To calculate heat losses with flue gases of coal-fired boilers

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Abstract. The article is devoted to solving the problem of increasing the efficiency of solid fuel boilers ' blast control systems. Existing algorithms for calculating losses with outgoing gases, the value of which determines the efficiency of the boiler blow control system, have significant disadvantages due to either high complexity of calculations or insufficient accuracy of the Siegert formula. The authors of the article experimentally confirmed the limitations of practical application of the Siegert formula in the logic of solid fuel boiler blow control systems. To eliminate the identified shortcomings, a new formula for calculating losses with outgoing gases is proposed, which can be used in solid-fuel boiler blast control systems, which has a sufficiently high accuracy and, at the same time, low computational complexity.

1 Introduction

Solid fuel hot water boilers used in autonomous heat supply systems, as a rule, have a design efficiency of 82..83%. The actual efficiency of boilers, determined by the results of commissioning tests, is lower than the calculated one by 5..20% and fluctuates within wide limits in the course of coal burning.

Such a decrease in the efficiency of solid fuel boilers is due to the peculiarities of solid fuel combustion: at the beginning of the cycle, a portion of fuel enters the boiler furnace, which heats up, moisture evaporates from it, and then the fuel begins to burn out with a gradual decrease in the amount of burning fuel. To increase the efficiency of solid fuel boilers, various air supply control systems are used. [1, 2]. As a rule, all these systems include a gas analyzer that calculates losses with flue gases based on measurements of the flue gas temperature, oxygen (O2), carbon dioxide (CO2) and carbon monoxide (CO) gases.

2 Analysis of existing methods for calculating losses with flue gases

Calculation of losses with flue gases can be done in two ways: by thermal calculation, or by Siegert's formula.

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Thermal calculation of losses with flue gases using the basic equations of fuel combustion is performed according to the following system of formulas [3, 4]:
1) coefficient which depends on fuel composition:

$$\beta = 2.37 \cdot \frac{H^P - 0.126 \cdot O^P + 0.038 \cdot N^P}{C^P + 0.368 \cdot S^P}$$

where: H^p,O^p,C^p,S^p,N^p – the content in the fuel, respectively, of hydrogen, oxygen, carbon, sulfur, nitrogen %

2) content of SO_2 and CO_2 in combustion products:

$$RO_2 = \frac{21 - O_2}{1 + \beta}$$

where: O_2 – oxygen content measured by the gas analyzer in flue gases, %;

3) excess air ratio:

$$\alpha = \frac{1659 + 21 \cdot \beta \cdot (RO_2 + CO) - 8.4 \cdot CO}{(100 \cdot \beta + 79) \cdot (RO_2 + CO) - 0.5 \cdot CO}$$

where: CO – CO content measured by the gas analyzer in flue gases,%;

4) volume of air entering the boiler furnace:

$$V_{dry}^{air} = 0.089 \cdot C^P + 0.266 \cdot H^P + 0.033 \cdot (S^P - O^P)$$

$$V^{air} = \alpha \cdot V_{dry}^{air} \cdot (1 + 0.0016 \cdot d_{air}) \cdot \frac{273 + T_{air}}{273} \cdot \frac{760}{h_{air}}$$

where: d_{air} – moisture content of air, g / kg;
T_{air} – air temperature, ^{0}C;
h_{air} – air pressure, mm Hg.
5) flue gas volume:

$$V_{RO_2+CO}^{smok} = 1.86 \cdot \frac{C^p}{100} + 0.684 \cdot \frac{S^p}{100}; V_{O_2}^{smok} = 0.21 \cdot (\alpha - 1) \cdot V_{dry}^{air}$$

$$V_{H_2O}^{smok} = \frac{9 \cdot H^p + W^p}{80.4} + \frac{1.293 \cdot d_{air}}{804} \cdot \alpha \cdot V_{dry}^{air}; V_{N_2}^{smok} = 0.79 \cdot \alpha \cdot V_{dry}^{air} + \frac{N^p}{125}$$

