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An indirect online method for measuring the boiling rate of BFG boiler economizer

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Abstract

In blast furnace gas (BFG) boiler, high flow and large velocity of the flue gas will cause more heat to be absorbed by tail heating surfaces such as economizers. This will increase the probability of water boiling and vaporizing in economizer, which may cause safety accidents. Therefore, to facilitate the safe operation of boilers, it is of vital importance to grasp the boiling rate of economizer in real time. However, due to the complex state of medium in the piping, it is difficult to measure the boiling rate of economizer directly. Aiming at this issue, this paper presents an indirect online method for measuring the boiling rate of BFG boiler economizer through boiler operation parameters, based on heat transfer balance calculation. In this method, the boiling rate of economizer can be obtained indirectly through the boiler operation parameters on flue gas side and steam–water side. The measuring result can be used as the basis for boiler operation and adjustment, thus make the economizer running in a safe state for a long time, which can prolong the operation life of economizer.

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Keywords: Boiling rate of economizer; BFG boiler; Heat transfer balance; Online calculation; Indirect measurement

1. Introduction

Plenty of blast furnace gas (BFG) is produced in the process of iron-making. BFG is characterized by high nitrogen content, low calorific value and poor combustion stability. Thus many iron and steel plants could not fully utilize BFG, and some of the excess BFG was even directly released, which resulted in regrettable energy waste.

How to make good use of the precious BFG resources has always been an issue of common concern for the relevant technical personnel in iron and steel plants.

In recent years, with the technology development of the low calorific value fuel combustion, BFG boilers have been widely used in iron and steel enterprises, especially in Asian countries, such as China, India, etc. [1–4].

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However, the design and operation of BFG boiler have not yet been fully rational, and there are still many details needed to be improved, among which the boiling problem of economizer is a hot issue.

For BFG boiler, the combustion and heat transfer characteristics are quite different from those of conventional coal-fired boilers, mainly in the following aspects [5]:

On the one hand, the theoretical combustion temperature of BFG is much lower than that of pulverized coal, for BFG contains a lot of non-combustible gas (of which, N₂ content is as high as 50%~60%, CO₂ content is as high as 16%~25%). For example, the theoretical combustion temperature of bituminous coal is about 1800 °C~2200 °C, and the theoretical combustion temperature of BFG is only 1300 °C~1450 °C, even BFG has been preheated by gas heater. As the thermal radiation force of the flame in the furnace is proportional to the fourth power of its absolute combustion temperature, the low combustion temperature of BFG will inevitably result in the weakness of its flame radiation force.

On the other hand, different from the flue gas produced the boiler burning coal or oil, the flue gas produced by the boiler burning BFG does not contain carbon black and ash particles, so the heat transfer in the furnace can only rely on the heat radiation through triatomic gas in the flue gas. This results in the weak radiation power of the flue gas in the BFG boiler, which is much lower than that of the conventional coal-fired boiler. In addition, due to the high flow rate and high velocity of flue gas in BFG boiler, the flue gas has flowed to the next heat exchange surface before it complete the heat transfer fully, and most heat is carried to the tail heating surface. For this reason, the evaporation heating surface (Water wall, etc.) in BFG boiler furnace can only complete about 55% of the total heat absorption required for the working fluid from water to saturated steam, and the rest of the heat absorption must be completed through the economizer, resulting in a certain degree of feed water vaporization in the economizer.

The boiling rate of economizer is an index parameter used to represent the percentage of steam mass flow and total feed water mass flow in economizer. Its design value is usually 10%~15%, generally not more than 20%. If the economizer boiling rate is too high, it will pose a great threat to the boiler safe operation, which is embodied in the following aspects [6–10]:

(1) Excessive boiling rate means strong vaporization of feed water, which will inevitably lead to an increase of the steam–water flow resistance thus result in a great increase of the economizer pressure drop, for the specific volume of steam is much larger than that of water.

