A Method for Calculating Thermal Efficiency Of the Solid Fuel Fired Boiler

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Abstract. This paper presents a simplified method for calculation of thermal efficiency of the solid fuel fired boiler on-line.Although this method simplifies complicated calculation and adopts some approximate calculation,it still includes almost all items of heat loss proposed in ASME PTC4[1],which makes it possible to replace the standard method to some degree. Besides,based on requirement of on-line calculation of thermal efficiency[2],the new method greatly reduces the number of parameters to be measured. At the end of the paper, the simplified method is proved to be practical by comparing the results of calculating efficiency with the two methods, i.e.the standard method specified in ASME PTC 4 and the simplified method proposed in this paper.

Introduction

Thermal efficiency is a key technical parameter that indicates the the performance of a boiler. Through thermal efficiency analysis, the the main sources of heat loss can be found, which provides the scientific basis for adjusting the boiler's operation in time, i.e. changing the running condition of the boiler so as to maximize the thermal efficiency.

In China ,coal is used as main fuel for boilers ,and the solid fuel fired boiler accounts for most part of boilers .So it's necessary to study the solid fuel fired boiled .This paper carries out study on calculating the thermal efficiency of the solid fuel fired boiler.Actually, many countries have established the standard methods for calculating the boiler energy efficiency ,including ASME PTC 4 ,GB10184 [3]and JIS B 8222[4] etc, but these methods are not applicable in on-line calculation of boiler thermal efficiency.To solve this problem,a simplified method applied in on-line calculation of boiler thermal efficiency are analyzed in this paper.

The Simplified Calculation of Efficiency of Solid Fuel Fired Boiler

Heat Loss Method. There are 2 methods in the calculation of solid fuel fired boilers efficiency ,including the heat input-output method and the heat loss method[4].Although the heat input-output method looks easier than the latter one, this method can only be carried out in condition of keeping steam pressure and the load unchanged in a long time ,which is almost impossible for a running boiler[2] . Moreover, the heat input-output method also needs to acquire the accurate consumption of coal ,which is in fact so difficult to get .Besides, The main sources of energy loss can't be found by this method. As a result the heat loss method is more practical ,and is widely used for the calculation of boiler energy efficiency .The mathematics formula of calculating thermal efficiency by using heat loss method [4] is:

$$h = (1 - \frac{L}{H_h}) \times 100\% \quad . \tag{1}$$

Where , η: boiler efficiency by heat loss method

L: sum of heat loss

H_h: higher heating value

Higher Heating Value and Lower Heating Value. There are two main ways of expressing the calorific value of coal , i.e. higher heating value and lower heating value[5]. Lower heating value actually equals to higher heating value minus the whole sensible heat of steam produced from fuel combustion. According to the formula (1), higher heating value is applied as fuel's calorific value to calculate boiler thermal efficiency .In reality ,previous researchers have find out the relationship between higher heating value and lower heating value ,which can be described as follow[4]:

$$H_l = H_h - 5.9(9h + w) \quad kcal/kg . \tag{2}$$

Where , H_l :lower heating value; h: mass percent of hydrogen in the fuel.

H_h: higher heating value; w: mass percent of water in the fuel.

If the higher heating value is used as calorific value to calculate thermal efficiency , the quantity of heat lost should include the quantity of steam sensible heat . Otherwise the quantity of heat lost shouldn't include quantity of steam sensible heat.

Analysis of the Key Parameters.

Theoretical Amount of Air. The theoretical amount of oxygen should be obtained from each of combustible elements(carbon c ,hydrogen h ,and sulfur s) in the fuel, and further more the ratio of oxygen occupying air is available.When the solid fuel is burning ,the following combustion reaction equations can be acceptable .

$$C + O_2 = CO_2 , C + 1/2O_2 = CO , S + O_2 = SO_2 , H + 1/4O_2 = 1/2H_2O .$$

Now explain $C + O_2 = CO_2$, and some conclusions can be obtained:

① The equation above shows that 1Kmol of carbon dioxide is produced when 1kmol of carbon reacts with 1Kmol of oxygen.

