Method development for the thermotechnical calculations utilizing reduced characteristics of the RDF fuels

N V Kornilova¹ and P A Trubaev²

¹Department of Electric Power Engineering and Automation, Belgorod State Technological University of V.G. Shukhov, Kostyukov St., 46, Belgorod, 308012, Russia
²Department of Energy Engineering of Heat Technology, Belgorod State Technological University of V.G. Shukhov, Kostyukov St., 46, Belgorod, 308012, Russia

E-mail: trubaev@gmail.com

Abstract. The paper presents method of calculation of the heat leakage and efficiency by using method of indirect heat balance, utilizing data from gas analysis, which can be employed for operational evaluation plant operation during burning of different types of waste materials. Taking into account that practically only oxygen and carbon dioxide is being measured in the exhaust gases, calculation method for heat leakage with exhaust gases, using measurements of only this component, without utilizing carbon dioxide content in combustion products, was developed. Carbon dioxide and oxygen calculated percentage content in dry complete combustion products in actual air consumption was measured with consideration of incomplete combustion. Heat leakage for low power boilers and furnaces was analyzed, heat leakage calculation method for this kind of plants was introduced. Using design factors analysis of the solid fuel boilers for burning low-calorie fuel and wood waste, was developed dependence of the outside walls specific area of the boiler on the boiler’s efficiency. Based on the developed method for seven types of the RDF fuels, tabular and graphic dependences for reduced factors, characterizing heat leakage to the atmosphere and incomplete combustion, were introduced. Suggested method was tested for calculating losses in solid fuel water heating boiler with grate stoker and designed output power of 200 kW during burning of the briquetted waste materials.

1. Introduction

The most efficient way to recycle solid municipal waste (MSW) is a thermal utilization with energy production [1]. The paper [2] shows, that from economic point of view, thermal utilization of MSW is more efficient compare to the other methods. Usage of the alternative fuel, in comparison to traditional energy plants on organic fuel, has similar impact on the environment [1]. Partial presence of RDF in the fuel mixtures decreased amount of SO₂ emission and didn’t change the amount of NOₓ emission [3]. Analysis of RDF and coal simultaneous combustion discovered that presence of RDF doesn’t affect SO²* emission, emission of NO, HCl, N2O slightly increases, and dioxin amount in slag grows in direct ratio to RDF percentage in fuel [4]. Findings in the paper [5] indicate that addition of the solid municipal waste to the bio fuel improves its energetic characteristics.

Additional advantage of the energy recuperation from combustion method is that for energy production can be used MSW with wide range qualities [6].

Use of different types of bio fuels and RDF with traditional organic fuels simultaneously requires information about combustion process characteristics and methods for evaluation of efficiency of the waste combustion plants for firing fuel with different component proportions [7, 8].

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Bio fuel has many different components [9], therefore its physical and chemical properties are varying in a big way and that takes effect on the combustion characteristics [10]. RDF presence has significant effect on the combustion characteristics, when RDF is over 10% effectiveness of combustion decreases [3]. The paper [11] explored combustion of different types of waste. Emissions of CO in flue gases, for the most conditions, have met the ecological requirements. Combustion thermal effectiveness was changing in a wide range and heat efficiency was as such:

| Material | Efficiency |
|----------|------------|
| Wood     | 65.0…98.9% |
| Paper    | 74.8…99.7% |
| Cellulose| 63.3…99.6% |
| RDF      | 50.1…91.8% |

Traditional direct balance method for efficiency test during fuel combustion at the waste firing plants has low accuracy because physical and chemical qualities of bio fuel varies in a wide range [2, 10, 12], in addition to that, waste management effectiveness in different regions is uneven [13]. As paper [14] states, carbon content in MSW fluctuated from 40 to 99 %. On an average organic part in MSW can be described by the empirical equation C_{32}H_{55}O_{3}.

During calorimetric properties of waste measurements determination, that defines precision of the calculation results for direct balance method, great difficulties emerges. Many publications show that MSW properties are much different from theoretical or reported values [15, 16] as well as thermal properties, calculated by experimental approach and by heat balance analysis [17].