(2) When the economizer boiling rate reaches a certain value, the mixture composition in the economizer will change from water-dominated to steam-dominated, and the flow state of the steam–water mixture will change accordingly. Under normal conditions, when the steam–water passes through the elbow in the piping, the scour on the inner surface of the elbow back is continuous and uniform. But under the large fluctuation of steam–water ratio, the water droplets in the steam (like sand and gravel in the wind) impact the elbow inner wall intermittently and vigorously, with the action of centrifugal force. Thus, longitudinal erosion trench textures are formed. With the accumulation of time, the inner wall of the piping will keep thinning and result in piping leakage, even explosion accident.

(3) If the boiling rate is too high, film boiling will occur easily in the local piping section of the economizer. The steam bubbles in the piping will be generated too fast, thus forming a continuous steam film and separating the feed water away from the piping wall. This will cause the deterioration of heat transfer, and the temperature of the piping wall will change frequently, with the change of external conditions. Then the piping will crack or break after a certain period of service.

Thus, if the boiling rate of BFG boiler economizer can be measured online, the boiler operators will grasp the boiling state and then adjust the operation of BGF boiler in real time. In this way, the danger caused by excessive boiling rate of economizer can be avoided and the safe operation of the boiler can be ensured. However, due to the immaturity of precise measurement technology under two-phase conditions, especially for steam–water in vertical upward pipelines, there is no reliable direct measurement equipment for the economizer boiling rate. In this case, indirect measurement becomes an option. According to the thermal instrumentation configuration condition of BFG boiler, combined with the combustion calculation model of BFG and the heat transfer model of economizer, an indirect online method for measuring the boiling rate of BFG boiler economizer was proposed based on the actual conditions of the steel plant site. This method can be used to analyze the boiling rate of BFG boiler economizer online, thus has certain practical significance.

2. Solving idea for measuring the boiling rate of BFG boiler economizer indirectly

For the existing technology cannot measure the boiling rate directly, the feasible method is to use soft sensor through boiler operating parameters. With the flue gas side parameters and the steam–water side parameters of the economizer, the boiling rate of BFG boiler economizer can be calculated indirectly.

As shown in Fig. 1, the calculation is based on the heat transfer mechanism of the economizer, and the specific calculating steps are as follows:

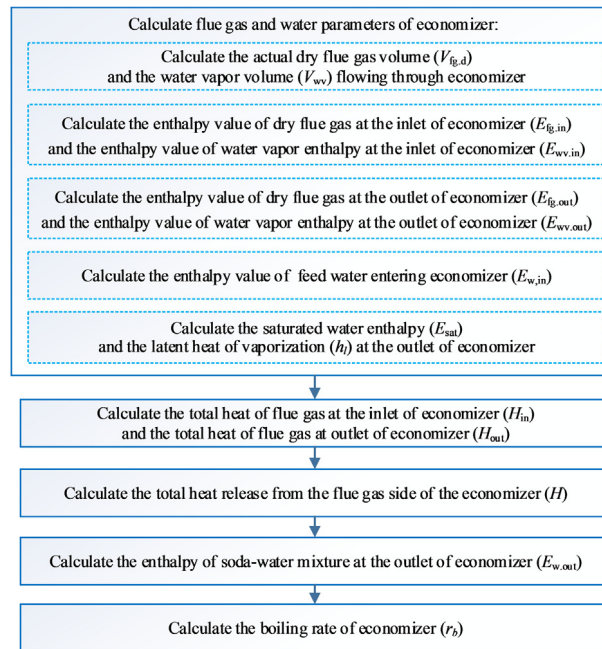


Fig. 1. Process diagram for calculating the boiling rate of BFG boiler economizer.