② When c kg of the carbon is contained in 1 kg of the fuel, (c /12)×22.4 m^3N of oxygen is needed because the mass of the carbon is c /12Kmol .

③ As a result of complete combustion, (c /12)×22.4 m^3N carbon dioxide is generated.

④ When c kg of the carbon is contained in 1 kg of the fuel,(1/0.21)×(c /12)×22.4 m^3N of air is needed (assume that the ratio of oxygen occupying air is 0.21).

The same procedure may be easily adapted to obtain the amount of air reacted with s kg of sulfur and h kg of hydrogen : (1/0.21)×(s /32)×22.4 m^3N and (1/0.21)×[(*h* –*o*/8)/4]×22.4 m^3N . So the theoretical amount of air is :

$$A_0 = (22.4/0.21)\times\{(c/12) + [(h - o/8)/4] + (s/32)\}\times 22.4 \quad m^3/kg . \tag{3}$$

Calculation of the Actual Amount of Exhaust Gas. Theoretically the actual amount of air for combustion is more than the theoretical amount,so some air remains in the exhaust gases, and the actual amount of exhaust gas can be acquired based on the the air ratio and the theoretical amount of exhaust gas.

Based on the descriptions in"theoretical amount of air", the theoretical amount of exhaust gas can be easily obtained:

$$G = 22.4\times\{(c/12) + (s/32) + (h/2) + (n/28) + (w/18)\} + 0.79A_0 \quad m^3/kg . \tag{4}$$

The amount of excess air for combustion remained in exhaust gas is $(a - 1)A_0$, and so the result of calculation of the actual amount of exhaust gas is :

$$\begin{aligned} G &= 22.4\times\{(c/12) + (s/32) + (h/2) + (n/28) + (w/18)\} + 0.79A_0 + (a - 1)A_0 \\ &= 22.4\times\{(c/12) + (s/32) + (h/2) + (n/28) + (w/18)\} + (a - 0.21)A_0 \quad m^3/kg . \end{aligned} \tag{5}$$

Calculation of Air Ratio. Air ratio can be obtained by taking nitrogen balance into consideration.When the fuel has been burned completely at α>1, and nitrogen in the fuel is little enough to be neglected; assume that the ratio of "volume of N_2 in the total supply " and "that of N_2 in the theoretical amount of air" is equal to the air ratio α.

$$a = N_2 / \{N_2 - (0.79/0.21) \times O_2\} \tag{6}$$

Assume that t N_2 =0.79 in equation (6), the following equation to be used for approximate calculation.

$$a = 0.21/(0.21 - O_2). \tag{7}$$

Calculation of the Amount of Unburned Carbon Exist in Slag and Flue Dust. In the coal combustion, ember carbon often remains in flue dust. When assuming the flue dust are composed of the ash and unburned carbon, and it is designated that:

C_{fh} : mass ratio of ember carbon in flue dust kg/kg

A^y : mass ratio of ash in the coal kg/kg

f : the amount of flue dust kg/kg

$A^y = f(1 - C_{fh})$ can be changed to $f = A^y/(1 - C_{fh})$

According to the balance of ash[6],the amount of the carbon in flue dust is

$$C_{fh} f = C_{fh} \times \frac{A^y}{1 - C_{fh}} = A^y \times \frac{C_{fh}}{1 - C_{fh}} \quad \text{kg / kg.} \tag{8}$$

That is, the amount of unburned carbon per unit mass can be calculated using analytical values A^y of the ash in the fuel and that of C_{fh} of the unburned carbon in flue dust .

Assume that the total amount of the carbon in the fuel is *c* kg/kg and that the amount of the carbon, which burns completely, is *c'* kg/kg.

$$c' = c - A^y \times \frac{C_{fh}}{1 - C_{fh}} \quad \text{kg / kg.} \tag{9}$$

The formula above only works when the ratio of the slag occupying the burning residue is small.Because those formulas established are based on ignoring the amount of the slag. However,if the amount of the slag remained in burning residue is large enough,using following formula[2] to calculate the amount of unburned carbon maybe more reasonable.

$$c^u = A^y \times \left\{ 0.9 \times \frac{C_{fh}}{1 - C_{fh}} + 0.1 \times \frac{C_{lz}}{1 - C_{lz}} \right\} \quad \text{kg/kg.} \tag{10}$$

Where, c^u : the amount of unburned carbon kg/kg

C_{lz} : mass ratio of ember carbon in slag kg/kg

Calculation of the Boiler Heat Loss.