The paper [18] presents research study of MSW characteristics by calorimetric and TGA methods that led to the empirical model for combustion value calculations, which demonstrated that combustion value of RDF fuel is within a broad range. The most significant differences are in the combustion heat and heat values that were calculated experimentally. This distinction is near 5% on average, as the paper [5] shows. The paper [19] made conclusion that method of determination of the combustion heat by calorimeters gives inaccurate information for RDF.

On the other hand, research of the composted RDF firing determined that self-supporting combustion process lasts a long time [20], that makes it difficult to find the exact amount of released heat energy for specified time length. It complicates application for calculation of burning of RDF methods of numerical and computer modeling [21, 22].

As a result of the performed analysis one can arrive at conclusion that the most precise method to evaluate operational effectiveness of the plants for waste combustion is the indirect balance method.

2. Boiler efficiency test utilizing indirect heat balance (M V Ravich method) with fuel reduced characteristics

It is difficult to determine exact characteristics and amount of the RDF being burnt during waste combustion. Also, this plant work in transient mode with RDF batch loading. In such conditions, calculations of the heat balance and efficiency by direct method have low accuracy and it is necessary to utilize indirect balance method calculations. During service conditions, method of indirect balance provides much more accuracy, having the same precision of measurements, for efficiency test against direct balance method and demands smaller number of the measured variables. In the indirect balance method heat leakage is being calculated using temperature and composition of the exhaust gases.

For the industrial plants, operating on the specific fuels, M V Ravich developed method of thermo-technical calculations utilizing fuel reduced characteristics, which gives options for generalization, simplification and measurements accuracy increase [23].

Efficiency can be determined by utilizing specific heat losses relative to fuel combustion value:

$$\eta = 100 - (q_2 + q_3 + q_4 + q_5 + q_6), \%,$$

where $q_2$ – losses due to exhaust gases; $q_3$ – losses due to chemical incomplete combustion (emitted combustibles); $q_4$ – losses due to mechanical incomplete fuel combustion; $q_5$ - losses due to thermal radiation from the surface of the boiler; $q_6$ - losses due to sensible heat of ash.
This section offers development of the method for calculating heat losses and efficiency of the plants for burning waste materials using indirect balance method based on gas analysis data. Taking in consideration that in practice, content of the exhaust gases is based on the oxygen and carbon dioxide content, method of calculation heat loss with exhaust gases $q_5$, using measurements of only these components, was developed. Heat loss for low power boilers and furnaces was analyzed, then method for heat loss $q_5$ calculation for those plants was suggested. Let’s examine specific heat loss calculation (parameters of the heat balance).

### 2.1. Losses due to exhaust gases $q_2$

Excess air coefficient $\alpha$ in the exhaust gases content can be determined by the following formula:

$$\alpha = 21/(21 - O_2 - 0.5CO)$$

During fuel combustion with excess air ($\alpha > 1$) specific heat losses due to exhaust gases $q_2$ determined by the equation

$$q_2 = 100 \frac{t_{fg} - t_a}{t_{max}} (c' + (h - 1) \cdot b \cdot k) = (t_{fg} - t_a) Z,$$

where $t_{fg}$ - flue gases temperature, °C; $t_a$ - temperature of the air being used for combustion, °C; $t_{max}$ - heat capacity of the fuel or maximum temperature that can be achieved during complete combustion of the moist fuel in theoretically necessary volume of the dry air at a temperature of 0°C and absence of heat leakage, determined by calculation, °C; $Z$ - reduced factor, characterizing heat losses into the outside atmosphere.

Coefficients in the equation (2) are determined in the following way.

Coefficient $c'$ - relation of the mean specific volume heat capacity of the combustion products $c_{cp}$ and $c_{cp \ max}$ determined for theoretical conditions at given $\alpha = 1$) in temperature range from 0°C to $t_{cp}$ and $t_{max}$ respectively:

$$c' = c_{cp}/c_{cp \ max}.$$

Coefficient $h$ - variation of the dry combustion products volume in comparison with theoretical one due to dilution with air. During solid fuel combustion (without considering CH$_4$ content in the incomplete combustion products) coefficient can be determined by the following formula

$$h = CO_2^{max}/(CO_2' + CO'),$$

where CO$_2^{max}$ - content of the CO$_2$ in dry combustion products in theoretical conditions (at given $\alpha=1$),%; CO$_2'$, CO' - gases content in dry combustion products, %.

