Accuracy Improvement Analysis of the Standard Indirect Method for Determining a Steam Boiler’s Efficiency

Andrej Senegačnik, Igor Kuštrin and Mihael Sekavčnik

Kurzfassung

Verbesserte Methoden zur Bestimmung des Kesselwirkungsgrades

The efficiency of coal-fired power plants is usually determined according to standardised procedures. Currently, the Guidelines VDI 3986 and standard DIN EN 12952-15 [1] are valid. If solid fuel is used, its mass flow is calculated indirectly according to the procedures stated in DIN 12952-15. The indirect method requires the determination of boiler losses. Losses can be measured directly except for radiation and convection losses which are estimated according to the standard procedure stated in DIN 12952-15. The article at hand proposes, presents and evalutes some modifications of the standardised indirect method DIN 12952-15 regarding the consistency of calculations and accuracy of the results. Most of the modifications were introduced recently in reference [2] where they were treated generally, i.e. from a stoichiometric calculation point of view. Additional research presented in this paper is focused on incorporating additional calculations into the standard procedure [3] and to evaluate their impacts using sensitivity analysis. The main flow of computations remains identical to DIN 12952-15. Six modifications are considered. Four of them affect the referred flue gas mass determination, i.e.: partial oxidation of carbon to CO, including unburned matter in ash and slag while determining the excess air ratio with two models and including residual water vapour content in the flue gas sample. The fifth modification studies the impact of cold uncontrolled leakage air. The sixth modification is applying the VDI 4670 procedure [4] for flue gas and combustion air enthalpies calculation. The impacts of modifications were studied for two real data sets – for hard coal and lignite.

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Introduction

The efficiency of coal-fired power plants is usually determined according to standardised procedures. Currently, the Guidelines VDI 3986 and standard DIN EN 12952-15 [1] are valid. If solid fuel is used, its mass flow is calculated indirectly according to the procedures stated in DIN 12952-15. The indirect method requires the determination of boiler losses. Losses can be measured directly except for radiation and convection losses which are estimated according to the standard procedure stated in DIN 12952-15. The article at hand proposes, presents and evaluates some modifications of the standardised indirect method DIN 12952-15 regarding the consistency of computations and accuracy of the results. Most of the modifications were introduced recently in reference [2] where they were treated generally, i.e. from a stoichiometric calculation point of view. Additional research presented in this paper is focused on incorporating additional calculations into the standard procedure [3] and to evaluate their impacts using sensitivity analysis. The main flow of computations remains identical to DIN 12952-15. Six modifications are considered. Four of them affect the referred flue gas mass determination, i.e.: partial oxidation of carbon to CO, including unburned matter in ash and slag while determining the excess air ratio with two models and including residual water vapour content in the flue gas sample. The fifth modification studies the impact of cold uncontrolled leakage air. The sixth modification is applying the VDI 4670 procedure [4] for flue gas and combustion air enthalpies calculation. The impacts of modifications were studied for two real data sets – for hard coal and lignite.

Air Ratio Determination

Partial Oxidation of Carbon to CO (I)

If some of the carbon from fuel burns to CO instead to CO₂, the actual oxygen consumption is lower than the calculated consumption according to DIN 12952-15. To evaluate the CO impact, the carbon from fuel should be divided into quantities of carbon combusted to CO₂ and to CO, respectively. Let the factor \( \alpha_{CO} \) be a quantity of carbon forming CO₂. The factor \( \alpha_{CO} \) can be calculated exactly with the next derivative formulae:

\[
\alpha_{CO} = \frac{1,8650 \left( \frac{\gamma_{CO2d}}{\gamma_{COd}} \right) \gamma_C - \lambda \gamma_{CO2d} \gamma_{COAd}}{\gamma_C \left( 1,8534 \cdot 1,8650 \frac{\gamma_{CO2d}}{\gamma_{COd}} \right)}
\]

Factor \( \alpha_{CO} \) is dependent on \( \lambda, \gamma_{COAd} \) and \( \gamma_{CO2d} \). If the \( \gamma_{COAd} \) is measured in the flue gas, the \( \gamma_{CO2d} \) value needs to be calculated with the formulae (6) and (7).