Step 1: Perform basic calculation, including the following objectives:

- (1) The actual dry flue gas volume $V_{fg,d}$ and water vapor volume V_{wv} flowing through the flue gas side of the economizer, calculated according to the gas characteristics and flue gas parameters;
- (2) The enthalpy value of dry flue gas at the inlet of economizer $E_{fg,in}$ and the enthalpy value of water vapor at the inlet of economizer $E_{wv,in}$, calculated according to the temperature of flue gas at the inlet of economizer;
- (3) The enthalpy value of dry flue gas at the outlet of economizer $E_{fg,out}$ and the enthalpy value of water vapor $E_{wv,out}$ at the outlet of economizer, calculated according to the temperature of flue gas at the outlet of economizer;
- (4) The enthalpy value of feed water at the inlet of economizer $E_{w,in}$, calculated according to the temperature and pressure of the feed water at the inlet of economizer, combined with the thermodynamic property table of water and steam;
- (5) The enthalpy value of saturated water E_{sat} and the latent heat value of vaporization h_l corresponding to the steam–water temperature at the outlet of economizer, calculated according to the steam–water temperature at the outlet of economizer, combined with the thermodynamic property table of water and steam.

Step 2: Calculate the total heat of flue gas at the inlet of economizer H_{in} and the total heat of flue gas at the outlet of economizer H_{out} as follows:

$$H_{in} = B_g(V_{fg,d} E_{fg,in} + V_{wv} E_{wv,in}) \quad (1)$$

$$H_{out} = B_g(V_{fg,d} E_{fg,out} + V_{wv} E_{wv,out}) \quad (2)$$

where, H_{in} is the total heat of flue gas at the inlet of economizer, kJ/h; H_{out} is the total heat of flue gas at the outlet of economizer, kJ/h; B_g is the volume flow rate of gas entering into the furnace, m³/h; $V_{fg,d}$ is the actual volume of dry flue gas produced by combustion of per unit volume gas, m³/m³; V_{wv} is the volume of water vapor contained in the flue gas produced by the combustion of per unit volume gas, m³/m³; $E_{fg,in}$ is the enthalpy of dry

flue gas corresponding to flue gas temperature at the inlet of economizer, kJ/m^3 ; $E_{\text{wv.in}}$ is the enthalpy of water vapor corresponding to the flue gas temperature at the inlet of economizer, kJ/m^3 ; $E_{\text{fg.out}}$ is the enthalpy of dry flue gas corresponding to the flue gas temperature at the outlet of economizer, kJ/m^3 ; $E_{\text{wv.out}}$ is the enthalpy of water vapor corresponding to the flue gas temperature at the outlet of the economizer, kJ/m^3 .

Step 3: Calculate the total released heat from the flue gas side of economizer H as follows:

$$H = H_{\text{in}} - H_{\text{out}} \quad (3)$$

where, H is the total released heat from the flue gas side of economizer, kJ/h .

Step 4: Calculate the enthalpy of steam–water mixture at the outlet of economizer $E_{\text{w.out}}$ as follows:

$$E_{\text{w.out}} = \frac{H}{G_{\text{fw}}} + E_{\text{w.in}} \quad (4)$$

where, $E_{\text{w.out}}$ is the enthalpy of steam–water mixture at the outlet of economizer, kJ/kg ; η is the heat transfer efficiency of economizer and can be set as 0.99; G_{fw} is the boiler feed water flow, kg/h .

Step 5: Calculate the boiling rate of economizer r_b as follows:

$$r_b = \frac{E_{\text{w.out}} - E_{\text{sat}}}{h_l} \quad (5)$$

where, r_b is the boiling rate of economizer; E_{sat} is the enthalpy value of saturated water corresponding to the steam–water temperature at the outlet of economizer; h_l is the latent heat value of vaporization corresponding to the steam–water temperature at the outlet of economizer.

3. Difficulties and solutions of the indirect measurement

3.1. Difficulties

The core of the indirect measurement is mainly reflected in the implementation of the online calculation. For the calculating steps shown in previous section, step 2 to step 4 are all secondary calculations based on step 1, they will not hinder the obtaining of economizer boiling rate. Thus, the key to the online calculation is step 1, which needs to be completed through the original measurement data and have the following difficulties:

- The difficulty of calculating the actual dry flue gas volume $V_{\text{fg.d}}$ and water vapor volume V_{mv} in procedure (1).

