Boiler Thermal Efficiency Test System Based on NB-IoT Technology

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Abstract: This paper combines the wireless NB-IoT technology with the traditional boiler thermal efficiency test, and uses LabVIEW to develop a test analysis system. By installing the data export module and the transmission module together on the existing equipment to perform wireless and digital upgrade of the detection equipment, the purpose of improving the automation degree of the thermal efficiency test is achieved, thereby reducing the number of test staff on site. At the same time, it will avoid the dust and high temperature danger that the staff will encounter on site. The complex boiler thermal efficiency calculation formula is simplified according to the wireless, real-time and accurate needs of the boiler thermal efficiency test. A formula for calculating the enhalpy value that satisfies the requirements of online testing, a formula for the heat loss of the incomplete combustion of the gas, and a formula for fitting the ash combustibles are proposed.

1. Background
Boiler thermal efficiency test is one of the starting points and the most important content for carrying out boiler energy-saving renovation and improving boiler thermal efficiency. Efficient, accurate and comprehensive thermal efficiency testing is the technical and data foundation for the effective implementation of the boiler thermal efficiency improvement project. The boiler thermal efficiency test, especially the product qualification test and detailed test, has the problems of long test time, poor working environment of the test staff, and difficulty in real-time feedback of the thermal efficiency of the boiler, which affects test quality and productivity. The boiler thermal efficiency testing is not an online test conducted on a fixed number of days. The unstable test cycle lasting one to five days makes it impossible to establish a wired data transmission system, and real-time recording, calculation and analysis of integrated data cannot be realized. Since it is difficult to display the trend of data changes, this is not conducive to the control of the test process by the test staff on site. At present, the research online test models related to boiler thermal efficiency at home and abroad focuses on power station boilers. Industrial boiler thermal efficiency testing is mostly off-line testing, which is difficult for on-site testing. In addition, there are few systematic studies on industrial boiler online test technology, especially the online thermal efficiency test system based on low-power IoT technology. [1-4] Therefore, for industrial boilers, it is of great practical value to develop a boiler thermal efficiency test system based on wireless transmission technology with universal, rapid and efficient performance.

2. Thermal efficiency test platform based on NB-IoT technology
The traditional thermal efficiency test is mainly based on single test, and the test parameters are numerous with poor correlations. The wired communication has high cost and complicated wiring, which can not fully meet the needs of industrial applications. In this paper, the existing thermal
efficiency devices, including the flue gas analyzer, the ultrasonic flowmeter and the thermometer, are used to carry out the wireless upgrade of the detection equipment by adding the data exporting module and the NB-IoT transmission module. The wireless NB-IoT technology is applied to boiler thermal efficiency testing to achieve real-time interaction between testers, test equipment, and boilers under inspection.

2.1 Network architecture of the NB-IoT thermal efficiency test system
The NB-IoT technology in low-power wide-area IoT technology has the advantages of low power consumption, shielding against metal components, deep coverage, long battery life, no need for self-organizing networks, no repeaters, and high scalability. It is enabled to well avoid the problem that the host is difficult to receive data stably due to the interference of the boiler steel frame and the wall, realizing the wireless and digital stable transmission of the thermal efficiency test data. The NB-IoT uses the license bands and can adopt three deployment modes: in-band, guard band, or independent carrier to coexist with the existing network. The communication module of NB-IoT technology connects multiple test equipment to form an efficient and stable data transmission wireless network. The wireless data acquisition terminal reads the data of various test equipment at the lower end through the connector. Through the NB-IoT wireless transmission module, the data is sent to the NB-IoT base station, and then uploaded to the management platform and directly forwarded to the host computer for analysis and calculation, as shown in Figure 1. The NB-IoT network includes an NB-IoT terminal, an NB-IoT base station, an NB-IoT packet core network, an NB-IoT connection management platform and an application end, as shown in Figure 2.