\[
\lambda - \gamma = \frac{\mu_{CO2d} - \gamma_{COAd}}{\gamma_{COAd} - \gamma_{CO2d}} + 1
\]

If \( \gamma_{CO2d} \) is measured \( \lambda \) is calculated according to:

\[
\lambda = \frac{V_{CO2d}}{V_{COAd}} \left( \frac{\gamma_{COAd} - \gamma_{CO2d}}{\gamma_{COAd} - \gamma_{CO2d}} \right) + 1
\]

The upper formulae for \( \lambda \) are given in [5]. Iteration is needed since factors \( \alpha_{CO} \) and \( \lambda \) are correlated. The CO impact on referred flue-gas mass \( \mu_{G} \) is always negative. This means that in presence of CO in flue gas, actual flue gas mass flow is lower than
flue gas mass flow calculated according to DIN 12952-15. Figure 1 shows the impact of CO content in dry flue gas on referred flue gas mass \( \mu_G \). Actual operating points are also marked. The CO impact on \( \mu_G \) is negative. If the CO content would rise to 1000 ppm, the difference of referred flue gas mass \( \mu_G \) would be in the case of hard coal – 0.28 % and in the case of lignite – 0.22 %. The gradient of CO impact is slightly higher in the case of hard coal due to the larger mass fraction of carbon in coal.

**Unburned Combustibles in Ash and Slag**

The air ratio is calculated on the basis of the measured flue gas composition at the boiler’s outlet and the fuel composition. Standard procedure for the flue gas mass flow calculation assumes that all the carbon from the “burned” fuel is burned completely and that the composition of the “burned” fuel matches the composition of the supplied fuel i.e. fuel sample. In practice, some of the larger coal dust particles do not burn completely; they leave the boiler with ash as coke. Therefore, the unburned carbon does not participate in CO2 formation. Actual oxygen consumption is therefore lower. In order to determine the excess air ratio more accurately, unburned carbon should be subtracted from the carbon mass fraction in the fuel and added to the ash mass fraction. The air ratio calculation should then be repeated using the new “apparent fuel composition”.

Two explanatory models are introduced in the following sections.

In the following paragraphs annotations “coalX” means composition of the fuel sample while “coalX” means apparent fuel composition (i.e. composition that actually burned). Model 1 – Unburned Combustible Matter in Ash and Slag is Pure Carbon (II)

Model 1: The assumption is that the combustible matter in ash and slag is pure carbon. New “apparent” fuel composition, which actually burns, is therefore:

\[
\begin{align*}
\gamma_C &= (1 - \delta_U) \text{coal}_C \\
\gamma_H &= \text{coal}_H \\
\gamma_S &= \text{coal}_S \\
\gamma_O &= (1 - \delta_U) \text{coal}_O \\
\gamma_N &= \text{coal}_N \\
\gamma_{\text{Ash}} &= \text{coal}_{\text{Ash}} + \delta_U (\text{coal}_C + \text{coal}_H + \text{coal}_S + \text{coal}_O + \text{coal}_N) \\
\gamma_{\text{H2O}} &= \text{coal}_{\text{H2O}}
\end{align*}
\]

**Model 2 – Composition of Unburned Combustible Matter in Ash and Slag Matches the Combustible Component of Fuel – Linear Model (III)**

Model 2: The assumption is that the combustible matter in ash and slag has the same composition as the combustible component of the fuel. New “apparent” fuel composition is therefore:

\[
\begin{align*}
\gamma_C &= (1 - \delta_U) \text{coal}_C \\
\gamma_H &= \text{coal}_H \\
\gamma_S &= \text{coal}_S \\
\gamma_O &= (1 - \delta_U) \text{coal}_O \\
\gamma_N &= \text{coal}_N \\
\gamma_{\text{Ash}} &= \text{coal}_{\text{Ash}} + \delta_U (\text{coal}_C + \text{coal}_H + \text{coal}_S + \text{coal}_O + \text{coal}_N) \\
\gamma_{\text{H2O}} &= \text{coal}_{\text{H2O}}
\end{align*}
\]

**Sensitivity Analysis**

Figure 2 shows the impact of unburned combustibles in ash and slag to referred flue gas mass. The x-axis of Figure 2 represents residual carbon content in dry flue gas. The y-axis shows the relative change of referred flue gas mass when unburned carbon is taken into account. The impact of unburned combustibles in ash and slag to referred flue gas mass is always negative. This means that in a presence of unburned combustibles in ash and slag, actual flue gas mass flow is always lower than flue gas mass flow calculated according to DIN 12952-15.

