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Cost Based Optimization of Excess Air for Fuel Oil / Gas-Fired Steam Boilers

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ABSTRACT

Computational method of determining an optimal value of excess air needed for firing fuel oil (or gaseous fuel) in a steam boiler is presented. The method is based on a cost approach aimed at minimizing the total expenses which include both (a) "internal costs" associated with incomplete combustion, unburned carbon, and heat loss with waste flue gas, and (b) "external costs" caused by emission of NO_x *and* SO_x *and other gaseous and particulate effluents from the boiler into the environment. Mathematical models for predicting the relevant heat losses, and also for estimation of* NO_x *and* SO_x *emission in a fuel-oil-fired / gas-fired furnace are presented. Some case studies concerned firing fuel oil in a steam boiler under various operating conditions have been considered.*

1. INTRODUCTION

As known, during operation of a (steam) boiler, some portion of available heat is inevitably lost [1]. When firing fuel oil (or gaseous fuel, in particular, natural gas), the heat losses due to incomplete combustion, q_3, (associated with presence of combustible gaseous compounds in waste gas) and with unburned carbon, q_4, (determined by the presence of soot particles in flue gas) characterize efficiency of the combustion process in the boiler furnace. These losses and also heat loss with waste, or chimney gas, q_2, significantly depend on the excess air delivered into the boiler furnace. The sum of the above heat losses as a function of excess air possesses the minimum that corresponds to highest thermal efficiency of the boiler at an "optimal excess air". In the past, such an approach was the main one in selection of the optimal excess air (ratio) for the operating boilers and for new units to be designed. High effective combustion was one of the main targets in boiler operation and furnace design.

Meanwhile, it is high effective combustion, usually followed by elevated temperatures, that causes intensive emission of NO_x and SO_3 in the boiler furnace, whose emission yields also depend on excess of air delivered into the furnace chamber. Moreover, on combustion of fuel oils (or gaseous fuels) the shortage of combustion air may cause formation of soot and highly hazardous benzpyrene particles whichh are carried off with waste gas from the boiler into the atmosphere. In such cases, the "optimal excess air" cannot be treated as the optimal one, in a view of both combustion efficiency and environmental aspects of boiler operation. Thus, in analysis both thermal efficiency of the boiler and its impact on the environment are to be considered simultaneously.

The main purpose of this study is to develop the computational method for determining excess air for a fuel oil/gas-fired boiler that corresponds to environmentally-friendly operation conditions and ensures possibly highest efficiency of the boiler.

2. COMPUTATIONAL MODEL

The model is based on the cost-estimating approach. According to the model, the sum of the excess air depended on (a) "internal costs", C_{int}, associated with heat losses due to incomplete combustion, unburned carbon, and with waste gas, and (b) "external costs", C_{ext}, treated as the damage done by the boiler unit to the environment (including human health) due to effluents [2], is required to be minimum:

$$C_{int} + C_{ext} \longrightarrow \min \tag{1}$$

The "internal" costs, US$/s, can be determined as fuel extra expenditures:

$$C_{int} = (q_2 + q_3 + q_4)10^{-2} P_f B \tag{2}$$

where:
B = boiler fuel consumption (kg/s or m^3/s)
P_f = coal price (US$/kg or US$/m^3)
q_k = respective relative heat losses (%)

The "external" costs (US$/s), are calculated as:

$$C_{ext} = (P_{CO} CO + P_{NOx} NO_x + P_{SO_3} SO_3 + P_{soot} C_{soot})\, 10^{-3} V_g B \tag{3}$$

where: CO, NO_x, SO_3, C_{soot} = content of respective effluents in combustion products (g/m^3)
V_g = volume of combustion products in the furnace (m^3/kg)
P_i = specific "external" costs due to damage done by 1 kg of the "i"-th airborne emission released into the atmosphere (US$/kg)

Emission of benzpyrene as well as the appearance of hydrogen and hydrocarbons are excluded from consideration since combustion is considered to be at sufficient air excess.

The total costs may be related to 1 kg/s (or 1 m^3/s) of fuel consumption. Therefore, the condition expressed by Eq.1 results in:

$$(q_2 + q_3 + q_4)10^{-2} P_f + (P_{CO} CO + P_{NOx} NO_x + P_{SO_3} SO_3 + P_{soot} C_{soot})\, 10^{-3} V_g \longrightarrow \min \tag{4}$$

In analysis of fuel oil-fired boilers all the prices and specific "external" costs can be represented in US$ /t.

Consider the terms of Eq. 4 which depend on excess of combustion air.

