Study of Design Theory and Application Software
Development of Correct Calculation for Air Heaters Performance Test

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Abstract. Based on performance test of tri-sector rotary air heaters, the paper briefly proposed a correct calculating method of gas temperature, air temperature, air leakage rate and resistance. A Correct calculation software of air heaters performance test was developed. It can normalize and unify computation, solve some problems such as the organic combination of manual intervention and computer calculation and the cyclic iteration of some parameters. The study will help to improve speed and accuracy of computation, improve the efficiency of the economy and cost savings, enhance the competitiveness of power generators, and has an important utility value.

1. Introduction
As last heating surface, the air heaters plays an important role in air heating and waste heat recovery of gas leaving steam-water endothermic section. The air heaters couples air and flue system, coal pulverizing system, combustion system and so on. Air heaters thermal performance test is usually required to test performance of air heaters for the thermal power unit. The air heaters thermal performance usually includes gas side efficiency, air leakage rate, correct coefficient, gas-air resistance and gas temperature. At present, the widely-adopted code are Chapte 8.6 of GB/T 10184—2015 Performance test code for utility boiler[1] and Air heaters performance test codes: ASMEPTC 4.3-2017[2]. But GB/T 10184—2015 Performance test code for utility boiler only provides basic definitions and simplified formulas for air heaters, and do not related to air leakage rate and resistance Correct calculation. It is short of important content such as thermal performance, X ratio, air leakage rate correction, resistance test, so Air heaters performance test codes: ASMEPTC 4.3-2017 is used in most acceptance test in China. Before 2017, the version is Air heaters performance test codes: ASME PTC 4.3—1968. Before this code was finalized, no tri-sector rotary air heaters was invented, so it should apply only to bisector rotary air heaters. North China Electric Power Research Institute wrote Air heaters performance test codes in order to regulate and help performance test of air heaters and apply to new equipment.

The purpose of air heaters performance test is identify thermal performance of air heaters. The difference between actual test and design condition is unavoidable in the process performance test. In order to compare with design performance of air heaters, test results need to be revised to design condition. Based on studying the outcomes in related fields at home and aboard, Air heaters performance test codes gave a correct and interoperable correcting computational method of air
2. Correct calculation

2.1. Gas temperature correction

Compared to design conditions, the influence of change parameters such as air leakage, inlet air temperature, inlet gas flow, inlet gas temperature, heat capacity ratio, air mass on outlet gas temperature of air heaters should be calculated in process of actual test. The calculation formula is as follows:

\[
 t_{fg, lv, nl, cr} = t_{fg, lv, nl} + \Delta t_{cr, a, en} + \Delta t_{cr, fg, en} + \Delta t_{cr, fg, qm} + \Delta t_{cr, fg, x} \quad (1)
\]

\( t_{fg, lv, nl, cr} \) Is exhaust gas temperature revised to design condition, \(^\circ\)C. \( t_{fg, lv, nl} \)  Is revised exhaust gas temperature taken into air leakage of air heaters, \(^\circ\)C. \( \Delta t_{cr, a, en} \) Is revised temperature taken into the inlet air temperature change, \(^\circ\)C.  \( \Delta t_{cr, fg, en} \) Is revised temperature taken into the inlet gas temperature change, \(^\circ\)C.  \( \Delta t_{cr, fg, qm} \) Is revised temperature taken into the inlet gas mass change, \(^\circ\)C.  \( \Delta t_{cr, fg, x} \) Is revised temperature taken into \( X_g \) deviate from the designed, \(^\circ\)C.

The change of inlet air temperature causes the change in exhaust gas temperature, the calculation formula of correct value is as follows.

\[
 \Delta t_{cr, a, en} = \frac{t_{a, en, ds} (t_{fg, en} - t_{fg, lv, nl}) + t_{fg, en} (t_{fg, lv, nl} - t_{a, en})}{t_{fg, en} - t_{a, en}} - t_{fg, lv, nl} \quad (2)
\]

\( t_{a, en, ds} \) Is inlet air design temperature of air heaters, \(^\circ\)C.

The change of inlet gas temperature causes the change in exhaust gas temperature, the calculation formula of correct value is as follows.

\[
 \Delta t_{cr, fg, en} = \frac{t_{a, en} (t_{fg, en} - t_{fg, lv, nl}) + t_{fg, en, ds} (t_{fg, lv, nl} - t_{a, en})}{t_{fg, en} - t_{a, en}} - t_{fg, lv, nl} \quad (3)
\]

\( t_{fg, en, ds} \) Is inlet gas design temperature of air heaters, \(^\circ\)C.

