.04 | 624 |
| 11 | 3.00 | 3.10 | 50/70 | Waist Drum | 25 | Full Mill | 90.22 | 561 |

The oxygen factor (A), the second/third air ratio (B), the secondary air distribution method (C) and the burnout wind opening (D) were selected to analyze the factors of boiler efficiency and their influence on NOx. It can be seen from the test results that as for the boiler efficiency, the range of the second/third air ratio (B) is the largest, so the item B has the greatest impact on the boiler efficiency. The optimal combination of boiler efficiency is B3C4D2A2. And as for the NOx value, the range of the secondary air distribution mode (item C) is the largest, and the item C has the greatest influence on the NOx value. As for the control of NOx emissions, the optimal combination of conditions is C3B1D3A4. See Table 4-5 and Table 4-6 for details.
Table 4-5 250MW Boiler Efficiency Orthogonal Test Analysis

|     | A     | B     | C     | D     |
|-----|-------|-------|-------|-------|
| k1/4| 88.18 | 88.06 | 88.03 | 88.45 |
| k2/4| 88.72 | 87.76 | 87.87 | 88.78 |
| k3/4| 87.56 | 90.22 | 89.30 | 87.55 |
| k4/4| 88.24 | 88.69 | 89.33 | 87.45 |
| Range| 1.17  | 2.46  | 1.46  | 1.33  |

Table 4-6 250MW NOx Emission Orthogonal Test Analysis

|     | A     | B     | C     | D     |
|-----|-------|-------|-------|-------|
| k1/4| 665.10| 517.68| 606.76| 638.51|
| k2/4| 616.50| 654.44| 599.49| 640.41|
| k3/4| 582.67| 561.05| 563.89| 542.06|
| k4/4| 576.57| 676.78| 729.71| 636.52|
| Range| 88.53 | 159.09| 165.83| 98.36 |

4.3 200MW Working Condition Test Result

Nine tests were carried out under 200MW working conditions. The factors were changed according to the orthogonal test factor level designed in Table 3-3. The test and analysis results are as follows:

Table 4-7 Summary of Working Conditions of 200MW Load

| Project Working Condition | Furnace Outlet Oxygen | Secondary/Third Wind | Secondary Air Distribution | Burnout Wind | Heat Load Distribution | Boiler Efficiency | NOx Value |
|---------------------------|-----------------------|----------------------|-----------------------------|--------------|------------------------|------------------|-----------|
|                           | %                     | %                   | %                           | %            | %                      |                  | mg/m³     |
| 1                         | 4.3                   | 3.9                 | 35/50                       | Equal        | 30                     | A Stopped        | 84.88     | 507       |
| 2                         | 4.6                   | 4.9                 | 45/70                       | Equal        | 20                     | A Stopped        | 86.47     | 525       |
| 3                         | 5.0                   | 4.2                 | 40/60                       | Waist Drum   | 0                      | A Stopped        | 87.54     | 633       |
| 4                         | 5.0                   | 4.3                 | 55/40                       | Waist Drum   | 10                     | A Stopped        | 89.25     | 591       |
| 5                         | 3.6                   | 4.1                 | 45/70                       | Waist Drum   | 10                     | Full Mill        | 88.79     | 609       |
| 6                         | 3.5                   | 5.6                 | 40/60                       | Equal        | 20                     | Full Mill        | 88.50     | 630       |
| 7                         | 3.3                   | 3.4                 | 55/65                       | Equal        | 20                     | Full Mill        | 89.04     | 584       |
| 8                         | 5.2                   | 6.6                 | 55/60                       | Waist Drum   | 20                     | B Stopped        | 89.26     | 731       |
| 9                         | 4.8                   | 4.1                 | 40/60                       | Constricted  | 10                     | A Stopped        | 88.73     | 559       |

Five factors including oxygen content (A), second/third air ratio (B), secondary air distribution method (C), burnout wind opening (D) and stop grinding (E) were selected to analyze various IMPACTS on boiler efficiency and NOx emission. It can be seen from the test results that for the boiler efficiency, the range of the second/third air ratio (B) is the largest, so the item B has the greatest impact on the boiler efficiency. The optimal combination of boiler efficiency is B3D2A4E3C2. As for the NOx value, the range of the second/third air ratio (item B) is the largest, so the item B has the largest influence on the NOx value. As for the control of NOx emissions, the optimal combination of conditions is B1D4E1A1C3. See Table 4-8 and Table 4-9 for details.