The results of Model 1 and Model 2 are presented in Figure 2. The proposed models are extreme cases. The actual impact lies somewhere in between. From the results we can conclude that the average impact gradient of unburned combustibles to referred flue gas mass is:

- hard coal: \(-0.87 \%\) of referred flue-gas mass per 1 % of unburned carbon
- lignite: \(-0.71 \%\) of referred flue-gas mass per 1 % of unburned carbon

The impact is larger for hard coal due to a higher mass fraction of carbon in the fuel. In the case of lignite, when the ratio \(\gamma_C/\gamma_H\) is lower, the gap between “pure carbon” and the “linear model” becomes wider.

**Residual Vapour Content in Gas Sample (IV)**

The standard procedure for the flue gas mass flow calculation requires a dry flue gas sample. The gas sample is usually dried by cooling to about 4 °C. Therefore, volume content of water vapour in the flue gas leaving the cooler is about 0.8 %. This means that the measured volume contents of the other flue gas components are lower than they would be if the flue gas sample was completely dry. To establish volume contents in completely dry flue gas sample the following correction should be applied:

\[
\text{water vapour content in dry flue gas} = \frac{v_{\text{Sat}}}{v_{\text{flue gas pressure in the cooler}}}
\]

where \(v_{\text{Sat}}\) is the saturation pressure of water at 4 °C and \(v_{\text{flue gas pressure in the cooler}}\) is the flue gas pressure in the cooler.

\[
\text{CO content in dry flue gas}\]

---

**Figure 1. Impact of CO content on referred flue gas mass \( \mu_G \).**

**Figure 2. Impact of unburned combustibles in ash and slag on referred flue gas mass \( \mu_G \).**
Accurate Analysis of Boiler Efficiency

Figure 2. Impact of unburned combustibles in ash and slag, hard coal.

where asterisk annotates measured volume contents of flue gas components in flue gas containing residual vapour. The annotations without an asterisk are used for volume contents of flue gas components in completely dry flue gas.

**Sensitivity Analysis**

The Bunte triangle in this point is used for explanatory purposes only because the triangle is valid only for completely dry gases. From the formulae (22) to (25) it is evident that during the correction procedure, values of γ_{CO2d} or γ_{O2d} are increased by an equal percentage. Therefore, the absolute variation ∆γ_{CO2d} or ∆γ_{O2d} formulae (26)

\[ \Delta \gamma_{d} = \gamma_{od} - \gamma_{ad} \]

is thus proportional to the value of γ_{CO2d} or γ_{O2d}. Usually in flue gas resulting from coal combustion the value γ_{CO2d} is 4 to 5 times larger than γ_{O2d}. Therefore, the absolute variation ∆γ_{CO2d} is also four to five times larger than ∆γ_{O2d}.

From the Bunte triangle, Figure 3, which graphically shows the relations between CO_2, O_2 content in flue gas and λ, it is obvious that we should distinguish between two cases with opposite effects:

a) oxygen content γ_{O2ad} is used to calculate the referred flue gas mass \( \mu_{G} \),

b) carbon dioxide content γ_{CO2ad} is used to calculate the referred flue gas mass \( \mu_{G} \).

Figure 3, Detail B, explains this graphically. Origin point C moves to D in the case when CO_2 is considered/measured (case b). If O_2 is considered/measured the origin point C moves to point E (case a) and the impact is positive.

This means that if the residual water vapour in the flue gas sample is not neglected the actual flue gas mass flow is greater than flue gas mass flow calculated according to DIN 12952-15. In case b, when CO_2 is considered/measured the impact changes sign and magnitude. For example the magnitude in hard coal case b is \( \approx 2.6 \) times larger than in hard coal case a, Figure 4.