According to the conventional method, they need to be calculated by gas composition, but at present, most steel plants have not installed the gas composition online analyzer, and cannot provide accurate gas composition in real time (most steel plants can only provide real-time gas calorific value at most). Therefore, how to get the actual dry flue gas volume $V_{\text{fg.d}}$ and water vapor content V_{mv} under the existing limited conditions is a problem that must be solved for online calculation of economizer boiling rate.

- The difficulty of calculating the enthalpy of dry flue gas and the enthalpy of steam at the inlet of economizer in procedure (2), along with the difficulty of calculating the enthalpy of dry flue gas and the enthalpy of steam at the outlet of economizer in procedure (3).

According to the conventional method, the enthalpy value of dry flue gas needs to be calculated according to the composition and the temperature of dry flue gas. However, currently, the BFG boiler usually only install an oxygen content online meter of flue gas, but not a full-component analyzer of flue gas, so the composition of dry flue gas cannot be obtained accurately in real time. Obviously, this will hinder the online calculation of the economizer boiling rate.

3.2. Solutions to the difficulties

For the difficulties of online calculation proposed in the previous section, we adopt the following solutions in this paper:

- For the actual dry flue gas volume $V_{fg,d}$ and water vapor volume V_{mv} , we get them by simplified calculation, through gas calorific value and oxygen content in flue gas. The specific treatment methods are as follows:

(1) Calculate the theoretical dry air volume by the following simplified model:

$$V_{a,d,th} = 1.955 \cdot 10^{-4} Q_{net,d} \quad (6)$$

where, $V_{a,d,th}$ is the theoretical dry air volume required for the combustion of per unit volume gas, m^3/m^3 ; $Q_{net,d}$ is the low calorific value of gas dry basis, kJ/m^3 .

(2) Calculate the theoretical dry flue gas volume by the following simplified model:

$$V_{fg,d,th} = 1.47 \cdot 10^{-4} Q_{net,d} + 1 \quad (7)$$

where, $V_{fg,d,th}$ is the theoretical dry flue gas generated by the combustion of per unit volume gas, m^3/m^3 .

(3) Calculate the fuel characteristic factor k by the following formula:

$$k = \frac{V_{fg,d,th}}{V_{a,d,th}} - 1 \quad (8)$$

where, k is the fuel characteristic factor.

(4) Calculate the excess air coefficient by the following formula:

$$= \frac{21 + k(O_2)}{21 - (O_2)} \quad (9)$$

where, α is the excess air coefficient; (O_2) is the oxygen content in flue gas.

(5) Calculate the actual dry flue gas volume $V_{fg,d}$ as follows:

$$V_{fg,d} = V_{fg,d,th} + (-1)V_{a,d,th} \quad (10)$$

(6) Calculate the water vapor content V_{mv} in flue gas by the following formula:

$$V_{wv} = 0.016 V_{a,d,th} + 0.098 \quad (11)$$

- For the enthalpy of dry flue gas and the enthalpy of water vapor, we get them by simplified calculation, through flue gas temperature. The specific treatment methods are as follows:

(1) Calculate the enthalpy value of dry flue gas and water vapor under the temperature of flue gas at the inlet of economizer, by formula (12) and formula (13), respectively:

$$E_{fg,in} = 2.238 \cdot 10^{-4} t_{fg,in}^2 + 1.393 t_{fg,in} - 1.7 \quad (12)$$

$$E_{wv,in} = 2.429 \cdot 10^{-4} t_{fg,in}^2 + 1.462 t_{fg,in} + 2.2 \quad (13)$$

where, $t_{fg,in}$ is the flue gas temperature at the inlet of economizer, $^{\circ}C$; $E_{fg,in}$ is the enthalpy of dry flue gas under $t_{fg,in}$, $kJ/N \cdot m^3$; $E_{wv,in}$ is the enthalpy of water vapor under $t_{fg,in}$, $kJ/N \cdot m^3$.