Usually, content of the CO$_2'$ in combustion products is not measured. Part of the CO$_2$ amount, during incomplete combustion, is being substituted for an equal amount of the CO, at the same time, in the combustion products and exhaust gases amount of the O$_2$ increases by amount equal 0.5 of the C contents. Therefore, amount of the dry combustion products $V'_{dry,cp}$, during incomplete combustion, can be determined from the dry complete combustion products volume $V_{dry,cp}$ in the following way:

$$V'_{dry,cp} = V_{dry,cp} + 0.5 \frac{CO'}{100} V'_{dry,cp} \text{ and } V'_{dry,cp} = \frac{V_{dry,cp}}{1 - 0.005CO'}.$$

Content of the CO$_2'$, % in dry incomplete combustion products $V'_{cyx,us}$ can be determined using content of the carbon dioxide in complete fuel combustion by the following formula:
\[
\text{CO}'_2 = \frac{V_{CO_2} - 0.01 \text{CO}' V_{dry.cp}'}{V_{dry.cp}} = \text{CO}_2 \text{dry}(1 - 0.005 \text{CO}') - \text{CO}',
\]

where \( \text{CO}_2 \) - calculated percentage content of the carbon dioxide in dry complete combustion products in actual air consumption; \( \text{CO}' \) - content of the carbon monoxide in the exhaust gases, determined by the gas analysis data, %. Therefore

\[
h = \frac{\text{CO}_2^{\text{max}}}{(\text{CO}_{2 \text{dry}}(1 - 0.005 \text{CO}'))}.
\]

In the absence of the \( \text{CO} \) data content, coefficient \( h \) can be determined by the fuel combustion calculation.

\[
h = \frac{\text{CO}_2^{\text{max}}}{\text{CO}_2^{\text{calc}}} = \frac{V_{dry.cp}}{V_{dry.cp \text{ theor}}};
\]

where \( \text{CO}_2^{\text{calc}} \) – calculated content of the \( \text{CO}_2 \), %, in dry combustion products at given \( \alpha \); \( V_{dry.cp \text{ theor}} \) – volume of the dry combustion products at given \( \alpha = 1 \).

Coefficient \( b \) – volume to volume ratio of dry and moist combustion products in theoretical conditions (at given \( \alpha = 1 \)):

\[
b = \frac{(V_{CO_2} + V_{N_2})}{(V_{CO_2} + V_{N_2} + V_{H_2O})},
\]

where \( V_{CO_2}, V_{N_2}, V_{H_2O} \) – volume of \( \text{CO}_2, \text{N}_2, \text{H}_2\text{O}, \text{m}^3 \) in combustion products.

Coefficient \( k \) – relation of the mean specific volume heat capacity of the air \( c_{a \text{ cp}} \) in temperature range from 0°C to \( t_{cp} \) and combustion products \( c_{cp \text{ max}} \) (calculated at given \( \alpha = 1 \)) in temperature range from 0°C to \( t_{max} \)

\[
k = \frac{c_{a \text{ cp}}}{c_{cp \text{ max}}}.
\]

2.2. Losses due to chemical incomplete combustion \( q_3 \)

Losses due to chemical incomplete combustion \( q_3 \) were determined by the formula:

\[
q_3 = 100 \frac{Q_{und}}{h/p},
\]

where \( Q_{und} \) – heat value of the incomplete combustion products, that are contained in the combustion products, kJ/m³;

\[
Q_{und} = 126,4 \text{CO},
\]

where \( \text{CO} \) – content of the gases in the combustion products, %; \( p \) – low operational heat value of the fuel, based on 1 m³ of dry combustion products, generated during combustion in theoretical conditions (at given \( \alpha = 1 \)).
2.3. **Losses due to mechanical incomplete combustion of the fuel** $q_4$

Heat loss due to mechanical incomplete combustion of the fuel $q_4$ can be omitted, because in practice, content and consumption of the burning waste determined with low accuracy, and due to big size of the briquettes, pieces of unburnt fuel stays in the boiler.