Figure 5 shows the sensitivity of the excess air ratio which is evaluated with partial derivatives (27). It shows how quickly the excess air ratio is changing if the content of CO_2 or O_2 are changing.

\[ \frac{\partial}{\partial \gamma_{CO2d}} = \frac{V_{Gad}}{V_{God}} \left( \frac{\gamma_{CO2d} - \gamma_{CO2Ad}}{\gamma_{CO2Ad}} \right)^{2} \]

or

\[ \frac{\partial}{\partial \gamma_{O2d}} = \frac{V_{Gad}}{V_{God}} \left( \frac{\gamma_{O2d} - \gamma_{O2Ad}}{\gamma_{O2Ad}} \right)^{2} \]

Sensitivity of the excess air is weakly dependent on the fuel composition and therefore on Figure 5 only the results for lignite are presented. Essentially the absolute impact of both gases O_2 and CO_2 is quite similar and that the sensitivity is increasing when air ratio is increasing. From Figure 3 it can also be concluded that in case a the impact of residual water vapour in the flue gas sample decreases when the γ_{O2d} approaches zero. In case b, the impact of residual water vapour in the flue gas sample maximises when γ_{CO2d} approaches the stoichiometric referred CO_2 volume. In this limiting case the ratio between the CO_2 and O_2 impact limits to \( \rightarrow \infty \).

The standard [1] includes a correction formula but it should be stated more clearly that at least a rough energy balance of the air heater should be made to estimate the quantity of leakage air.

From the provided data, for a hard coal-fired power plant, a simple energy and mass balance for the air heater was established. The result shows that there is about 13.5 % of leakage air. To evaluate the impact of air leakage, the following assumptions were used:

- the mass content of leakage air is \( x_{LA} = 0.135 \)
- the temperature of leakage air is 15 to 30 °C lower than controlled-air temperature.
DIN 12952-15 calculates the specific heat of flue gas and combustion air using polynomial equations. This calculation procedure takes into account just air, water vapour and CO\textsubscript{2} content. More accurate calculation procedures take into account all flue gas components, i.e. N\textsubscript{2}, O\textsubscript{2}, Ar, Ne, H\textsubscript{2}O, CO\textsubscript{2}, CO and SO\textsubscript{2} as given in VDI-Richtlinien, VDI 4670 – “Thermodynamische Stoffwerte von feuchter Luft und Verbrennungsgasen” [4].

For the VDI 4670 calculation of mass fractions of flue gas and the combustion air of the components (N\textsubscript{2}, O\textsubscript{2}, Ar, Ne, H\textsubscript{2}O, CO\textsubscript{2}, CO, SO\textsubscript{2}) should be known. All the necessary formulae for the determination of referred masses \(\mu\) (kg/(kg of fuel)) were taken from Brandt [5].

Figure 4. Impact of residual vapour content in gas sample, hard coal.

Sensitivity Analysis
Leakage combustion air has an impact just on the heat input proportional to the fuel burned \(Q_{ZF}\). Therefore, there is no impact on the referred flue gas mass \(\mu_G\).

Different amounts of delivered heat to the boiler at the same useful heat output \(Q_N\), means also different boiler efficiency and consequently also different mass flow of burned fuel. Figure 6 presents the impact of leakage air on the flue gas mass flow \(m_{\dot{G}}\), leaving the air heater. In Figure 6 several temperature differences between controlled and leakage air are introduced. The impact of not neglecting the cold air leakage is positive, i.e. the flue gas mass flow leaving the air heater is increased.

Air and Flue Gas Enthalpy Calculation (VI)

DIN 12952-15 presents the impact of VDI 4670 on the boiler’s flue gas loss. It is evident that the VDI 4670 enthalpy calculation lowers flue gas loss. In the lignite case, the influence is almost twice as large as for hard coal. The reason for this is the water vapour content in the flue gas. The water content amounts 4.5\% for hard coal and 14.0\% for lignite. The overall impact of VDI 4670 as used in DIN 12952-15 is therefore dependent on the flue gas composition or fuel composition.

Data

Some major input data used in the computations are summarised in Table 1.

Results

Figure 8 graphically represents the main results of this research – the absolute change of boiler efficiency for particular modification and all for modifications simultaneously. The data from Table 1 were used in the calculation.