$$V_{CO}^{smok} = \frac{CO}{100} \cdot (V_{RO_2+CO}^{smok} + V_{O_2}^{smok} + V_{N_2}^{smok}); \; V_{RO_2}^{smok} = V_{RO_2+CO}^{smok} - V_{CO}^{smok}$$

where: W^p, N^p – content in fuel, respectively, moisture and nitrogen,%

6) enthalpy of air and flue gases:

$$J^{air} = V^{air} \cdot c_{air} \cdot T_{air} \cdot \frac{760}{h_{air}}$$

$$J^{smok} = (V_{RO_2}^{smok} \cdot c_{RO_2} + V_{CO}^{smok} \cdot c_{CO} + V_{O_2}^{smok} \cdot c_{O_2} + V_{N_2}^{smok} \cdot c_{N_2} + V_{H_2O}^{smok} \cdot c_{H_2O} \times T_{smok} \cdot \frac{760}{h_{smok}}$$

where: $c_{air}, c_{RO2}, c_{co}, c_{o2}, c_{N2}, c_{H2O}$ – heat capacity of air and combustion products, kcal/m3·0C;

T_{smok} - flue gas temperature, ^{0}C;

h_{smok} - flue gas pressure, mm Hg.

7) relative losses with flue gases:

$$qA = \frac{Q_H - (J^{smok} - J^{air})}{Q_H} \cdot 100$$

where: Q_H – lower heat of combustion of fuel, kcal/kg;

There are two options for Siegert's formula [5]:

$$qA = f \cdot \frac{FT - AT}{CO_2} \quad (1)$$

or

$$qA = (FT - AT) \cdot \left(\frac{A1}{CO_2} + B \right) \quad (2)$$

$$CO_2 = CO_2^{max} \cdot \left(1 + \frac{O_2}{O_2^{max}} \right)$$

where: qA – flue gas losses, %

FT – flue gas temperature, ^{0}C

AT – ambient temperature, ^{0}C

O_2 – flue gas oxygen value (rounded towards the nearest whole number), %

f, A1, B – conversion factors depending on the fuel type

CO_2 – concentration of carbon dioxide in flue gases, %

Both methods of calculating losses with flue gases have their disadvantages: the thermal calculation contains many formulas that are often difficult to implement in the logic of an industrial controller and which require a lot of calculations; Siegert's formula is more an estimate of efficiency than an exact calculation.

Practical tests carried out at the boiler house of the Selikhino village of the Khabarovsk Territory using 3BR coal and having the following characteristics, according to the certificate: C^p=55.0, S^p=0.33, A^p=8.7, W^p=35.97 and the net calorific value $Q_н$=4248 kcal/kg, showed that the value of losses with flue gases, determined by the Siegert formula, is lower than on the basis of thermal calculation. The summary data of practical tests are given in Table 1.

Table 1. Result of practical tests.

№	T_{air}	O_2	CO	T_{smok}	Siegert's formula (1)	Siegert's formula (2)	Thermal calculation
1	26,6	16,9	9,83	175,8	19,70	16,71	28,01
2	26,6	16,4	8,34	205,9	21,10	18,07	30,44
3	26,6	17,1	9,78	187,8	22,37	18,90	31,78
4	26,6	19	8,93	110,8	22,79	18,53	30,67
5	26,6	17,9	2,14	141,5	20,06	16,68	28,57
6	26,6	18	8,67	149,8	22,23	18,45	31,00
7	26,6	17,7	2,02	140,9	18,75	15,65	26,76
8	26,6	16,3	15,29	213,3	21,50	18,45	30,64
9	26,6	16,4	15,82	194,3	19,73	16,90	27,98
10	26,6	16,8	8,87	189,3	20,97	17,82	29,99
Average					20,92	17,62	29,58

As follows from the table, for the test performed, the results of calculating qA by the Siegert formula differ from the results of the thermal calculation by 30..40% downward. This experience confirms that the Siegert formula gives an underestimated value of the losses with flue gases. In addition, the practical application of this formula is limited to a small set of possible values of the conversion factors depending on the fuel type. As a rule, these coefficients are given only for the enlarged type of fuel: coal, brown coal, gas, fuel oil, etc.