2.1 Heat Loss with Waste Gas

According to [1], the heat loss (in percent) with waste gas is found to be:

$$q_2 = (H_{wg} - \alpha_{wg} H_{ca})(100 - q_4) / Q_{av} \tag{5}$$

where H_{wg} = enthalpy of flue gas leaving the steam boiler (kJ/kg)
α_{wg} = excess air ratio in waste gases
H_{ca} = enthalpy of (cold) air at the ambient temperature (kJ/kg)
Q_{av} = available heat (kJ/kg or kJ/m^3)

In Eq. 5 both enthalpy and excess air ratio of waste gas depend on the excess air ratio in the boiler furnace.

2.2. Heat Loss due to Incomplete Combustion and Unburned Carbon

Basically, dependence of the particular heat loss on the excess air ratio is the individual characteristic of a boiler. The respective reliable data might be obtained experimentally. Meanwhile, as shown in a study by Kouprianov [3], in rough calculation the total relative heat losses ($q_3 + q_4$), measured in percent, could be predicted to be:

$$q_3 + q_4 = k_b(q_{min} + 50\,\Delta\alpha^{1.2}) \tag{6}$$

where: k_b = factor dependent on the burner type; this can be assumed to be $k_b = 1$ for vortex burners and $k_b = 1.2$ for straight-flow burners
q_{min} = minimum value of the heat losses estimated as $q_{min} = 0.1\%$ to 0.5% for utility boilers
$\Delta\alpha$ = deviation of the value of the excess air ratio in the combustion zone, $\Delta\alpha_c$, from the "critical" (basically, recommended) value, α_{cr}, or $\Delta\alpha = \alpha_{cr} - \Delta\alpha_c$

Equation 6 is available for both fuel oil and gaseous fuel boiler types when $\alpha_c < \alpha_{cr}$. For cases when $\alpha_c > \alpha_{cr}$ the equation takes the form:

$$q_3 + q_4 = k_b q_{min} \tag{7}$$

For large (> 100 MW) utility and industrial boilers firing fuel oils or gaseous fuels, the critical excess air ratio can be estimated as $\alpha_{cr} = 1.03$. With less boiler capacities α_{cr} increases up to 1.25 - 1.30, and the greater values are referred to small capacity industrial boilers. At the same time, for the small boilers the values of α_{cr} (and of q_{min} as well) become different for fuel oil- and gaseous fuel-fired boilers.

It should be noted that with load reduction the values for both q_{min} and α_{cr} are being increased in various degrees for different boilers and kinds of fuel.

In rough calculations the relative heat loss with unburned carbon, q_4, can be estimated as much as (0.1 - 0.2) q_3, or neglected.

2.3 Carbon Monoxide Content in Waste Gas

The presence of carbon monoxide in flue gas is associated with incomplete combustion characterized by q_3. Neglecting the hydrogen and hydrocarbon contents and soot particle presence in waste gas (which is justified at excess air, i.e. at $\alpha > 1$), it is possible to estimate the volume content of CO, percent, in flue gas by:

$$CO = [Q^r_{av}\, q_3]/[12640\, Vg] \tag{8}$$

2.4 Nitrogen Oxides Emission

The model for approximate estimation of the yield of nitrogen oxides from the boiler furnace is given in a study by Bezgreshnov, Lipov, and Shleipher [4] and was evaluated in a study by Paiboonpanupong and Kouprianov [5]. The thermal NO_x content (recalculated to NO_2 concentration and referred to standard conditions), g/m³, in flue gases downstream from the furnace is found to be [4]:

$$NO_2^{th} = 7.03 \times 10^3 C_{O2}^{0.5} \exp(-10860/T_m)\, \tau_{cr}/\tau_0 \tag{9}$$

where: C_{O2} = concentration of the residual air (kg/m³) in combustion products

τ_{cr}, τ_0 = respectively, time of chemical reaction proceeding and time needed to attain the state of equilibrium in the system (s)

T_m = maximum temperature in the flame core of the burner zone (K)

For estimation, τ_{cr} the temperature of combustion products at the furnace outlet as well as geometrical dimensions of the furnace are needed. All these data can be found by recommendations [1].