- Modification I – partial oxidation of carbon to CO: the change is small due to a very low CO content in the flue gas.
- Modifications II and III – composition of unburned combustibles in ash and slag: as expected, these two modifications have important effects. The effect is proportional to the content of the unburned combustibles in ash and slag. Unburned combustibles affect the computed referred flue gas mass due to the application of the apparent
Accurate Analysis of Boiler Efficiency

Table 1. Major input data.

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Units</th>
<th>Hard coal</th>
<th>Lignite</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ content in flue gas (by volume, dry) AH outlet</td>
<td>-</td>
<td>0.058</td>
<td>0.030</td>
</tr>
<tr>
<td>CO content in flue gas (by volume, dry) AH outlet</td>
<td>-</td>
<td>3.274E-05</td>
<td>9.500E-05</td>
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<td>Flue gas temperature, AH outlet °C</td>
<td></td>
<td>137.1</td>
<td>168.7</td>
</tr>
<tr>
<td>Air temperature, AH inlet °C</td>
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<td>55.5</td>
<td>51.91</td>
</tr>
<tr>
<td>Calorific value of coal kJ/kg</td>
<td></td>
<td>23,150</td>
<td>10,597</td>
</tr>
<tr>
<td>Carbon content, fuel (by mass)</td>
<td>-</td>
<td>0.5978</td>
<td>0.2906</td>
</tr>
<tr>
<td>Hydrogen content, fuel (by mass)</td>
<td>-</td>
<td>0.0361</td>
<td>0.0259</td>
</tr>
<tr>
<td>Sulphur content, fuel (by mass)</td>
<td>-</td>
<td>0.0074</td>
<td>0.0169</td>
</tr>
<tr>
<td>Oxygen content, fuel (by mass)</td>
<td>-</td>
<td>0.0511</td>
<td>0.0621</td>
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<tr>
<td>Nitrogen content, fuel (by mass)</td>
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<td>0.0124</td>
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<td>Ash content, fuel (by mass)</td>
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<td>Water content, fuel (by mass)</td>
<td>-</td>
<td>0.1349</td>
<td>0.5238</td>
</tr>
<tr>
<td>Ash collection efficiency</td>
<td>-</td>
<td>0.390</td>
<td>0.053</td>
</tr>
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<td>Unburned combustibles content (by mass), slag</td>
<td>-</td>
<td>0.0000</td>
<td>0.0027</td>
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<tr>
<td>Unburned combustibles content (by mass), ash</td>
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<td>0.0323</td>
<td>0.0010</td>
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<td>Calorific value of unburned combustibles, slag</td>
<td>kJ/kg</td>
<td>33,000</td>
<td>27,200</td>
</tr>
<tr>
<td>Calorific value of unburned combustibles, ash</td>
<td>kJ/kg</td>
<td>33,000</td>
<td>27,200</td>
</tr>
<tr>
<td>Slag temperature °C</td>
<td></td>
<td>1500</td>
<td>330</td>
</tr>
<tr>
<td>Volatile matter content, ash</td>
<td>-</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Figure 6. Impact of air leakage on computed flue gas mass flow, hard coal.

fuel composition instead of the actual fuel composition. Losses directly connected to the referred flue gas mass are therefore affected. Modifications II and III cannot be applied simultaneously. The difference in results of modifications II and III is not significant.

– **Modification IV** — residual water vapour in the flue gas sample: magnitude and direction of change depends on which gas is considered in the calculation and the flue-gas sample temperature (4 °C is used in Figure 8). Due to opposite impacts, both results for CO₂ and O₂ can be introduced simultaneously. It is evident that the impact of CO₂ is the largest and most important factor.

– **Modification V** — combustion-air heat input: in cases when the amount of leakage air is less than 20 %, the flue gas loss increases up to 0.01 %.

– **Modification VI** — VDI 4670 guidelines application: flue gas loss is lower up to 0.02 %. The water vapour content in the flue gas dictates the deviation magnitude.

– **All modifications simultaneously**: From Figure 8 it is clear that the particular modifications cause deviations in both directions — positive and negative. Therefore, they compensate for each other to some degree. The final overall deviation is somehow proportional to the “total sum” of the particular deviations. The final overall deviation of the boiler efficiency is positive.