![Fig.1 NB-IoT based thermal efficiency test system](image1)

![Fig.2 NB-IoT network composition](image2)

2.2 Founding of a calculation analysis system
Using the virtual instrument technology of the graphical programming language LabVIEW, the real-time data transmitted by the NB-IoT is read in order to develop a calculation analysis system. The system includes six module functions: test project management, test data management, result analysis and judgment, data self-learning, instrument and equipment management, and standard data. These modules can display values, averages and overall trend lines at each time point. The test module has a data manual resume function. The host calculates each data to obtain thermal efficiency, heat loss...
values, instantaneous values of the output values, or an average of selected time periods. Besides, the rationality of key data is determined, alarm prompt values are set, and improvements are proposed.

3. Thermal efficiency calculation model analysis

The selection and improvement of the thermal efficiency calculation model is an important part of the boiler thermal efficiency test system design. This test system adopts three paths, including GB/T10180-2003 Thermal Performance Test Code for Industrial Boilers, TSG G0003-2010 Energy Efficiency Test and Evaluation Rules for Industrial Boilers and engineering experience formulas to achieve accurate and efficient calculation results of the test system. Formulas (1)-(3) are the ones for calculating the positive balance thermal efficiency, and formulas (4)-(9) are the ones for calculating the negative balance and the heat loss. Among them, the formula (3) corrects the problem that the positive balance thermal efficiency formula of the superheated steam boiler fails to calculate the difference in enthalpy between the superheated steam and the saturated steam in the GB/T10180-2003 Thermal Performance Test Code for Industrial Boilers. Formula (6) gives a simplified engineering calculation formula for the incomplete combustion heat loss of gas [7]. Formula (7) based on the Energy Efficiency Test and Evaluation Rules for Industrial Boilers further simplifies the engineering calculation formula for incomplete combustion heat loss. Based on the principle that accuracy and efficiency are equally important, the water and water vapor enthalpy is calculated with the least squares fitting formula.

Positive balance thermal efficiency:
For hot water boiler:
\[
\eta_p = \frac{G(h_s - h_l)}{BQ_c} \times 100\%
\]
(1)

For saturated vapor boiler:
\[
\eta_p = \frac{D_q(h_s - h_l)}{G} \times 100\%
\]
(2)

For superheated steam boiler:
\[
\eta_p = \frac{D_q(h_s - h_l) + G(h_s - h_g)}{BQ_c} \times 100\%
\]
(3)

\(G\)——the circulating water of the hot water boiler or the circulating oil of the hot oil carrier boiler(kg/h);
\(h_s\)——Outlet enthalpy of the hot water boiler or the hot oil carrier boiler(kJ/kg);
\(h_l\)——Intake enthalpy of the hot water boiler or the hot oil carrier boiler(kJ/kg);
\(h_s\)——Enthalpy of superheated steam(kJ/kg) (under test temperature and pressure);
\(D_q\)——Feedwater flow of steam boiler(kg/h);
\(h_s\)——Enthalpy of saturated steam(kJ/kg);
\(h_g\)——Feedwater enthalpy of steam boiler(kJ/kg);
\(r\)——Latent heat of vaporization(kJ/kg);
\(w\)——Steam moisture(\%);
\(G_c\)——Boiler water sampling(kg/h);
\(B\)——Fuel consumption(kg/h);

Negative balance thermal efficiency:
\[
\eta_n = 100 - (q_2 + q_3 + q_4 + q_5 + q_6)
\]
(4)

Exhaust heat loss:
\[
q_2 = (m + n) \frac{f_{py} - f_n}{100} \left(1 - \frac{q_L}{100}\right)
\]
(5)

Gas incomplete combustion heat loss:
3.2 Processing of boiler output calculation parameters

Boiler output is the primary parameter for boiler thermal efficiency positive balance testing and characterizing the performance of the boiler. Calculations involve pressure, medium flow, medium temperature, and enthalpy. In this system, the medium flow, medium temperature and flue gas composition can be tested in real time by test equipment and transmitted to a thermal efficiency analysis platform. The boiler pressure is relatively stable, but the pressure gauge is connected to the pressure-bearing components, so it is not easy to disassemble on site. The system is processed by manual entry. The enthalpy value is obtained by the medium pressure and temperature fitting formula.