The maximum temperature in the active combustion (burner) zone is predicted to be:

$$T_m = \beta_{ac} T^*_{ad} (1 - \psi_{ac})^{0.25} (1 - r^{1+nr})\, m_b \tag{10}$$

where: β_{ac} = fraction of fuel burned out in the active combustion zone [3]

ψ_{ac} = thermal efficiency factor of water walls [1]

r = fraction of gas recirculated into the furnace [1]

T^*_{ad} = adiabatic temperature (K) to be determined without gas recirculation effect [4]

n and m_b = empirical factors assumed by [4]

The total yield of fuel and prompt NO_x (also recalculated to NO_2) can be found by the method represented in [4]. The respective formulae are available for two ranges of maximum temperatures in the burner zone:

- at temperatures $2100 > T_m \geq 1850$ K the total yield of the fuel and prompt nitrogen oxides, g/m³, is calculated to be:

$$NO_2^{f+p} = (0.4 - 0.1N^r)N^r[(\alpha_{bz} + r)/(1 + r)]^2[(2100 - T_m)/125]^{0.33} \tag{11}$$

- at temperatures $1850 > T_m \geq 800$ K it is predicted to be:

$$NO_2^{f+p} = 1.25\,(0.4 - 0.1N^r)N^r[(\alpha_{bz} + r)/(1 + r)]^2[(T_m - 800)/1000]^{0.33} \tag{12}$$

where: N^r = nitrogen content (%) in fuel of mass as-received
α_{bz} = estimated excess air ratio in the active combustion zone that depends on both excess air in the furnace and inleakage of cold air into the furnace

Equations 11 and 12 are available for firing fuel oil in a boiler furnace. For case studies when gaseous fuel is used for firing boilers, the yield of prompt nitrogen oxides is to be found by equation given in [4]:

$$NO_2{}^p = 0.1[(\alpha_{bz} + r)/(1 + r)]^2[(T_m - 800)/1000]^{0.33} \tag{13}$$

It should be noted that in gas-fired boiler the value of maximum temperature must be assumed by 1% greater than that obtained by Eq. 10 [4].

The predicted total content of nitrogen oxides in flue gas leaving the furnace is then

$$NO_x = NO_2{}^{th} + NO_2{}^{f+p} \tag{14}$$

2.5 Sulphuric Anhydrite Content in Flue Gas

Emission of SO_3 in the boiler furnace depends on the partial pressure of sulphur dioxide in flue gas, p_{SO2}, which is the function of the sulphur content in fuel [4], the concentration of residual air, $C_{O2,}$ the heat release rate per unit cross-sectional area of the furnace [1], q_f, and load ratio, D/D_r (D is the current load of the boiler, and D_r is the rated, or nominal one) and is estimated (in volume percent) to be [4]:

$$SO_3 = 0.424\, p_{SO_2} (C_{O2})^{0.5}\, q_f (D/D_r)^2 \tag{15}$$

3. CASE STUDIES

The computational investigations of the proposed method have been carried out for the fuel oil-fired steam boiler of 640 t/hr capacity, schematically represented in Fig. 1. The boiler furnace is equipped with vortex type burners arranged in two levels.

The superheated steam at temperature of 540 °C and at pressure of 14 MPa is delivered from the boiler to the 200 MW turbine. Reheating is also used in the power cycle.

The analysis of fuel oil (on as-received basis) is as follows: $C^r = 84.75\%$, $H^r = 12.0\%$, $S^r = 1.58\%$, $O^r = 0.1\%$, $N^r = 0.55\%$, $W^r = 1\%$, $A^r = 0\%$.

Three case studies have been considered with different fraction of recirculating gas (0.1, 0.2, 0.3) that was assumed to be extracted from the flue gas duct between the economizer and air heater and then mixed with the flow of air upstream the burners.

In calculations the temperature of hot air and the temperature of waste gas have been assumed to be constant: 270 °C and 160 °C, respectively.

The computations included the following stages:

- determining heat losses, gross efficiency of the boiler and its fuel consumption,
- calculation of thermal characteristics of the boiler furnace,
- predicting the emission of involved effluents in the boiler furnace, and
- optimization of excess of combustion air.

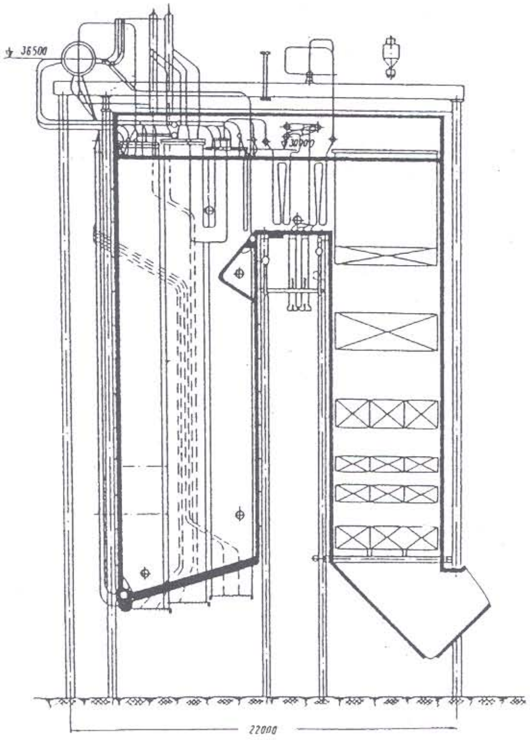

Fig. 1. Schematic diagram of the boiler.