2.4. **Losses due to thermal radiation from the wall surface of the boiler** $q_5$

As opposed to the rest of the overall efficiency components $\eta$ to calculate specific heat loss $q_5$, it is necessary to know heat value $Q$, kW, that is entering the boiler. Heat loss from the wall surface of the boiler $q_5$, %, is written as:

$$q_5 = \frac{Q_{wall}}{Q} \times 100\%,$$

where $Q_{wall}$ – heat loss from the wall surface of the boiler, kW.

Value $Q_{wall}$ can be determined by utilizing value of the fuel consumption rate and its heat value or utilizing power and efficiency of the boiler or furnace:

$$q_5 = 0,01\eta \frac{Q_{wall}}{P} = \frac{Q_{wall}}{G_f Q_l} \times 100\%,$$

where $G_f$ – fuel consumption rate, kg/s; $Q_{wall}$ – heat loss from the wall surface of the boiler, kW; $P$ – power, kW.

Heat loss from the wall surface of the boiler $q_5$ for small volume furnaces or boilers will be critical due to big value of the relation of the surface area to the inside volume. In general, taking into account value of the loss $Q_{wall}$, kW, can be written as:

$$Q_{wall} = \left( \frac{1}{\alpha_{inn}} + \frac{1}{\lambda_i} + \frac{1}{\alpha_{out}} \right)^{-1} (F_{wall} + F_{arch} (t_c - t_a)), \quad (3)$$

where $\alpha_{inn}$, $\alpha_{out}$ – coefficients of the heat transfer from gases to the furnace’s inner wall surface of the furnace (boiler) and from the outer wall surfaces and the arch into the outside atmosphere, W/(m$^2$·K); $x_i$, $\lambda_i$ – thickness, m, and coefficient of conductivity, W/(m·K), of the layers in the wall design; $F_{wall}$, $F_{arch}$ – surface area of the wall and arch of the furnace, m$^2$; $t_c$, $t_a$ – mean temperature inside furnace (boiler) and outside temperature, °C.

Based on the design parameters analysis of the solid fuel boilers for combustion of the low calorie fuel and wood waste, dependence of the specific area of the boiler’s outer surface $f_{wall}$, m$^2$/kW, on the power $P$ was developed (figure 1):

$$f_{wall} = \frac{F_{wall}}{P} = 0,00656 + \frac{1,23}{p^{0,5}}. \quad (4)$$

In the equation (1) attempt to determine coefficient of the heat transfer $\alpha_{inn}$ from gases to the furnace’s inner wall surface can be difficult, because in the standard literature [24, 25] dependences were obtained for high productivity boilers during conventional fuel burning, but calculating formulas for engineering calculations of the heat transfer processes, that are presented in the reference book [26] and similar ones, were obtained for ideal conditions, which are much different from presented here.

Let’s accept an assumption, that inner temperature of the boiler’s or furnace's wall equal to mean temperature of the combustion products $t_c$. 
Figure 1. Dependence of the specific area of the solid fuel boilers for burning low calorie fuel on the power: 1 - Boilers AO “Motor Sich” (Ukraine), boilers NPP “Belkotlomash” (Belarus); 2 - series KB-PM2; 3 - series KB-Srm (wood waste); 4 - industrial boilers “TEPLOV T” (OOO “ZKO Teplov”, Russia); 5 – approximating curve (1).

Using tubular's data, shown in the papers [25, 27], equations for calculation of the heat transfer coefficient from the boiler’s outside walls into the outside atmosphere were obtained, that include heat transfer by means of convection and radiation, W/(m²·K):

\[ \alpha_{\text{out}} = 5.7 + 0.14t_{\text{out,wall}} - 6.65 \times 10^{-4}t_{\text{out,wall}}^2 + 1.7 \times 10^{-6}t_{\text{out,wall}}^3, \]  

for which range of use: \( t_{\text{out,wall}} = 25...200 \degree C \); mean error of the approximation 0.9%; maximum error of the approximation 3.2%.

Or

\[ \alpha_{\text{out}} = 7 + 0.072t_{\text{out,wall}}, \]  

at given \( t_{\text{out,wall}} = 0...500 \degree C \).

In accordance with technical standards outside surface temperature of the hot water boilers parts shouldn’t be more than 45\degree C during making of the hot water with temperature up to 115\degree C and no more than 55\degree C for water with higher temperature.