Table 4-8 Orthogonal Test Analysis on Efficiency of 200MW Boiler

|     | A     | B     | C     | D     | E     |
|-----|-------|-------|-------|-------|-------|
| k1/4| 86.834| 84.88 | 88.71 | 87.54 | 88.78 |
| k2/4| 88.93 | 88.26 | 88.73 | 88.92 | 87.37 |
| k3/4| 87.01 | 89.18 | 87.16 | 88.32 | 89.26 |
| k4/4| 89.00 | 87.63 | /     | 84.88 | /     |
| Range| 2.16  | 4.30  | 1.57  | 4.04  | 1.89  |
### 4.4 150MW Working Condition Test Results

Six tests were carried out under 150 MW working conditions. The factors were changed according to the orthogonal test factor level designed in Table 3-4. The test and analysis results are as follows:

#### Table 4-10 Summary of Working Conditions of 150MW Load

| Project Working Condition | Furnace Outlet Oxygen | Secondary/Third Air Distribution | Burnout Burnout Wind | Heat Load Distribution | Boiler Efficiency | NOx Value mg/m³ |
|---------------------------|-----------------------|-----------------------------------|----------------------|-----------------------|------------------|-----------------|
|                           | Left                  | Right                             | %                   | %                    | %                | %               |
| 1                         | 2.4                   | 3.8                               | 40/70               | Equal                | 10               | B Stopped       | 90.57           | 676             |
| 2                         | 2.5                   | 3.6                               | 45/65               | Equal                | 20               | B Stopped       | 88.26           | 659             |
| 3                         | 3.0                   | 5.2                               | 50/60               | Equal                | 30               | B Stopped       | 90.53           | 669             |
| 4                         | 4.9                   | 5.4                               | 45/65               | Equal                | 20               | A Stopped       | 89.69           | 658             |
| 5                         | 4.6                   | 5.2                               | 40/70               | Equal                | 10               | A Stopped       | 88.48           | 665             |
| 6                         | 4.3                   | 5.1                               | 40/70               | Equal                | 10               | A Stopped       | 88.75           | 647             |

The three factors of oxygen content (A), second/third air ratio (B) and burnout air opening (C) were selected to analyze the influence of various factors on boiler efficiency and NOx emission. It can be seen from the test results that it the item A has the greatest impact on the efficiency of the boiler. The optimal combination of boiler efficiency is A³B³C³. As for the NOx value, the second/third air ratio (B) and the burnout air opening (C) have the same difference, so the factors B and C have the same effect on the NOx value and they are relatively important. For the control of NOx emissions, the optimal combination of conditions is B²C²A¹. See Table 4-11 and Table 4-12 for details.

#### Table 4-11 Orthogonal Test Analysis on 150MW Boiler Efficiency

| A  | B  | C  |
|----|----|----|
| k1/3 | 89.66 | 89.27 | 89.27 |
| k2/3 | 88.37 | 88.98 | 88.98 |
| k3/3 | 90.11 | 90.53 | 90.53 |
| Range | 1.74 | 1.56 | 1.56 |

#### Table 4-12 Orthogonal Test Analysis on 150MW NOx Emissions

| A  | B  | C  |
|----|----|----|
| k1/3 | 661.23 | 662.40 | 662.40 |
| k2/3 | 662.11 | 658.66 | 658.66 |
| k3/3 | 663.31 | 668.78 | 668.78 |
| Range | 1.20 | 10.13 | 10.13 |

### 4.5 Comprehensive Analysis

Under different loads, the influence of various control parameters on boiler efficiency and NOx is different. We suggest to formulate corresponding control measures for different loads based on the results of this test.