The change of inlet gas mass causes the changes in some parameters such as air velocity, the average temperature, heat transfer coefficient. The calculation formula of correct value is as follows:
$$\Delta t_{cr.fg.qm} = t_{fg.lv.qm} - t_{fg.lv.nl}$$ (4)

$$t_{fg.lv.qm} = \frac{t_{fg.en} - \eta_{fg} (t_{fg.en} - t_{a.en})}{100 f_{qm}}$$ (5)

$t_{fg.lv.qm}$ is exhaust gas temperature under current inlet gas mass of air heaters, °C. $\eta_{fg}$ is heat transfer efficiency of gas, %. $f_{qm}$ is correction factor under the changed inlet gas mass of air heaters, °C.

The change of heat capacity ratio causes the changes in beside gas mass, such as the change of air mass causes the changes in exhaust gas temperature. The calculation formula of correct value is as follows.

$$\Delta t_{cr.fg.xr} = t_{fg.lv.xr} - t_{fg.lv.nl}$$ (6)

$$t_{fg.lv.xr} = \frac{t_{fg.en} - \eta_{fg} (t_{fg.en} - t_{a.en})}{100 f_{xr}}$$ (7)

$t_{fg.lv.xr}$ is exhaust gas temperature under current heat capacity ratio, °C. $f_{xr}$ is correction factor under the changed inlet gas mass of air heaters, °C.

2.2. Air temperature correction

The outlet air temperature of air heaters can be computed with revised gas temperature based on heat balance, the calculation formula is as follows:

$$H_{ha.lv.cr} = H_{a.en.d} + \frac{q_{m.fg.en.d} \left( H_{fg.en.d} - H_{fg.lv.nl.cr} \right)}{q_{m.pa.lv.d} + q_{m.sa.lv.d}}$$ (8)

2.3. Air leakage correction

In tri-sector rotary air heaters, the gas bin next to primary air bin and secondary air bin. There is a considerable difference in air leakage between air bin and gas bin. The calculation formula of air leakage ratio is as follows:

$$\eta_{lg,i} = \frac{q_{m.fg.en.i}}{q_{m.fg.en.d}} \left( \frac{\Delta P_{pf.d} (t_{pa.en.i} + 273.15)}{\Delta P_{pf.i} (t_{pa.en.d} + 273.15)} + \frac{\Delta P_{sf.d} (t_{sa.en.i} + 273.15)}{\Delta P_{sf.i} (t_{sa.en.d} + 273.15)} \right)$$ (9)

$\Delta P_{pf.d}$ is the design difference between inlet pressure of primary air bin and outlet pressure of gas bin, Pa. $\Delta P_{pf.i}$ is the actual difference between inlet pressure of primary air bin and outlet pressure of gas bin, Pa. $t_{pa.en.i}$ is the cold primary air design inlet temperature of air heaters, °C. $t_{pa.en.d}$ is the cold primary air actual inlet temperature of air heaters, °C.
2.4. Resistance correction

1) Gas resistance correction

\[
\Delta P_{fg,cr.i} = \Delta P_{fg,i} \left( \frac{q_{m fg, en.d}}{q_{m fg, en.i}} \right)^{1.8} \frac{t_{fg, en.d} + t_{fg, lv.nl.d} + 546.30}{t_{fg, en.i} + t_{fg, lv.nl.i} + 546.30} 
\]

\( \Delta P_{fg,cr,i} \) is gas resistance revised to design condition, Pa. \( \Delta P_{fg,i} \) is actual gas resistance, Pa. \( t_{fg, en,i} \) is gas inlet temperature of air heaters, \( t_{fg, en.d} \) is gas design inlet temperature of air heaters, \( t_{fg, lv.nl,i} \) is gas outlet temperature of air heaters without air leakage, \( t_{fg, lv.nl.d} \) is gas design inlet temperature of air heaters without air leakage, \( ^\circ \text{C} \).

2) Air Resistance Correction

\[
\Delta P_{pa,cr,i} = \Delta P_{pa,i} \left( \frac{q_{m pa, lv.d}}{q_{m pa, lv,i}} \right)^{1.8} \frac{t_{pa, en.d} + t_{pa, lv.d} + 546.30}{t_{pa, en,i} + t_{pa, lv,i} + 546.30} 
\]

\[
\Delta P_{sa,cr,i} = \Delta P_{sa,i} \left( \frac{q_{m sa, lv.d}}{q_{m sa, lv,i}} \right)^{1.8} \frac{t_{sa, en.d} + t_{sa, lv.d} + 546.30}{t_{sa, en.i} + t_{sa, lv,i} + 546.30} 
\]