Figure 2 presents obtained by the equations (5) and (6) dependences for determining losses \( q_5 \) utilizing known outside surface temperature of the boiler’s or furnace’s body, that were determined by the following formula

\[ Q_{cr} = \alpha_{\text{out}}F_{\text{wall}}(t_c - t_a) = (7 + 0.072t_{\text{out,wall}})F_{\text{wall}}(t_c - t_a). \]  

Figure 2. Heat losses into the outside atmosphere for different temperatures of the outside surface of the frame and outside atmosphere temperature at 0\degree C: a - in accordance with the amount of heat that entered boiler or furnace; b - in accordance with boiler’s power.
Disadvantage of utilizing formula (5) is in big error, related to the fact of averaging values of the surface temperatures and different factors having impact on the heat loss coefficient.

In such a manner, one can use simplified equation (1) with regard of equations (2) and (3) to calculate heat loss into the outside atmosphere using known outside walls surface temperature of the plant:

\[ Q_{\text{wall}} = \left( \sum \frac{x_i}{\lambda_i} + \frac{1}{7 + 0,072 t_{\text{out,wall}}} \right)^{-1} F_{\text{ct}} (t_c - t_a), \]

or

\[ Q_{\text{wall}} = \left( \sum \frac{x_i}{\lambda_i} + \frac{1}{7 + 0,072 t_{\text{out,wall}}} \right)^{-1} (0,00656P + 1,23P^{0.5})(t_c - t_a). \]

(8)

### 2.5. Losses due to sensible heat of ash \( q_6 \)

On condition that carryover of the heat loss with ash, being removed from the boiler, is absent

\[ q_6 = h_{\text{ash}} A^w / Q_l^w, \]

where \( h_{\text{ash}} \) – sensible heat of ash, kJ/kg, that can be determined by the following formula \( h_{\text{ash}} = c_{\text{ash}} t_{\text{ash}} \).

Heat capacity of the ash is presented in the paper [24], using data from this paper equation of linear regression \( h_{\text{ash}} = 0,96 t_{\text{ash}} \) was developed. Utilizing this formula, losses due to sensible heat of ash can be as follows:

\[ q_6 = 0,96 t_{\text{ash}} A^w / Q_l^w. \]

### 3. Reduced coefficient calculation for different types of RDF fuel

Objective of this section is to put in use simplified thermotechnical calculation methods (developed by M.B.Ravich) for boilers, firing wastes of different types. Components of waste presented in the table 1.

| Number of fuel | Name                          | Component content, wt. | Non-flammable mass | Total |
|----------------|-------------------------------|------------------------|---------------------|-------|
| 1              | Paper                         | Paper 1 – – – – – – – – | 0,10                | 1     |
| 2              | Wood                          | – – – 1 – – – – – – –  | 0,03                | 1     |
| 3              | MSW 30% and wood 70%          | 0,30 0,30 0,05 0,05 0,01 0,15 0,04 | 0,05                | 1     |
| 4              | MSW 50% and wood 50%          | 0,09 0,09 0,015 0,715 0,003 0,045 0,012 | 0,03                | 1     |
| 5              | Plastic 30% and wood 70%      | 0,15 0,15 0,025 0,525 0,005 0,075 0,02 | 0,05                | 1     |
| 6              | Plastic 50% and wood 50%      | – – – 0,7 – 0,3 – – – | 0,05                | 1     |
| 7              |                              | – – – 0,5 – 0,5 – – – | 0,05                | 1     |
For all listed kinds of RDF fuel, for humidity levels 0, 10, 20, 30, 40, 50%, elemental operational content was determined. Based on section 2.1.2 coefficients $Z$ and $p$ were determined. Dependence of the coefficient $Z$ on the CO content in the exhaust gases takes the linear form, therefore it can be taken into account utilizing correction coefficient $k$.

$$Z = Z_0(1 + k \cdot \text{CO}),$$

where $Z_0$, coefficient $Z$ with amount of CO = 0% in combustion products; CO – amount of the carbon oxide in the exhaust gases, vol.%. Coefficient $k$ determined by the values of the coefficients $Z$.

$$k = \frac{\sum_{W=0,10,20,30,40,50\%} \frac{Z \text{CO}=2\%}{Z \text{CO}=0\%} }{2} / 6 - 1,$$

where $Z \text{CO}=2\%$ and $Z \text{CO}=0\%$ – coefficient $Z$ with amount of the carbon oxide 2 and 0% in the combustion products.