(2) Calculate the enthalpy value of dry flue gas and water vapor under the temperature of flue gas temperature at the outlet of economizer, by formula (14) and formula (15), respectively:

$$E_{fg,out} = 2.238 \cdot 10^{-4} t_{fg,out}^2 + 1.393 t_{fg,out} - 1.7 \quad (14)$$

$$E_{wv,out} = 2.429 \cdot 10^{-4} t_{fg,out}^2 + 1.462 t_{fg,out} + 2.2 \quad (15)$$

where, $t_{fg,out}$ is the flue gas temperature at the outlet of economizer, $^{\circ}C$; $E_{fg,out}$ is the enthalpy of dry flue gas under $t_{fg,out}$, $kJ/N \cdot m^3$; $E_{wv,out}$ is the enthalpy of water vapor under $t_{fg,out}$, $kJ/N \cdot m^3$.

4. Layout scheme of measuring parameters

According to the online calculation model, in order to realize online measuring of economizer boiling rate, the following eight parameters need to be measured:

- (1) Low calorific value of BFG (dry basis) $Q_{net,d}$
- (2) The volume flow of BFG entering into the furnace B_g
- (3) Oxygen content in dry flue gas (O_2)
- (4) Flue gas temperature at the inlet of economizer $t_{fg,in}$

- (5) Flue gas temperature at the outlet of economizer $t_{fg.out}$
- (6) Boiler feed water flow G_{fw}
- (7) Feed water temperature at the inlet of economizer $t_{fw.in}$
- (8) Feed water pressure at the inlet of economizer $p_{fw.in}$
- (9) Steam–water temperature at the outlet of economizer $t_{w.out}$

The layout of measuring parameters for the above parameters is as follows:

- For the BFG boiler with single-stage (only one stage) economizer, the layout scheme is shown in Fig. 2.
- For the BFG boiler with multi-stage economizer, a stage air preheater is generally arranged in the middle of the adjacent two stage economizers. To facilitate calculation, we suggest using the parameters of the high temperature section (boiling usually occurs in the high temperature section of economizer), and the relevant measuring points and layout scheme are set as shown in Fig. 3.

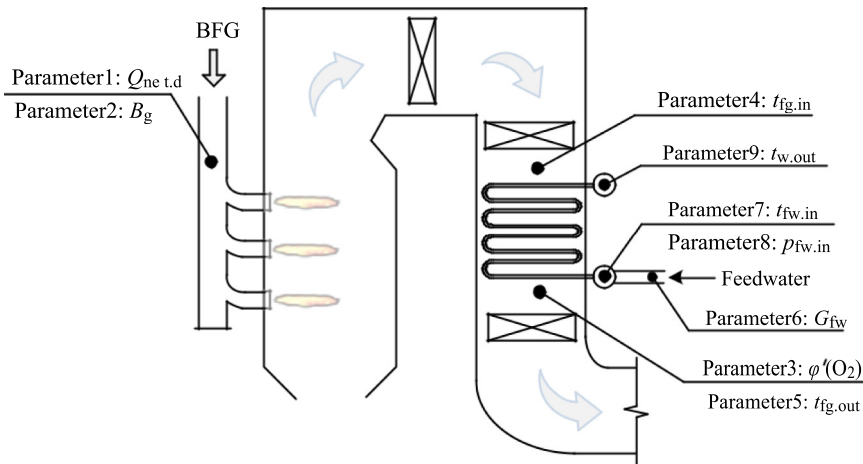


Fig. 2. Layout scheme of relevant measuring parameters for BFG boiler with single-stage economizer.