\( \Delta P_{pa,i} \) is primary air resistance, Pa. \( \Delta P_{pa,cr,i} \) is primary air resistance revised to design condition, Pa. \( \Delta P_{sa,i} \) is secondary air resistance, Pa. \( \Delta P_{sa,cr,i} \) is secondary air resistance revised to design condition, Pa. \( t_{pa, en,i} \) is primary air temperature of air heaters inlet, \( t_{pa, en.d} \) is primary air design temperature of air heaters inlet, \( t_{pa, lv,i} \) is primary air temperature of air heaters outlet, \( t_{pa, lv.d} \) is primary air design temperature of air heaters outlet, \( t_{sa, en,i} \) is secondary air temperature of air heaters inlet, \( t_{sa, en.d} \) is secondary air design temperature of air heaters inlet, \( t_{sa, lv,i} \) is secondary air temperature of air heaters outlet, \( t_{sa, lv.d} \) is secondary air design temperature of air heaters outlet, \( ^\circ \text{C} \).

3. The function of program

The program can control the order of thermodynamic calculation and perform calculation of performance test correction of air heaters by combining air model, coal model, gas model and air heaters model. The overall structure of software is shown in Figure 1.
3.1. Coal category
Coal is the main fuel of coal-fired power plant. There are many classification methods of coal in China. The content of components is different for different coal. The sum for each content of component should be equal to 100. The main function of the coal category as follow: judge whether the sum equal to 100.

3.2. Gas category
Main functions of gas category: Set and calculate the related parameters of gas. Take one power plant as an example, input the related parameters to main program. The calculation results are as follows.

Table 1. The related parameters and calculation results of gas

| NO. | Calculation results                                    | Unit    | Value  |
|-----|--------------------------------------------------------|---------|--------|
| 1   | Vapour volume in gas                                   | m³/kg   | 0.625  |
| 2   | The actual combustion carbon of coal-based             | %       | 41.59  |
| 3   | Theoretical dry air volume                             | m³/kg   | 4.120  |
| 4   | Theoretical nitrogen volume                            | m³/kg   | 3.837  |
| 5   | Triatomic gas volume                                   | m³/kg   | 0.783  |
| 6   | Theoretical vapour volume                             | m³/kg   | 0.652  |
| 7   | Theoretical dry gas volume                             | m³/kg   | 4.042  |
| 8   | Actual gas volume                                      | m³/kg   | 4.774  |
| 9   | Vapour volume in gas                                   | m³/kg   | 0.625  |
| 10  | Actual wet gas volume                                  | m³/kg   | 5.399  |
| 11  | Average excess air coefficient of air heaters inlet    | /       | 1.143  |
| 12  | Gas design heat capacity under constant pressure of air heaters inlet | kJ/(kg.K) | 1.086 |
| 13  | Gas design enthalpy of air heaters inlet               | KJ/(kg.°C) | 7.462 |

3.3. Air category
To facilitate the calculation of the software program, the air class is set separately. Main functions of air category: Set and calculate the related parameters of air. To return to the example of one power plant, input the related parameters to main program. The calculation results are as follows.
Table 2. The related parameters and calculation results of air

| NO. | Calculation results                                      | Unit   | Value  |
|-----|---------------------------------------------------------|--------|--------|
| 1   | Average air temperature of air heaters inlet           | ℃      | 80.46  |
| 2   | Air heat capacity under constant pressure of air heaters inlet | KJ/(kg.℃) | 1.009 |
| 3   | Air temperature of air heaters inlet                   | ℃      | 25.12  |
| 4   | The difference between primary air pressure and gas pressure | pa      | 11645  |
| 5   | The difference between secondary air pressure and gas pressure | pa    | 2695.5 |
| 6   | The difference between primary air pressure and secondary air pressure | pa | 8949.5 |
| 7   | Air leakage temperature                                | ℃      | 65.01  |
| 8   | The design difference between primary air pressure and gas pressure | pa | 15145  |
| 9   | The design difference between secondary air pressure and gas pressure | pa | 5145   |
| 10  | Air outlet temperature                                 | ℃      | 337.00 |
| 11  | Air design enthalpy of air heaters inlet               | KJ/kg.℃ | 5.351 |
| 12  | Air leakage factor from primary air to secondary air     | /      | 0.74   |
| 13  | Air leakage factor from primary air to gas              | /      | 0.65   |
| 14  | Air leakage factor from secondary air to gas            | /      | 0.35   |

3.4. Air heaters category

Main functions of air heaters category mainly includes four parts: gas temperature correction, air temperature correction, air leakage correction and resistance correction. The gas temperature correction include correction taken into the inlet air temperature change, correction taken into the inlet gas temperature change, correction taken into the inlet gas mass change and correction taken into $X_R$ deviate from the designed. The resistance correction include gas resistance correction and air resistance correction. The overall structure of software is shown in Figure 2:

![Figure 2. Structure of air heaters category](image)

Main functions of air heaters category: Set and calculate the related parameters correction computation of air heaters performance test. To return to the example of one power plant, input the related parameters of coal, air, gas and thermal power unit to main program. The calculation results are as follows:
Table 3. The related parameters and calculation results of air heaters

| NO. | Calculation results                                                | Unit | Value       |
|-----|-------------------------------------------------------------------|------|-------------|
| 1   | Excess air coefficient of air heaters inlet                      |      | 1.11        |
| 2   | Excess air coefficient of air heaters outlet                     |      | 1.18        |
| 3   | Air leakage rate                                                 | %    | 5.65        |
| 4   | Gas temperature of air heaters outlet without air leakage        | °C   | 139.81      |
| 5   | Revised temperature taken into the inlet air temperature change  | °C   | -0.47       |
| 6   | Revised temperature taken into the inlet gas temperature change  | °C   | 0           |
| 7   | Heat transfer efficiency of gas                                  | %    | 67.22       |
| 8   | Assume gas temperature of air heaters outlet without air leakage | °C   | 137         |
| 9   | Air temperature correction of air heaters outlet                 | °C   | 335.36      |
| 10  | Heat capacity ratio of air and gas                               |      | 1.31912     |
| 11  | Intermediate variable D                                          |      | -0.97351    |
| 12  | Intermediate variable U                                          |      | -0.00156    |
| 13  | Generalized heat transfer coefficient K                          | W/°C | 682.18      |
| 14  | Gas mass ratio of design and actual                              |      | 1.03337     |
| 15  | Air mass ratio of design and actual                              |      | 0.95387     |
| 16  | Gas heat capacity ratio of design and actual                     |      | 0.99987     |
| 17  | Air heat capacity ratio of design and actual                     |      | 0.99995     |
| 18  | Heat transfer coefficient correction of air and gas              | W/°C | 676.15      |
| 19  | Assume gas temperature of air heaters outlet without air leakage | °C   | 137         |
| 20  | Intermediate variable Up                                         |      | -0.00143    |
| 21  | Gas outlet temperature correction                                | °C   | 140.03      |
| 22  | Revised temperature taken into the inlet gas mass change         | °C   | 0.22        |
| 23  | Revised temperature taken into $X_R$ deviate from the designed   | °C   | 335.36      |
| 24  | Heat capacity ratio of air and gas taken into $X_R$ change V1    |      | 1.32612     |
| 25  | Intermediate variable taken into $X_R$ change D1                 |      | -0.99486    |
| 26  | Intermediate variable taken into $X_R$ change U1                 |      | -0.00159    |
| 27  | Generalized heat transfer coefficient taken into $X_R$ change K1  | W/°C | 694.19      |
| 28  | Gas mass ratio of design and actual taken into $X_R$ change      |      | 1.03337     |
| 29  | Air mass ratio of design and actual taken into $X_R$ change      |      | 0.95387     |
| 30  | Gas heat capacity ratio of design and actual taken into $X_R$ change |      | 0.99987     |
| 31  | Air heat capacity ratio of design and actual taken into $X_R$ change |      | 0.99995     |
| 32  | Heat transfer coefficient correction taken into $X_R$ change Kp1  | W/°C | 688.05      |
| 33  | Heat capacity ratio correction of air and gas taken into $X_R$ change |      | 1.31046     |
| 34  | Intermediate variable taken into $X_R$ change Up1                |      | -0.00147    |
| 35  | Gas outlet temperature correction taken into $X_R$ change         | °C   | 139.96      |
| 36  | Revised temperature taken into the inlet gas mass change taken into $X_R$ change | °C   | 0.15        |
| 37  | Gas enthalpy of air heaters outlet without air leakage           | kJ/(kg.°C) | 7.283       |
| 38  | Air enthalpy correction of air heaters outlet                     | kJ/(kg.°C) | 5.580       |
| 39  | Air temperature correction of air heaters outlet based on gas temperature correction | °C   | 343.23      |
| 40  | Air leakage rate correction                                      | %    | 6.71        |
| 41  | Gas resistance correction                                        | Pa   | 1112.41     |
| 42  | Primary air correction                                           | Pa   | 174.26      |
| 43  | Secondary air correction                                         | Pa   | 623.03      |
4. Conclusion
The study proposed a correct calculating method of tri-sector rotary air heaters and developed a correct calculation software. According to the design theory and calculation method, the software has high calculation accuracy. A power plant as an example, computation result coincides with real hydrocarbon test, especially the calculating process is easy and economical. It can be applied to the actual work to provide accurate technical data for the optimal operation and variable operating conditions of air heaters.

References
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