

A MACROSCOPIC DETERMINATION OF THE  
IMPACT OF LETHABO COAL QUALITY  
UPON THE OPTIMUM  
COMBUSTION AIR QUANTITY

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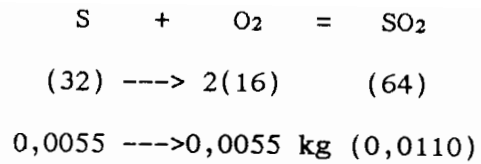
# **APPENDIX A**

## **SAMPLE CALCULATIONS**

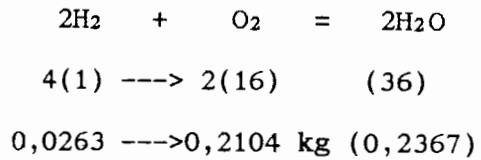
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Similarly:



and



The remaining components do not require oxygen, since they do not combust. The inherent oxygen should be subtracted: - 0,0893 kg

Thus, for every 1 kg of coal, 1.211 kg of oxygen is required. Since air contains 23,15 % oxygen (by mass):

For every 1 kg of coal, 5.233 kg of air is required.

During this operation the actual coal flow was 376.3 tons/h  
= 104.5 kg/s

The stoichiometric air quantity is thus = 547,0 kg/s

During the acceptance test, the measured total air flow was 746,0 kg/s. The excess air for this operation would then be 36,40%. This indicates the possible error discussed in the script, suggesting that

the total air flow indication is not correct. This led to the investigation and method of calibration of the total air measuring aerofoil and the air flow calculation illustrated in Sample calculation A.2. The motivation for the above argument emanates from the existing formulae commonly used to obtain an approximate value for excess air from measured volumetric oxygen in flue gas:

$$\% \text{ Excess air} = \frac{\% \text{ O}_2 \times 100}{20.95 - \% \text{ O}_2}$$

From this formula the measured 3% O<sub>2</sub> would produce a figure of ± 17% excess air. Had the excess air been the more likely 17% the total air flow would be 640,0 kg/s.

Thus: Stoichiometric plus 17% excess air = 547,0 + 92,98

The exhaust gases due to 1 kg of coal:

CO <sub>2</sub> -	1,492
SO <sub>2</sub> -	0,011
H <sub>2</sub> O -	0,237
Moisture in coal -	0,112
N <sub>2</sub> in coal -	0,009
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	1,860 kg

But the total coal flow was 104,5 kg/s, thus the exhaust gases for 104,5 kg/s of coal:

$$\begin{array}{r} \text{CO}_2 - 155,910 \\ \text{SO}_2 - 1,150 \\ \text{H}_2\text{O} - 24,740 \\ \text{Moisture in coal} - 11,680 \\ \text{N}_2 \text{ in coal} - 0,962 \\ \hline 194,440 \text{ kg/s} \end{array}$$

The N<sub>2</sub> from the total air supplied (17% excess air included):

$$\begin{aligned} &0,7686 \times 640,0 \text{ kg/s} \\ &= 491,9 \text{ kg/s} \end{aligned}$$

The O<sub>2</sub> from only the excess air supplied = 0,2315 x 92.98 kg/s

$$= 21,53 \text{ kg/s}$$

The atmospheric moisture in the combustion air supplied to the furnace (acceptance test values):

$$T_{wb} = 14,3 \text{ }^\circ\text{C}$$

$$T_{db} = 28,3 \text{ }^\circ\text{C}$$

$$\text{Thus } \phi = 0,22$$

(from Figure A.2: psychrometric chart at 1500 m altitude)

From saturation steam tables<sup>(18)</sup>:

$$P_s = 3845,8 \text{ Pa at } T = 28,3 \text{ }^\circ\text{C}$$

$$\phi = P_w / P_s$$

(per definition)

$$\text{thus } P_w = 846,1 \text{ Pa}$$

$$\begin{aligned} P_a &= P_{atm} - P_w \\ &= 85556 - 846,1 \\ &= 84709,9 \text{ Pa} \end{aligned}$$

from  $Pv = RT$  :

$$\begin{aligned} v_a &= RT/P \\ &= 287,1 \times 301,45/84709,9 \\ &= 1,0217 \text{ m}^3/\text{kg} \end{aligned}$$