According to the type of working substance, the calculation of substance enthalpy value is divided into three parts, namely unsaturated water area, saturated steam area and superheated steam area. According to the water and water vapor property table data and the nature of the medium itself, the enthalpy values of the three areas are respectively fitted by least squares.
(1) Calculation of superheated steam enthalpy

The steam enthalpy near the boiler operating point can be obtained by look-up table method or by the IAPWS-IF97 fitting formula. However, in online applications in industrial sites, the look-up table method is too inefficient. In the meantime, the IAPWS-IF97 fitting formula is too complicated. Therefore, this paper selects the range of expected parameters of superheated steam, and uses the least squares method to perform quadratic fitting to obtain the calculation formula of superheated steam enthalpy under different temperatures and pressures.

The industrial boilers in this study are expected to have a pressure range of 1.6 MPa to 3.2 MPa and a temperature of 240° C to 360° C. This paper is dedicated to find a fitting formula that satisfies engineering applications in this area. After checking, the steam enthalpy value of the area is obtained, as shown in Table 1:

| Table 1. Enthalpy table near the working point of industrial boiler | kJ/kg |
|---|---|
| T/°C | P/MPa | 1.6 | 1.8 | 2 | 2.2 | 2.4 | 2.6 | 2.8 | 3 | 3.2 |
| 240 | 2889.56 | 2880.34 | 2870.81 | 2860.94 | 2850.72 | 2840.12 | 2829.1 | 2817.62 | 2805.65 |
| 260 | 2938.39 | 2930.7 | 2922.8 | 2914.69 | 2906.37 | 2897.81 | 2889.01 | 2879.94 | 2870.6 |
| 280 | 2985.46 | 2978.89 | 2972.19 | 2965.35 | 2958.37 | 2951.24 | 2943.95 | 2936.5 | 2928.89 |
| 300 | 3031.32 | 3025.62 | 3019.83 | 3013.94 | 3007.96 | 3001.88 | 2995.69 | 2989.4 | 2983 |
| 320 | 3076.35 | 3071.34 | 3066.26 | 3061.12 | 3055.91 | 3050.63 | 3045.28 | 3039.85 | 3034.35 |
| 340 | 3120.82 | 3116.36 | 3111.86 | 3107.31 | 3102.71 | 3097.96 | 3093.36 | 3088.61 | 3083.81 |
| 360 | 3164.91 | 3160.91 | 3156.88 | 3152.81 | 3148.71 | 3144.57 | 3140.4 | 3136.18 | 3131.93 |

Since the enthalpy value is a binary function \( h = f(T, P) \) of temperature and pressure, the \( T \) is regarded as the first independent variable and the least squares polynomial fitting is used to obtain the fitting result in Table 2:

| Table 2. Results of fitting the temperature |
|---|---|
| P/MPa | \( h = aT^2 + bT + c \) |
| 1.6 | \( h = -0.0011T^2 + 2.9739T + 2241.9 \) |
| 1.8 | \( h = -0.0014T^2 + 3.1691T + 2200.6 \) |
| 2 | \( h = -0.0017T^2 + 3.3796T + 2156.6 \) |
| 2.2 | \( h = -0.002T^2 + 3.6086T + 2109.4 \) |
| 2.4 | \( h = -0.0023T^2 + 3.8562T + 2058.9 \) |
| 2.6 | \( h = -0.0027T^2 + 4.1251T + 2004.7 \) |
| 2.8 | \( h = -0.0031T^2 + 4.4168T + 1946.6 \) |
| 3 | \( h = -0.0035T^2 + 4.7373T + 1883.6 \) |
| 3.2 | \( h = -0.004T^2 + 5.0874T + 1815.5 \) |