Dry Exhaust Gas Heat Loss. Dry exhaust gas loss can be calculated by the following formula :

$$L_1 = 0.333 \times G_D \times (T_2 - T_0) \quad Kcal/kg \cdot F \quad . \tag{11}$$

Where, L_1: dry exhaust gas loss; G_D: the actual amount of dry exhaust gas.
T_2: exhaust gas temperature; T_0: atmospheric temperature.

Heat Loss Due to Moisture from H in the Fuel. Heat loss of this part is consist of sensible heat and latent heat of steam,which are produced from water and hydrogen in the fuel.According to the combustion equation,we can deduce the following formula.

$$L_2 = 22.4 \times \{(\text{h}/2) + (\text{w}/18)\} \times (482 + 0.362 \times (T_2 - T_0)) \quad Kcal/kg \cdot F \; . \tag{12}$$

Where, L_2: heat loss due to moisture from H in the fuel.
h: mass ratio of hydrogen in the fuel.
w: mass ratio of water in the fuel.

Heat Loss Due to Atmospheric Moisture.

$$L_3 = 0.362 \times A_0 \times a \times r \times (T_2 - T_1) \quad Kcal/kg \cdot F \; . \tag{13}$$

Where, L_3: heat loss due to atmospheric moisture
A_0: theoretical amount of air
r : absolute air moisture

Heat Loss Due to Leakage of Air.

$$L_4 = 0.311 \times A_0 \times a \times \Delta a \times (T_2 - T_1) \quad Kcal/kg \cdot F \quad . \tag{14}$$

Where, L_4: Heat loss due to leakage of air
Δa : air leakage factor(Δa is generally between 0.01 to 0.03)

Heat Loss Due to Incomplete Combustion.

$$L_5 = 5660 \times (c + \frac{12}{32} s) \times \frac{co \times G_D}{(c/12) \times 22.4} \quad Kcal/kg \cdot F \; . \tag{15}$$

Where, L_5: heat loss due to incomplete combustion
co: volume ratio of CO in dry exhaust gas
c : mass ratio of carbon in the fuel
s : mass ratio of sulfur in the fuel

Heat Loss Due to Unburned Carbon in Refuse. Based on the formulas (8) and (10), the following formulas are obtained.

When the amount of the slag is small enough :

$$L_6 = 8100 \times A^y \times \frac{C_{fh}}{1 - C_{fh}} \quad Kcal/kg \cdot F \; . \tag{16}$$

When the amount of the slag is large :

$$L_6 = 8100 \times A^y \times \left\{ 0.9 \times \frac{C_{fh}}{1 - C_{fh}} + 0.1 \times \frac{C_{lz}}{1 - C_{lz}} \right\} \qquad Kcal / kg \cdot F \,. \tag{17}$$

Heat Loss Due to Radiation. The ratio of heat loss L_7 due to various radiation shall be determined according to the following formula [7]:

$$h_7 = q_7^e \times \frac{D_e}{D} \,. \tag{18}$$

Where, D_e: the rated capacity of the boiler ; D: the actual capacity of the boiler
q_7^e : The rate of heat loss due to radiation when D equals to D_e [8].

Other Heat Loss .Other heat loss is derived from all kinds of reasons,and the value of this part is hard to be acquired accurately .Based on previous research[8],heat loss of this part approximately equals to the sensible heat of the slag .Even so,the ratio of other heat loss occupying total heat is still so small that the following value are approximately used as the ratio of other heat loss[8,9].

$$h_8 = \frac{L_8}{H_h} = 0.005 \,. \tag{19}$$

Comparison of the Two Methods for Calculating Thermal Efficiency

Calculation Example. In order to examine the effectiveness of the method proposed, the calculation of a pulverized coal boiler has been carried .Based on the data(shown in table 1) supplied by the former research[10] ,the standard method specified in AMSE PTC 4 and simplified method proposed in this paper are applied respectively for calculating the thermal efficiency.