From steam tables:

$$\begin{aligned} v_s &= 36,142 \text{ m}^3/\text{kg} \\ \infty &= \phi \times v_a / v_s \text{ (per definition)} \\ &= 0,00622 \text{ kg}_{\text{water}}/\text{kg}_{\text{air}} \end{aligned}$$

Thus, for 640,0 kg/s air flow, 3.98 kg/s of water vapour entered the furnace. This is to be added to the other moisture in coal. The total exhaust gases for 104,5 kg/s of coal & 17% excess air (this is the wet flue gas gravimetric analysis):

	CO <sub>2</sub> - 155,90	-	21,95
	SO <sub>2</sub> - 1,15	-	0,16
Moisture (in coal, in air, H <sub>2</sub> combustion)	- 40,39	-	5,69
N <sub>2</sub> (in coal, in air)	- 491,38	-	69,17
O <sub>2</sub> (in excess air)	- 21,53	-	3,03
	<u>710,36</u>	kg/s	<u>100,0%</u>

The equivalent dry flue gas gravimetric analysis would be:

	CO <sub>2</sub> - 155,91	-	23,27
	SO <sub>2</sub> - 1,15	-	0,17
N <sub>2</sub> (in coal, in air)	- 491,38	-	73,34
O <sub>2</sub> (in excess air)	- 21,53	-	3,21
	<u>669,0</u>	kg/s	<u>100,0%</u>

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## A.2: TOTAL AIR FLOW MEASURING AEROFOIL CALIBRATION

This example is numerically illustrated from measurements taken from an actual calibration exercise of the aerofoils prior to the main tests.

Manometer readings:

$$P_{stag} = -560 \text{ units}$$

$$P_{stat} = -3500 \text{ units}$$

Manometer fluid temperature reading:

$$T = 28 \text{ }^{\circ}\text{C}$$

Barometer reading:

$$P_{atm} = 86,48 \text{ kPa}$$

Air temperature readings at duct intakes, 73 m level:

$$T_{db} = 30,8 + 273,15 = 303,9 \text{ K}$$

$$T_{wb} = 14,0 + 273,15 = 287,2 \text{ K}$$

Thus:

$$P_{stag} = -(560/5 - (0,0007 \times 560/5 \times (28 - 20))) = -111,4 \text{ Pa}$$

$$P_{stat} = -(3500/5 - (0,0007 \times 3500/5 \times (28 - 20))) = -696,1 \text{ Pa}$$

The factor 5 is for the 1:5 incline of the manometer, the other constants are for the temperature compensation of the manometric fluid, which has a reference at 20 °C. The negative sign means the duct is under suction. The absolute value of the total pressure is thus still greater than that of the static pressure.

Thus:

$$\begin{aligned} P_{dyn} &= P_{stagn} - P_{stat} \\ &= -111,4 - (-696,1) \\ &= 584,7 \text{ Pa} \end{aligned}$$

The value of the dynamic pressure has to be positive for the flow not to be in the reverse direction.

Relative humidity: At the  $T_{db}$  and  $T_{wb}$  values measured above, the relative humidity is read off the psychrometric chart, for 84.6 kPa and 1500 m.a.s.l. seen in Figure A.2.

$$\phi = 0,157 \text{ (or 15\%)}$$

Saturation pressure of water vapour at  $T_{db}$  (interpolated) from saturation steam tables<sup>(18)</sup>:

$$P_s = 4428,5 \text{ Pa}$$

# PSYCHROMETRIC CHART

NORMAL TEMPERATURES

SI METRIC UNITS

Barometric Pressure 84.600 kPa

1500m Above SEA LEVEL

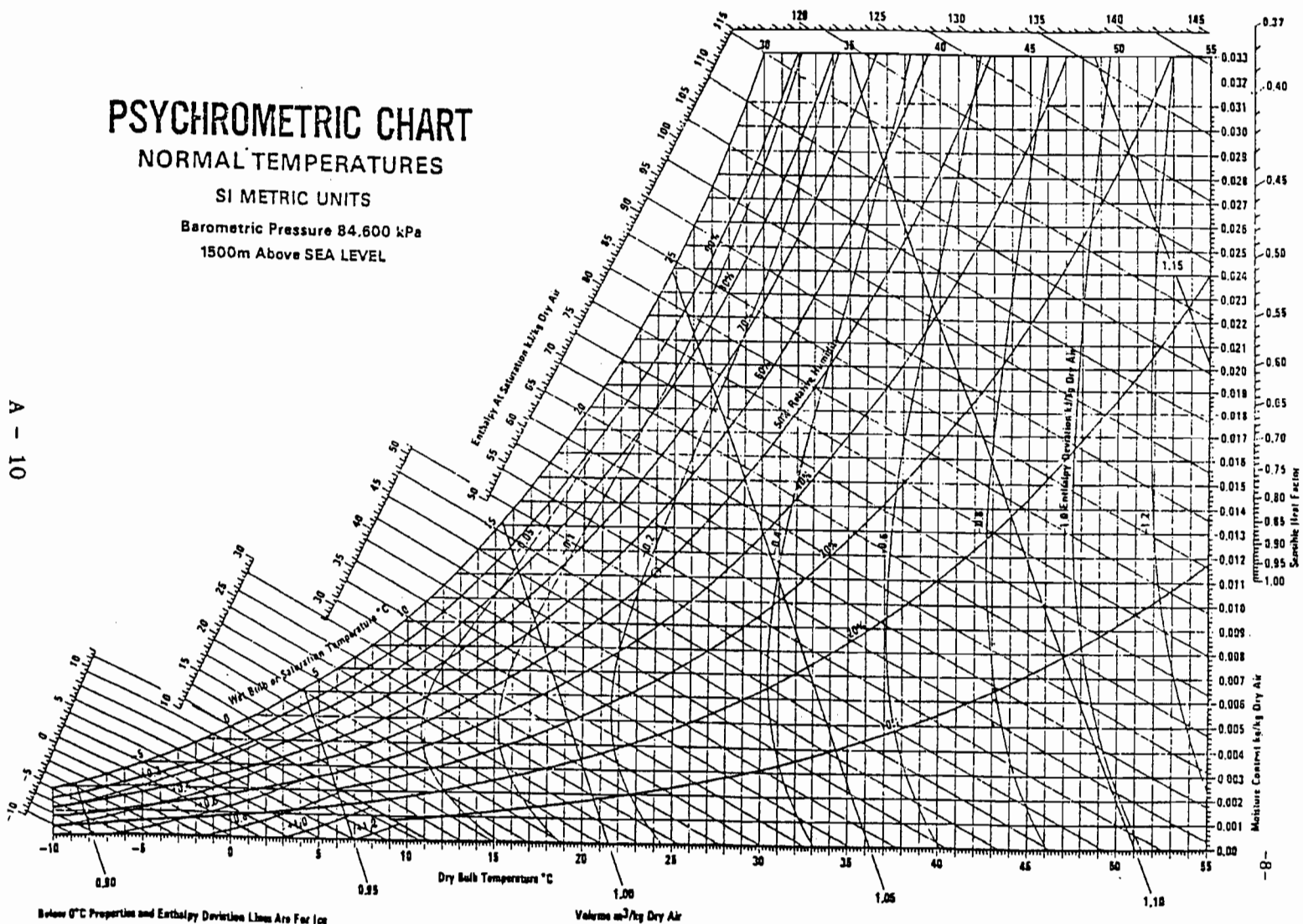


Figure A.2: PSYCHROMETRIC CHART FOR 1500 m.a.s.l.

Below 0°C Properties and Enthalpy Deviation Lines Are For Ice

Volume m<sup>3</sup>/kg Dry Air

DB

Partial pressure of water vapour (from  $\phi = P_w / P_s$ , per definition):

$$\begin{aligned} P_w &= \phi \times P_s \\ &= 0,157 \times 4428,5 \\ &= 695,3 \text{ Pa} \end{aligned}$$

Partial pressure of dry air:

$$\begin{aligned} P_{air} &= P_{mixture} - P_w \\ &= (P_{atm} + P_{stat}) - P_w \\ &= (86480 - 696,1) - 695,3 \\ &= 85089 \text{ Pa} \end{aligned}$$

Specific volume of dry air (from  $Pv = RT$ ):

$$\begin{aligned} v_{air} &= RT/P \\ &= 287,1 \times 303,9 / 85089 \\ &= 1,025 \text{ m}^3/\text{kg} \end{aligned}$$