Then \( P \) is regarded as the second independent variable and the least squares polynomial fitting is performed. Through the error comparison, the final determination is based on a sixth-order polynomial fit, which in Table 3 is:

| Table 3. Results of fitting the pressure |
|---|---|
| \( a \) | \(-0.002026P^6 + 0.028767P^5 - 0.16813P^4 + 0.517321P^3 - 0.883562P^2 + 0.79278P - 0.2923 \) |
| \( b \) | \(-0.047888P^6 + 0.69069P^5 - 4.0903P^4 + 12.773P^3 - 22P^2 + 20.651P - 5.6984 \) |
| \( c \) | \( 6.7998P^6 - 98.818P^5 + 589.45P^4 - 1854.3P^3 + 3212P^2 - 3086.5P + 3612 \) |
The maximum and minimum ultimate pressures that... sensitive to temperature. This paper selects t...

Table 4. Comparison of the error between fitting point and true value under different pressure and temperature

| P/MPa | T=260°C | T=280°C | T=300°C | T=320°C |
|-------|---------|---------|---------|---------|
|       | Fitting Value | Truth Value | Relative Error | Fitting Value | Truth Value | Relative Error | Fitting Value | Truth Value | Relative Error | Fitting Value | Truth Value | Relative Error |
| 1.6   | 2941.80 | 2938.39 | 0.12     | 2989.546 | 2985.46 | 0.14     | 3036.416 | 3031.42 | 0.16 | 3082.415 | 3076.35 | 0.20     |
| 1.8   | 2931.598 | 2930.7 | 0.03     | 2980.094 | 2978.89 | 0.04     | 3027.487 | 3025.62 | 0.06 | 3073.777 | 3071.34 | 0.08     |
| 2     | 2922.026 | 2922.8 | -0.03    | 2971.513 | 2972.19 | -0.02    | 3019.626 | 3019.83 | -0.01 | 3066.395 | 3066.26 | 0.00     |
| 2.2   | 2915.614 | 2914.69 | 0.03     | 2966.642 | 2965.35 | 0.04     | 3016.104 | 3013.94 | 0.07 | 3063.999 | 3061.12 | 0.09     |
| 2.4   | 2908.158 | 2906.37 | 0.06     | 2960.719 | 2958.37 | 0.08     | 3011.458 | 3007.96 | 0.12 | 3060.377 | 3055.91 | 0.15     |
| 2.6   | 2897.801 | 2897.81 | 0.00     | 2951.558 | 2951.24 | 0.01     | 3003.185 | 3001.88 | 0.04 | 3052.682 | 3050.63 | 0.07     |
| 2.8   | 2887.087 | 2889.01 | -0.07    | 2942.12 | 2943.95 | -0.06    | 2994.684 | 2995.69 | -0.03 | 3044.779 | 3045.28 | -0.02    |
| 3     | 2878.624 | 2879.94 | -0.05    | 2935.446 | 2936.5 | -0.04    | 2989.456 | 2989.4 | 0.00  | 3040.654 | 3039.85 | 0.03     |
| 3.2   | 2864.148 | 2870.6 | -0.22    | 2921.974 | 2928.89 | -0.24    | 2976.544 | 2983 | -0.22 | 3027.858 | 3034.35 | -0.21    |

According to the statistical results of Table 4 and Table 5, the absolute value of the relative error is between 0 and 0.24%, which is acceptable in engineering.