To identify the limitations of Siegert's formula, a comparative calculation of losses with exhaust gases for brown coal used at the boiler house of the village of Selikhino, Khabarovsk Territory, was performed for a wide range of input parameters:

1) CO content in flue gases: from 0% to 20%

2) O_2 content in flue gases: from 0% to 20%

3) flue gas temperature: from 100^0C to 300^0C

As a result of a comparative calculation, it was found that Siegert's formula not only gives a constant underestimated value of losses with flue gases, but also the accuracy of the formula fluctuates within a fairly wide range, and the error can reach 50%. The result of the comparative calculation is shown in Figure 1.

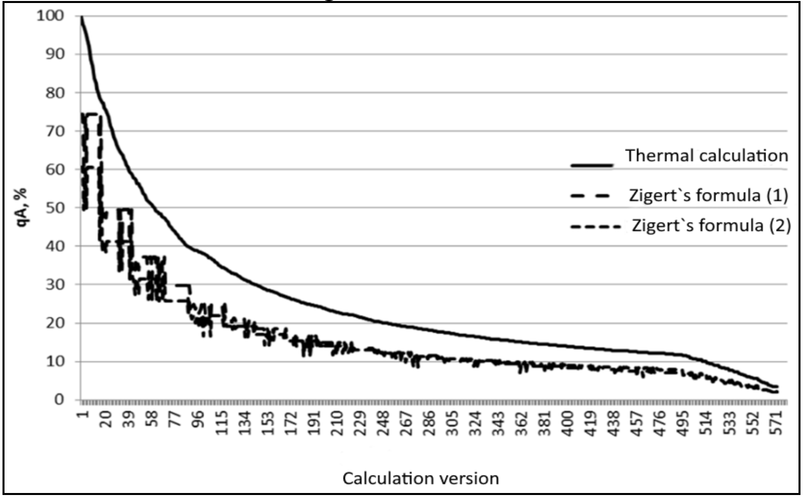

Fig. 1. Comparative calculation of qA

Thus, the application of the Siegert formula to determine the losses with flue gases in the control systems of the blast of solid fuel boilers can lead to control errors due to the reasons indicated above.

3 The proposed method for calculating losses with flue gases

The appearance of the loss curve with flue gases obtained on the basis of thermal calculation suggests that there may be a different formula besides Siegert's formula, devoid of both the drawbacks of Siegert's formula and having less computational complexity compared to thermal calculation.

To determine such a formula, many calculations of losses with flue gases were carried out on the basis of thermal calculation formulas for the following ranges of values of input parameters:

1) CO content in flue gases: from 0% to 20%

2) O_2 content in flue gases: from 0% to 20%

3) flue gas temperature: from 100^0C to 300^0C

4) fuel carbon content: from 50% to 70%

5) ash content in fuel: from 5% to 15%

6) the content of hydrogen, oxygen, nitrogen in the fuel was taken to be 0%, sulfur - 0.33%, which corresponds to the average content of these substances in coal and brown coal.

The moisture content in the fuel was determined for the given parameters by the formula:

$$W^p = 100 - H^p - O^p - C^p - S^p - N^P$$

The results obtained were processed by statistical methods and the following formula for determining the losses with flue gases was obtained:

$$qA = 0.03 \cdot (FT - AT) \cdot \left(2.1 \frac{C^p}{100} + 1.2 \cdot (\alpha - 1) \right) + \\ + \left(1.446 - 0.64 \cdot \frac{C^p}{100} - 0.42 \cdot \frac{A^p}{100} \right) \cdot (\alpha - 1)$$

where: qA – flue gas losses, %

FT – flue gas temperature, 0C

AT – ambient temperature, 0C

C^p,A^P – content of carbon and ash in the fuel %

α – excess air ratio

The proposed formula, in comparison with Siegert's formula, has a number of advantages:

1) there are no coefficients depending on the type of fuel, and parameters such as ash content and carbon content may be from a coal certificate;

2) the formula is applicable for all types of coal.