It can be seen from Figure 8 that just the inclusion of leakage air always lowers the boiler efficiency. Residual water vapour in the flue gas sample can lower or raise efficiency, depending on whether CO₂ or O₂ is used in the boiler efficiency calculation. If O₂ is use, we get the overall results shown in column ALL 1, Figure 8. If CO₂ is used we get dramatically different results as shown in column ALL 2.

For these two studied examples with hard coal and lignite, with particular input data from Table 1, the overall absolute change in boiler efficiency due to the proposed modifications is relatively small. In this particular case when the oxygen content is used for boiler efficiency determination, the overall change of efficiency is +0.009 % for hard coal, and +0.002 % for lignite (Figure 8). If the carbon dioxide content is used, the overall change of efficiency is +0.07 % for hard coal and +0.06 % for lignite.

It can be concluded from Figure 8 that the proposed modifications, which provide more accurate calculations, increase the calculated value of boiler efficiency in almost all cases. This means that the actual (more accurate) boiler efficiency is higher than the value of efficiency given according to DIN 12952-15. In some extreme cases with very cold air leakage, high O₂ value with high residual water vapour with low unburned carbon etc. can lead to the opposite situation.

**Conclusion**

The article at hand presents and evaluates some modifications of the standardised indirect method for steam boiler efficiency determination, DIN 12952-15. The proposed modifications improve consistency of computations and accuracy of results. Six modific-
The analysis shows that boiler efficiency is decreased only by including leakage air and residual water vapour in the flue-gas sample if O₂ is used in the λ calculation. All other modifications increase the boiler efficiency compared to the standard procedure. The overall impact of all modifications is expected to be positive. This means that the actual boiler efficiency is higher than the efficiency calculated according to DIN 12952-15. The actual flue gas mass flow leaving the air heater is also lower up to 2 %.

Acknowledgment

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References


List of Symbols

Nomenclature and meanings of symbols matches the nomenclature in DIN 12952-15

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tr>
<td>α</td>
<td>kg/kg</td>
<td>Share of carbon forming CO₂</td>
</tr>
<tr>
<td>m</td>
<td>kg/j</td>
<td>Fuel content – fuel sample (by mass)</td>
</tr>
<tr>
<td>I₀</td>
<td>–</td>
<td>Ratio of unburned combustibles to supplied fuel mass flow</td>
</tr>
<tr>
<td>m</td>
<td>kg/s</td>
<td>Mass flow</td>
</tr>
<tr>
<td>Q</td>
<td>kW</td>
<td>Heat flow</td>
</tr>
<tr>
<td>V</td>
<td>m³/kg</td>
<td>Combustion air and flue gas volume (per unit mass of fuel)</td>
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### Accurate Analysis of Boiler Efficiency

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Subscripts and superscripts</th>
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<tbody>
<tr>
<td>(v)</td>
<td>m(^3)/m(^3) Specific volume</td>
<td>* Measured value</td>
</tr>
<tr>
<td>(x)</td>
<td>kg/kg Flue gas/combustion air components by mass</td>
<td>^ Maximum</td>
</tr>
<tr>
<td>(x_{Ad})</td>
<td>kg/kg Combustion air content by mass</td>
<td>A Air</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>m(^3)/m(^3) Content by volume</td>
<td>Ar Argon</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>Difference</td>
<td>Ash Ash</td>
</tr>
<tr>
<td>(\mu)</td>
<td>kg/kg Combustion air/flue gas mass to fuel mass ratio</td>
<td>CO Carbon</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Air ratio</td>
<td>CO(_2) Carbon dioxide</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>kg/kg Fuel content – actual burned (by mass)</td>
<td>d Dry (basis)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F Fuel, burned fuel</td>
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<tr>
<td></td>
<td></td>
<td>FA Flue dust (dry ash)</td>
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<td></td>
<td></td>
<td>Fo Fuel supplied</td>
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<tr>
<td></td>
<td></td>
<td>G Flue gas (combustion gas)</td>
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<tr>
<td></td>
<td></td>
<td>H Hydrogen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H(_2)O Water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LA Leakage (infiltrated) air/tramp air</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N, N(_2) Nitrogen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N Useful, effective</td>
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<td>O, O(_2) Oxygen</td>
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<td></td>
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<td>SO(_2) Sulfur dioxide</td>
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