(2) Calculation of saturated steam enthalpy

The saturated steam enthalpy is relatively simple compared to the superheated steam enthalpy. The medium pressure has a one-to-one correspondence with temperature and enthalpy, so it is easy to get a fitting formula (11).

\[ h = 4.0091P^3 - 29.694P^2 + 79.347P + 2727.7 \]  

(11)

Table 6 shows the error between the fitting point and the true value of the saturated steam enthalpy at different pressures:

Table 6. Comparison of the error between fitting point and true value under different pressures

| Enthalpy /Pressure MPa | 1  | 1.2 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 2   | 2.2 |
|------------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| Fitting Value kJ/kg    | 2781.36 | 2787.08 | 2791.58 | 2793.4 | 2795.06 | 2796.47 | 2797.69 | 2799.69 | 2801.23 |
| Truth Value kJ/kg      | 2781.32 | 2787.11 | 2791.56 | 2793.40 | 2795.02 | 2796.43 | 2797.68 | 2799.71 | 2801.19 |
| Relative Error %       | 0.00129 | -0.00094 | 0.0007 | 0.00117 | 0.00131 | 0.00121 | 0.00039 | -0.00069 | 0.00126 |

The maximum relative error between the fitted value and the true value is only 0.0013%, which shows high accuracy of the fitting formula.

(3) Calculation of unsaturated water enthalpy

Similar to the case of superheated steam, there are multiple temperatures corresponding to different enthalpy values at the same pressure. However, the enthalpy here is not sensitive to pressure changes but is sensitive to temperature. This paper selects the maximum and minimum ultimate pressures that
can be encountered in the test and the average pressure between them (0.1MPa, 2.0MPa, 1.0MPa), and lists the corresponding water enthalpy values at common temperatures. By comparison, it can be found that the maximum relative error of enthalpy due to pressure changes is only 0.28%. In fact, the pressure difference between the inlet and outlet of the boiler water is generally about 0.2-0.5 MPa, and the above error should be reduced by about 0.14%, which is acceptable in engineering. The formula (11) for fitting the enthalpy value based on 1.0 MPa is:

\[ h = 0.000006t^3 - 0.00084t^2 + 4.2327t - 0.0631 \]  

(11)

The maximum relative error between the fitted value and the true value is only 0.05%. It can be seen that the fitting of unsaturated water also has higher accuracy.

3.3 Gas incomplete combustion heat loss \( q_3 \)

In the actual test, the unburned combustible gas mainly refers to the CO content. TSG G0003-2010 Energy Efficiency Test and Evaluation Rules for Industrial Boilers only gives the table value of the incomplete combustion heat loss of the gas based on the CO content of the exhaust gas. However, there is a large error between look-up table and calculation, and the maximum difference is nearly 30 times. The main influencing factors of \( q_3 \) are the carbon monoxide content \( CO' \) and the excess air ratio \( a_{py} \) at the exhaust. Although natural gas is dangerous to sample but its composition is relatively stable, the typical natural gas composition in Tianjin is selected as the reference fuel component. Simplified calculation formula (12) based on theoretical formula is obtained:

\[ q_3 = (3.36a_{py} - 0.34) CO' \]  

(12)

In order to verify the accuracy of the derived formula and the results when the fuel composition changes greatly, this paper uses the data of the thermal efficiency test of some gas and coal-fired boilers in our college since 2015 (number 1 ~ 6 are the gas boilers, number 7 ~ 8 are coal-fired boilers, number 9 to 10 are biomass boilers, and number 11 to 12 are oil-fired boilers). At the same time, the calculation of \( q_3 \) in the simple test under the operating conditions of TSG G0003-2010 is compared. The results are shown in Table 8.