However, this formula does not take into account the content of hydrogen and oxygen in the fuel. It is possible that for such fuels a similar formula can be obtained.

To check the accuracy of the proposed formula, a comparative calculation of losses with flue gases was carried out on the basis of thermal calculation formulas for the following ranges of values of input parameters:

1) CO content in flue gases: from 0% to 20%

2) O_2 content in flue gases: from 0% to 20%

3) flue gas temperature: from 100^0C to 300^0C

4) fuel carbon content: from 50% to 70%

5) ash content in fuel: from 5% to 15%

Comparative calculation of the determination of losses with flue gases based on the formulas for thermal calculation and the proposed formula showed that this formula gives a fairly accurate result, and the average deviation is no more than 1.2%. The result of the comparative calculation is shown in Figure 2.

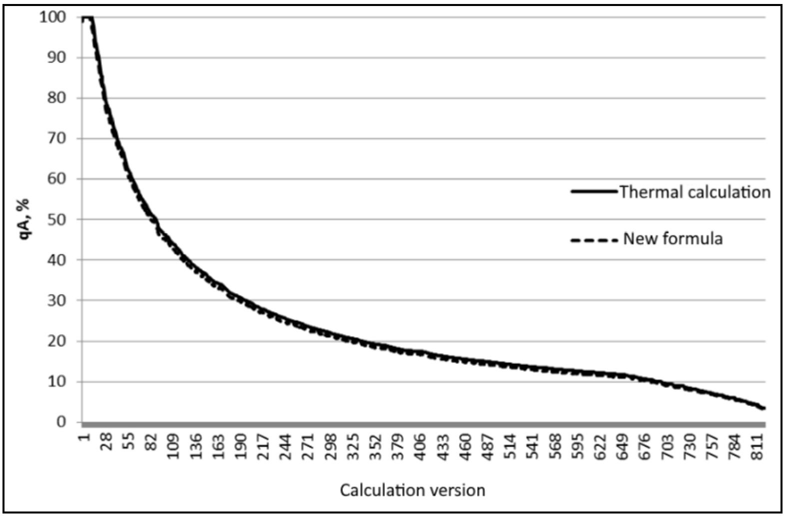

Fig. 2. Comparative calculation of qA according to the new formula

4 Conclusion

1. According to the results of a comparative calculation, it was shown that the Siegert formula used in modern gas analyzers gives an underestimated value of qA, as well as a nonlinear accuracy.
2. For each type of fuel, a formula can be obtained that is similar to Siegert's formula, but with a higher accuracy.
3. The proposed formula for calculating losses with flue gases has low computational complexity and can be used in any automation systems for coal-fired boilers.

References

1. A.E. Medvedev, K.P. Volykov Automatic regulation of the operating mode of a water-heating boiler with a layered coal furnace - Bulletin of Kuzbass State Technical University. № 3 (73). P. 65-69. (2009)

2. S.A. Gordin, I.V. Zaychenko. About intelligent adaptation of PID-regulation in control systems of low-power boilers. - Modern science: topical problems of theory and practice. Series: Natural and technical sciences. № 3. P.95-99 (2020)
3. Thermal calculation of boiler units (Standard method). Edited by N.V. Kuznetsova et al., M., Energy. (1973)
4. GOST R 56777-2015 Boiler plants. Method for calculating energy consumption and efficiency. (2015)
5. The practical guide to the gas analyzer - Testo - https://mcgrp.ru/files/viewer/132637/55.