Table 1. The data measured in boiler field.

Project	Value
Carbon(arb) (%)	41.75
Hydrogen(arb) (%)	1.88
Oxygen(arb) (%)	2.71
Nitrogen(arb) (%)	0.57
Sulfur(arb) (%)	2.52
Water(arb) (%)	7.10
Ash(arb) (%)	43.47
Low calorific value(arb Kcal /kg)	15380
Unburned carbon in slag (%)	1.23
Unburned carbon in flue dust (%)	3.59
Slag temperature (℃)	147.9
Exhaust gas temperature (℃)	123.6
Oxygen in exhaust gas(%)	5.81
Carbon monoxide in exhaust gas(%)	0.0118

Table 2. The calculation results of the rate of various heat loss .

Project	ASME PTC4—1998	Method proposed in this paper
Dry exhaust gas heat loss (%)	4.69	5.11
Heat loss due to water produced from combustion (%)	0.40	4.1
Heat loss due to water in the fuel (%)	1.12	
Heat loss due to unburned carbon in refuse (%)	3.24	3.32
Heat loss due to combustion dehydration and combustion of desulfurizer (%)	1.67	--
Heat loss due to radiation (%)	0.45	0.45
Other heat loss (%)	0.33	0.5
Heat loss due to atmospheric moisture (%)	0.11	0.11
Heat loss due to incomplete combustion (%)	0.059	0.057
Heat loss due to leakage of air (%)	--	0.151
Heat from the outside (%)	3.24	3.24
Boiler thermal efficiency (%)	91.7	89.4

Based on the data in table 1 and table 2, the calculation results obtained through the simplified method almost equals to that through the method introduced in AMSE PTC-98; the value of heat loss due to water produced from combustion, according to ASME PTC4-1998, is bigger than that of the method proposed. The reason is that the lower heating value is adopted as calorific value to calculate thermal efficiency in ASME PTC4-1998, thus the sensible heat of steam is not included in the quantity of heat loss. However, the method proposed in this paper adopts the higher heating value as calorific value to calculate thermal efficiency.That is, the two values of thermal efficiency are more close when both the two methods use higher heating value as calorific value to calculate thermal efficiency.So the method mentioned in this paper is proved practicable to some degree, and then can satisfy the need of engineering.

Comparison and Analysis. According to the analysis and the calculation above, tracing the variation of thermal efficiency real time is important for improving boiler energy efficiency; but the premise is that the on-line calculation of boiler thermal efficiency can be carried out. Actually, applying the standard method make it so difficult to carry out on-line calculation because all the parameters must be measured, however some of them can’t be measured easily while a boiler is running, so the the value of thermal efficiency can’t be calculated. This means that the method can’t satisfy the requirement of real time calculating the thermal efficiency.

By comparison, the method introduced in this paper have simplified many of complicated calculations; and it reduces the number of parameters to be measured, from dozens of parameters to several ones. In this way, the calculation of thermal efficiency in real time can be carried out according to the running boiler’s data. When applying this method, only 6 parameters are enough, including the temperature of exhaust the gas,the atmospheric temperature,absolute air moisture ,the actual evaporation amount and the volume ratio of CO and O_2 in exhaust gas .All of these parameters are easy to be acquired.As a result, calculating the variation of thermal efficiency in real time become practical.

Conclusions

①One simplified method for calculation of thermal efficiency has been presented, in which only 6 parameters should be measured, so it is more easy to be applied to measure a solid fuel fired boiler in real time.But dozens of parameter should be determined with respect to the standard method,which is almost impossible to calculate thermal efficiency in real time.

②The calculation results obtained through the simplified method is close to that of the method introduced in AMSE PTC-98; as a result the simplified method proposed for calculating energy efficiency of solid fuel fired boilers is practicable and can satisfy the need of engineering testing.

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