| Serial Number | \( a_{py} \) | \( CO' \) (%) | Type Testing \( q_3 \) (%) | Simple Testing \( q_3 \) (%) | Error of Simple Testing \( q_3 \) (%) | Engineering Formula \( q_3 \) (%) | Error of Engineering formula \( q_3 \) |
|---------------|--------------|----------------|-----------------|----------------|----------------|----------------|----------------|
| 1             | 1.15         | 0              | 0               | 0.2            | 0.2            | 0              | 0              |
| 2             | 1.13         | 0.01           | 0.035           | 0.2            | 0.165          | 0.034568       | -0.00043       |
| 3             | 1.15         | 0.03           | 0.11            | 0.2            | 0.09           | 0.10572        | -0.00428       |
| 4             | 1.09         | 0.005          | 0.017           | 0.2            | 0.183          | 0.016612       | -0.00039       |
| 5             | 1.29         | 0.062          | 0.25            | 0.5            | 0.25           | 0.247653       | -0.00235       |
| 6             | 1.16         | 0.081          | 0.29            | 0.5            | 0.21           | 0.288166       | -0.00183       |
| 7             | 1.47         | 0.0054         | 0.023           | 0.2            | 0.177          | 0.024836       | 0.001836       |
It can be seen from the calculation results that the results of the derivation formula are very close to the test results and the error rate is slight for different fuels. The gas boiler is repaired by retaining two significant figures, and the error between the calculation result and the final test is 0.0043%. The maximum error for coal-fired, biomass-burning, and oil-fired boilers does not exceed 0.0039%. The calculation accuracy is one lever higher than the calculation method of the simple test under the operating conditions of TSG G0003-2010.

3.4 Solid incomplete combustion heat loss $q_4$

In the simplified calculation formula of the solid incomplete combustion heat loss $q_4$, the ash and the net calorific value as received basis of the fuel are basically stabilized to a known amount, and the ash and combustible content need to be determined experimentally. Standard calculation of the ash content share is performed after the test is completed, so it is impossible to provide real-time data of the test process. From the experience of the previous customary thermal efficiency test, the data relates to the slag weighing, the slag moisture content and the fly ash combustible content, the calculation accuracy is not high and the process is cumbersome. Therefore, the data in this paper is selected based on the empirical table of engineering application in TSG G0003-2010 Energy Efficiency Test and Evaluation Rules for Industrial Boilers, and the values are selected according to Table 9.

| Table 9. Weight percentage of fly ash and slag ash content in total ash content of furnace fuel (%) |
|----------------------------------|----------------------------------|
| Combustion Mode                  | Type of Coal                     |
|                                 | Fly Ash ($\alpha_{fh}$)          | Slag ($\alpha_{lz}$)          |
| Reciprocating Grate              | 20–10                            | 75–85                          |
| Chain Grate                      | 20–10                            | 75–85                          |
| Stoker Grate                     | 30–20                            | 65–75                          |
| Fluidized Bed                    | 50–40                            | 50–60                          |
| Pulverized Coal                  | 90–80                            | 10–20                          |
| Fired Boiler                     |                                  |                                |
| Coal Water Slurry                | 80–70                            | 20–30                          |

Note: When selecting, $\alpha_{fh}+\alpha_{lz}=100$ should be satisfied. For fuel and gas boilers, $q_4$ is 0

For technical and economic reasons, it is difficult to achieve accurate on-line measurement of slag and fly ash combustibles contents. In the case where the hardware detection device cannot complete the measurement, a statistically-based soft measurement scheme can be used to solve the problem. The author has previously studied the application of the above calculation method for $q_4$ in engineering, and derived the simplified fitting formula, which will not be elaborated here.

4. Conclusion

In this paper, NB-IoT technology is applied to boiler thermal efficiency test, and wireless transformation based on existing thermal efficiency test equipment is realized. By establishing a thermal efficiency test software platform, real-time interaction between testers, test equipment, and boilers under inspection can be realized to form an efficient and stable data transmission wireless network.

The simplified boiler thermal efficiency calculation formula, the enthalpy value calculation formula and the ash combustible fitting formula are obtained by theoretical derivation and experimental
verification. This not only takes into account the wireless, real-time and accurate calculation of boiler thermal efficiency, but also can be used for on-line monitoring of boiler thermal efficiency. However, due to the single subject and few experimental samples, it needs to be supplemented and revised in the subsequent actual study.

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