1) Oxygen Content. Under high load conditions, the oxygen content is low, which belongs to anoxic combustion. The oxygen content has a less effect on boiler efficiency and NOx emissions. As
the load decreases, the operating oxygen increases, the oxygen level gradually affects the boiler efficiency and NOx emission; when it falls to the low load, the combustion is in the oxygen-rich zone, and the oxygen content has less influence on NOx.

2) Second/third wind ratio. At high loads, it has a great influence on NOx emissions. At low loads, it has less impact on NOx emissions; the full load section has a greater impact on furnace efficiency.

3) Air distribution method. With the load reduces, the effect of the air distribution method on the furnace efficiency gradually increases; the impact on NOx emissions reaches the maximum in the 250MW working condition.

4) Burn out wind opening. The effect of the burn-out wind opening on the furnace efficiency is basically the same as the influence of the oxygen quantity and the distribution method; the impact on the NOx emission is less at low load.

The effects of various control parameters on furnace efficiency and NOx emissions under different loads are shown in Table 4-13 and Table 4-14.

| Table 4-13 Orthogonal Test Range of Different Load Boiler Efficiency |
|---------------------------------------------------------------|
| Furnace Outlet Oxygen                                         |
| 300MW 250MW 200MW 150MW                                       |
| 1.04 1.17 2.16 1.74                                           |
| Second/Third Wind Ratio                                       |
| 3.55 2.46 4.30 1.56                                           |
| Air Distribution                                              |
| 1.27 1.46 1.57 /                                             |
| Burnout Wind Opening                                          |
| 1.63 1.33 4.04 1.56                                           |

| Table 4-14 NOx Orthogonal Test of Different Loads             |
|---------------------------------------------------------------|
| Furnace Outlet Oxygen                                         |
| 300MW 250MW 200MW 150MW                                       |
| 33.57 88.53 87.49 1.20                                        |
| Second/Third Wind Ratio                                       |
| 122.78 159.09 128.56 10.13                                    |
| Air Distribution                                              |
| 50.86 165.83 73.56 /                                          |
| Burnout Wind Opening                                          |
| 46.07 98.36 126.36 10.13                                      |

5. Conclusion
When the boiler is under 85-100% load, the secondary/third air ratio has a great influence on the efficiency and NOx emission. Under the premise that the NOx emission does not exceed the standard requirement, increasing the secondary damper opening as much as possible to realize the optimal efficiency of the boiler. When the boiler is under the 60-85% load, the effect of oxygen on the boiler efficiency is much greater than the other three parameters; the oxygen, second/third wind ratio, air distribution mode, and burnout air opening have less effects on NOx emissions. We suggest that under this load section, the oxygen amount shall be adjusted to get the optimal efficiency and control the NOx emissions through the second/third air distribution, the air distribution mode, the burnout air opening. When it is under 50-60% load, the oxygen control is high, and it is in an oxygen-rich combustion state. The adjustment of each parameter has little effect on NOx emissions, and the economics of the boiler should be considered.

References
[1] Zhou, W. T., Yang, T. Y., Li, W. K., et al. (2019) Experimental study on combustion adjustment of economic optimization of supercritical “W” flame boiler. Boiler Technology, 50(1): 47-51.
[2] Jun, L., et al. (2019) Experimental study on combustion optimization adjustment of 600MW supercritical unit boiler in a power plant. Metallurgy and Materials, 39(3): 7-8.
[3] Li, M. (2005) Comparison and Application of support Vector Machine and Orthogonal Design Method. Tianjin University, Tianjin.
[4] Gao, W. (2010) The Information Theory Models of DOE about Optimization Experiments and Explore Experiments. China University of Geosciences, Beijing.
[5] Jiang, X.Y., Liang L.J., et al. (1995) Application of orthogonal experimental optimization design in determining the best production conditions, Xian Dai Yin Xin, 1995(1):52-55.