Calculations concerning the heat losses, boiler efficiency and fuel consumption have been carried out based on the methodology given in [1]. Thermal characteristics of the furnace have been found by the method represented in [1] with some particular recommendations given in [3].

4. RESULTS AND DISCUSSIONS

Effect of excess air ratio on the heat loss with waste gas, q_2, and the total losses associated with incomplete combustion and due to unburned carbon, $(q_3 + q_4)$, is shown in Fig. 2. In determining $(q_3 + q_4)$ by Eq. 6, the critical excess air ratio was assumed to be $\alpha_{cr} = 1.05$ that means an increase in the heat losses at low excess air $(\alpha < \alpha_{cr})$ in the furnace. From the predicted data, the recirculation of gas has no influence on these variables, that is explained by assumption of identical waste gas temperature and neglecting the inleakages of air into the gas path in boiler computations.

One of the variables of Eq. 3, sulphuric anhydrite, does not practically depend on gas recirculation as well. Meanwhile, the effect of excess air ratio on SO_3, as shown in Fig. 3, is rather strong at lower excess air ratios and weakened with increase in oxygen content in combustion products. Obviously, the yield of SO_3 (at a given value of excess air ratio) is proportional to the sulphur content in fuel oil. Based from analysis of Eq. 15, SO_3 emission in the furnace diminishes significantly with reduced boiler capacity.

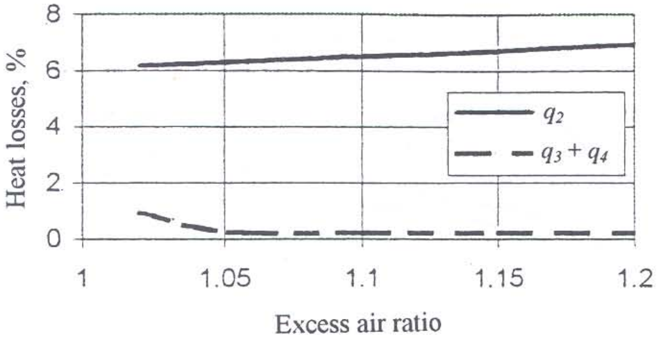

Fig. 2. Effect of excess air ratio on boiler heat losses.

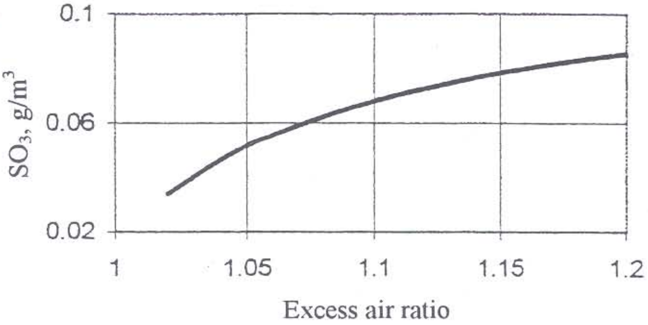

Fig. 3. Effect of excess air ratio on SO_3 emission in the boiler.

The predicted profiles of NO_x emission in the boiler furnace at various fractions of gas recirculation are represented in Fig. 4. At low gas recirculation ($r = 0.1$) the peak of the NO_x profile that corresponds to excess air of 5%, is mostly defined by emission of "thermal" nitrogen oxides. With gas recirculation increase (up to 20% and higher), "thermal" NO_x are suppressed due to decreasing temperature in flame zone, and the nitrogen oxides form due to "fuel" and "prompt" NO_x. This effect should be ensured on an operating boiler, therefore optimization of excess air for the considered boiler has been carried out for the case study with $r = 0.2$ when the "thermal" peak was suppressed.

The profile of interest is shown in Fig. 5. The minimum of total costs corresponds to excess air of 6%.

Suppose the boiler is allowed to operate, maintaining an excess air of 8%, a savings of 0.02 US$/s, or about 500,000 US$/year per one unit may be obtained, when excess air is changed from 8% to 6% (obtained by optimization).