Values of the coefficient $Z$ and correction coefficient $k$ for different types of RDF presented on the figure 3–11.

**Figure 3.** Coefficient $Z$ (at given CO = 0%) for Fuel 1

**Figure 4.** Coefficient $Z$ (at given CO = 0%) for Fuel 2

**Figure 5.** Coefficient $Z$ (at given CO = 0%) for Fuel 3
Figure 6. Coefficient $Z$ (at given CO = 0%) for Fuel 4

Figure 7. Coefficient $Z$ (at given CO = 0%) for Fuel 5

Figure 8. Coefficient $Z$ (at given CO = 0%) for Fuel 6

Figure 9. Coefficient $Z$ (at given CO = 0%) for Fuel 7

Figure 10. Correction coefficient $k$ for RDF

Figure 11. Coefficient $p$ for RDF
4. Application of a method for the analysis of operation of the boiler

Utilizing proposed method, calculation of the losses in hot water solid fuel boiler with grate stoker and design power of 200 kWt during briquetted waste combustion was made. [28, 29]. Each measurement series correspond to single fuel stowing (figure 12-15).

**Figure 12.** Measuring data and calculated values of heat loss during combustion of the briquettes, consisting of 70% of wood and 30% of plastic (Fuel 6)

**Figure 13.** Measuring data and calculated values of heat loss during combustion of the briquettes, consisting of 70% of wood and 30% of plastic (Fuel 6). Boiler operated: 12:48…13:23 – with forced flow; 13:40…13:58 – without forced flow

**Figure 14.** Measuring data and calculated values of heat loss during combustion of the briquettes, consisting of 70% of wood and 30% of plastic (Fuel 6)

**Figure 15.** Measuring data and calculated values of heat loss during combustion of the briquettes, consisting of 50% of wood and 50% of plastic (Fuel 7)
Boilers operated with batch loading during the test, therefore listed data include not only active combustion period but also fuel remains afterburning. This fact allowed to apply proposed method for the combustion mode with different efficiency.

Calculated losses were as such:

- with exhaust gases $q_2$ ................................ 27.9…55.2%;
- with chemical incomplete combustion $q_3$ ......... 0.2…7.6%;
- into outside atmosphere $q_5$ ................................ 1.6…4.3%;
- boiler’s overall efficiency.............................. 35.2…67.7%.

Therefore, by using data presented in the tables and pictures, it is possible to calculate heat balance of boilers and furnaces utilizing simplified method for combustion of different types of waste.

The offered method can be also used when calculating burning of landfill gas which is characterized by non-constant composition [30].

5. Conclusions

Method of calculation of the heat leakage and efficiency of the plants for waste combustion, using method of indirect heat balance, based on data from gas analysis, was developed. Taking into account, that practically only oxygen and carbon dioxide is being measured in the exhaust gases, was developed calculation method for heat leakage with exhaust gases, using measurements of only this component, without utilizing carbon dioxide content in combustion products. Carbon dioxide and oxygen calculated percentage content in dry complete combustion products in actual air consumption was measured with consideration of incomplete combustion.

Heat leakage for low power boilers and furnaces was analyzed, heat leakage $q_5$ calculation method for this kind of plants was introduced. Based on design factors analysis of the solid fuel boilers for burning low-calorie fuel and wood waste, was developed dependence of the outside walls specific area of the boiler on the boiler’s efficiency. This article introduced graphic dependences of the specific heat loss into the atmosphere, with different temperatures of the outside walls surface and atmosphere, on the amount of heat, that entered boiler or furnace and on the boiler’s efficiency.

Based on the developed method for seven types of the RDF fuels, tabular and graphic dependences for reduced factors, characterizing heat leakage to the atmosphere and incomplete combustion, was introduced. It was discovered, that dependence of the coefficient $Z$ on the CO content in the exhaust gases takes linear form, therefore to calculate amount of CO correction coefficient $k$ should be used. Calculated tabular and graphic dependences can be used for plants operational evaluation during combustion of different types of waste.

Suggested method was utilized for calculating losses in solid fuel water heating boiler with grate stoker and designed output power of 200 kW during burning of the briquetted waste materials.

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