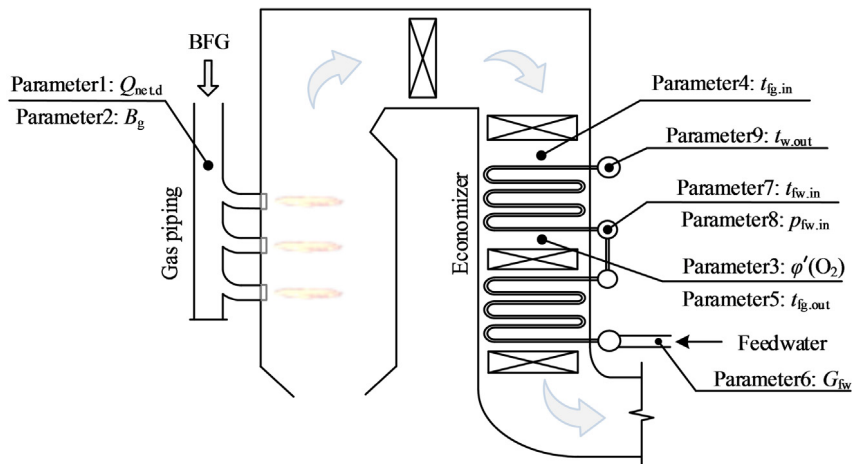


Fig. 3. Layout scheme of relevant measuring parameters for BFG boiler with multi-stage economizer.

5. Application example

Combined with the performance testing data of a BFG boiler in a steel plant, the boiling rate of the boiler economizer was measured by the online model proposed in this paper. Table 1 shows the relevant original data and the measuring result.

Table 1. Measuring example of the economizer boiling rate.

Parameter	Symbol	Testing condition 1	Testing condition 2	Testing condition 3
Low calorific value of BFG	$Q_{\text{net.d}}$ (kJ m^{-3})	3502	3401	3469
Volume flow of BFG entering into the furnace	B_g ($\text{m}^3 \text{h}^{-1}$)	188 287	175 249	158 963
Oxygen content in dry flue gas	(O_2) (%)	2.95	3.11	3.50
Boiler feed water flow	G_{fw} (t h^{-1})	221	204	182
Feed water temperature at the inlet of economizer	$t_{\text{fw.in}}$ ($^{\circ}\text{C}$)	214	208	195
Feed water pressure at the inlet of economizer	$p_{\text{fw.in}}$ (MPa)	11.6	11.1	10.7
Flue gas temperature at the inlet of economizer	$t_{\text{fg.in}}$ ($^{\circ}\text{C}$)	578	561	528
Flue gas temperature at the outlet of economizer	$t_{\text{fg.out}}$ ($^{\circ}\text{C}$)	291	279	252
Steam–water temperature at the outlet of economizer	$t_{\text{w.out}}$ ($^{\circ}\text{C}$)	321	317	314
Indirect measuring result of the economizer boiling rate	r_b (%)	13.49	11.97	9.06

6. Conclusions

There are obvious differences in flue gas characteristics between BFG boiler and traditional boiler (burning traditional fuels). In BFG boiler, much heat of flue gas is absorbed by the tail heating surface, resulting in water boiling and vaporization in the economizer, thus causing safety accidents. Therefore, it is necessary to measure the boiling rate of BFG boiler economizer online. However, the precise measurement technology under two-phase (steam–water) condition is not yet mature, especially for vertical upward piping, so it is difficult to measure boiling rate directly, which will undoubtedly make the reliable and safe operation of the BFG boiler cannot be guaranteed.

In this paper, an indirect online method for measuring the boiling rate of BFG boiler economizer is provided. The boiling rate can be obtained by operating parameters of flue gas side and steam–water side of the economizer, based on heat transfer balance calculation. The measuring results can be used as the basis for the operation adjustment of the boiler, so that the economizer can operate within the allowable boiling range, which will ensure the safe operation of the BFG boiler.

Acknowledgments

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