The presented method can be applied in experimental investigations as well. In such cases all effluents included in Eq. 3 are to be measured on dry gas basis, and the volume of gas V_g (that is referred to the wet combustion products) is to be replaced with the volume of dry flue gas.

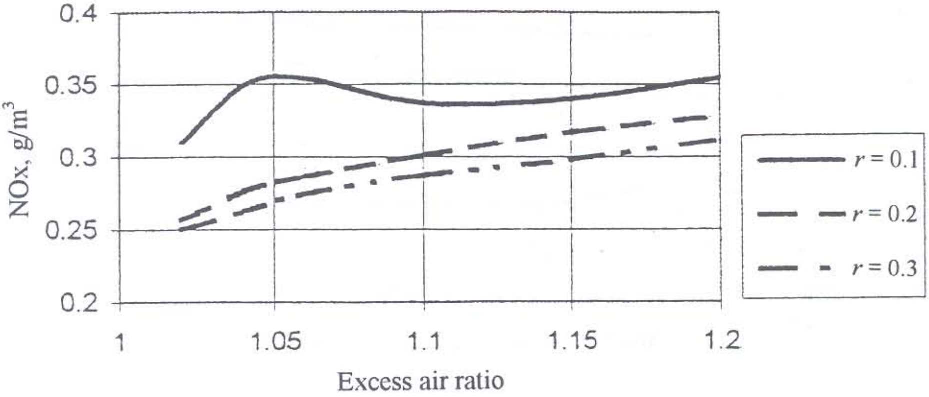

Fig. 4. Effect of excess air ratio and gas recirculation on NO_x emission in the boiler.

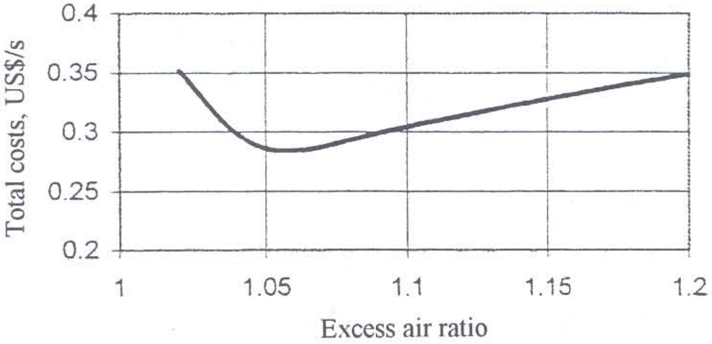

Fig. 5. Influence of excess air on the total "internal" and " external" costs.

The proposed method is to be more valuable in analyses of utility and industrial boilers of medium and low capacities when combustion heat losses increase, and the recommended values of excess air for the boilers vary within a wide range, respectively.

5. CONCLUSIONS

A computational model for the optimization of an excess air ratio for fuel oil- and gaseous fuel-fired boilers has been developed. The condition of minimum of total ("internal" and "external") costs is chosen as the optimization criterion in the mathematical model.

With the proposed model it is possible to determine the optimal excess air ratio for the given boiler firing given fuel under various combustion conditions.

The preliminary analysis of NO_x emission is to be done. It is required that the "thermal" nitrogen oxides emission in the furnace be minimized thereby allowing to provide excess air optimization.

The method is more valuable in analyses of medium and low capacity boilers.

6. REFERENCES

1. Kouznetsov, N. V., and Mitor V. V. (Editors). 1973. *Heat Calculation of Boiler Plants*. Moscow: "Energiya" Publisher (in Russian).
2. Energy Efficiency. 1995. *Guidebook for Energy Consultants and Service Companies in Asia*. New York: United Nations.
3. Kouprianov, V.I. 1995. A model for predicting thermal characteristics of furnaces firing fuel oil and natural gas. In *Proceedings of The 2nd International Chemical Engineering Conference*, Bangkok, Thailand, 19-21 December, Section 1, pp. 32-39.
4. Bezgreshnov, A.N.; Lipov, Yu. M;. and Shleipher, B.M. 1991. *Computation of Steam Boilers (Examples and Problems)*. Moscow: "Energoatomizdat" Publisher (in Russian).
5. Paiboonpanupong, O., and Kouprianov, V.I. 1996. Computational estimation of NO_x emission in furnaces of steam boilers. In *Proceedings of The 6th National Chemical Engineering Conference*, Bangkok, Thailand, 24-25 October, Section E6, pp. 1-10.