Specific volume of water vapour,  $v_s$  (from steam tables<sup>(18)</sup> at  $T_{db}$ ):

$$v_s = 31,72 \text{ m}^3/\text{kg}$$

$$\begin{aligned}
 \text{Absolute humidity } \omega &= \phi \times v_{\text{air}} / v_s \\
 &= 0,157 \times 1,025 / 31,72 \\
 &= 0,0051 \text{ kg}_{\text{water vapour}} / \text{kg}_{\text{air}}
 \end{aligned}$$

From the continuity equation:

$$\text{mass flow} = \text{density} \times \text{cross-sectional area} \times \text{average velocity}$$

and the equation for the velocity or dynamic pressure:

$$P_{\text{dyn}} = 1/2 \times \text{density} \times \text{velocity}^2$$

thus:

$$\text{velocity} = \sqrt{(2 \times P_{\text{dyn}} / \text{density})}$$

substituting this velocity in the continuity equation above, the theoretical mass flow ( $C_d$  factor not yet taken into account) of the mixture of air and water vapour ( $\dot{m}_{\text{mt}}$ ), becomes:

$$\dot{m}_{\text{mt}} = A \times (\sqrt{(2 \times P_{\text{dyn}} / \text{density})}) \times \text{density}$$

$$\dot{m}_{\text{mt}} = A \times (\sqrt{(2 \times P_{\text{dyn}} / \text{density})}) \times \sqrt{(\text{density})^2}$$

$$\dot{m}_{\text{mt}} = A \times \sqrt{(2 \times P_{\text{dyn}} \times \text{density})}$$

since density =  $1 / v$ , from  $Pv = RT$ , density =  $P/RT$

Dalton's law of partial pressures states:

$$P_{\text{mixture}} = P_{\text{air}} + P_{\text{water vapour}}$$

thus:

$$\begin{aligned} \dot{m}_{mt} &= A \times \sqrt{(2 \times P_{dyn} \times (P_{air}/R_{air}T_{air} + P_w/R_wT_w))} \\ &= 11.008 \times \sqrt{(2 \times 584,7 \times (85089 / (287,1 \times 303,9) + 695,3 / (461,5 \times 303,9)))} \\ &= 372,7 \text{ kg/s} \end{aligned}$$

As said, this is the theoretical (ideal) mass flow, the  $C_d$  factor is not yet taken into account. A CFD study was performed on the whole duct including the aerofoil<sup>(19)</sup>. For this purpose, a  $C_d$  factor was determined.

From the graph in Figure A.3 at 372,7 kg/s mixture flow:

$$C_d = 0,833$$

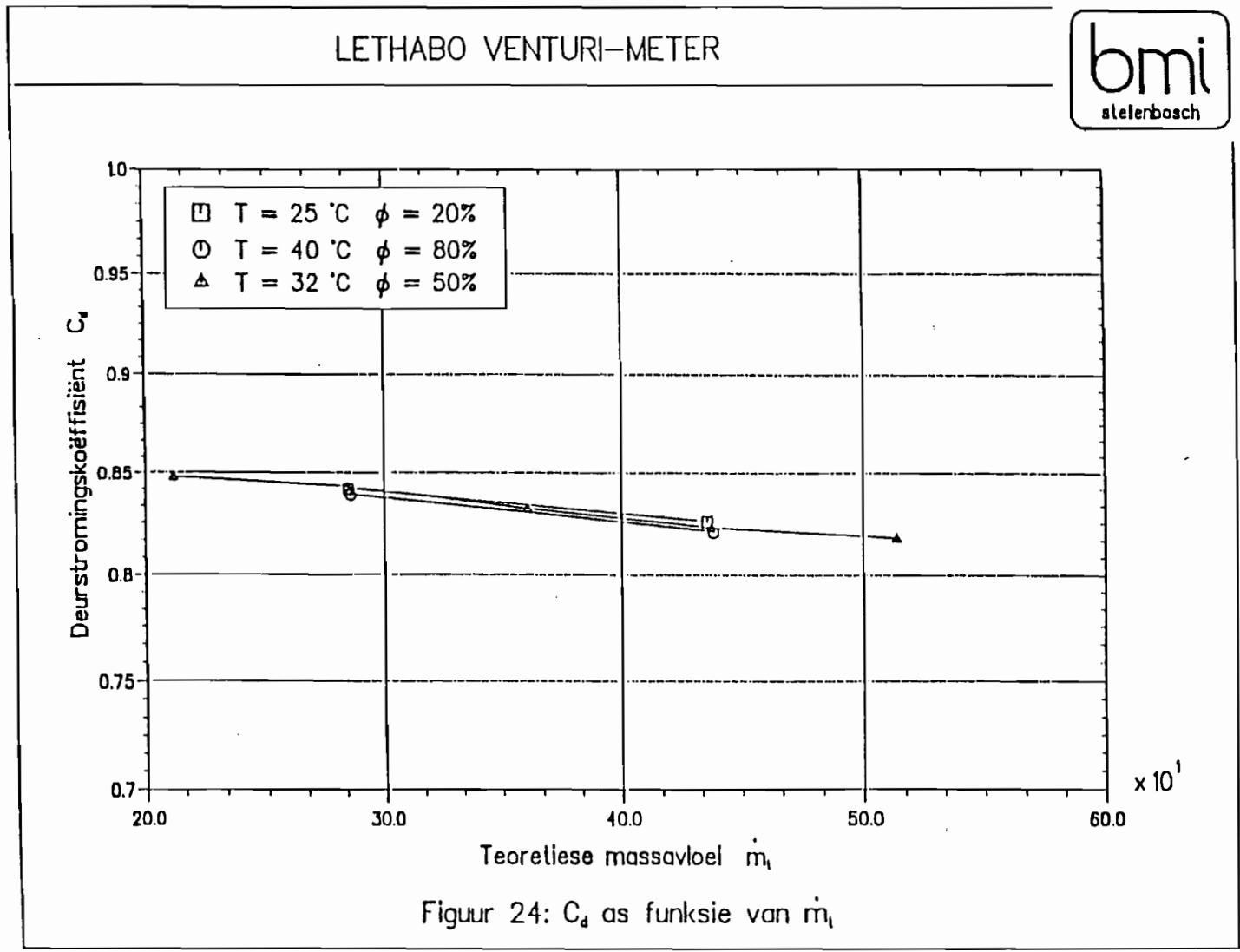
Thus: The actual mass flow of the mixture:

$$\begin{aligned} \dot{m}_m &= \dot{m}_{mt} \times C_d \\ &= 372,7 \times 0,833 \\ &= 310,5 \text{ kg/s} \end{aligned}$$

Mass flow of dry air only:

$$\begin{aligned} \dot{m}_{air} &= \dot{m}_m / (1 + \varphi) \\ &= 310,5 / (1 + 0,00508) \\ &= \underline{308,9 \text{ kg/s}} \end{aligned}$$

Figure A.3: C<sub>d</sub> FACTOR OF TOTAL AIR MEASURING AEROFOIL



At a required load and flow, the above exercise is done for the left and right hand side ducts of the boiler. The pressure differences versus the mass flow (corrected for temperature and humidity) are then given to C & I department for calibration of the indication.

The whole calculation and methodology above is written into a procedure<sup>(20)</sup> which is accepted, authorised and used at Lethabo Power Station as the method to determine the total air flow to the boiler and the calibration of these measuring aerofoils.

The above method was verified by means of separate tests, utilising a thermal anemometer (hot wire flow meter) and pitot tube traverses<sup>(21)</sup>, which compared favourably on the estimated  $C_d$  factor.

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A.3: AIR HEATER LEAKAGE COMPENSATION AND FLUE GAS PROPERTIES

A.3.1: Flue Gas properties

The flue gas analysis (% gravimetric) from sample calculation A.1 is taken as example. The significance of the difference between the volumetric vs. gravimetric percentage of a gas component of the flue gas is to be evaluated and other properties of the flue gas such as the molecular mass (M), polytropic expansion coefficient (n), specific heat capacities at constant pressure (cp) and constant volume (cv), as well as the specific gas constants (R) are also determined.

Wet flue gas analysis:

GAS	GRAV ANAL (kg/100kg)	MOLE MASS (kg/mole)	MOLES (/100kg)	VOL ANAL %mole	n	cp kJ/kgK	cv kJ/kgK	R kJ/kgK
CO <sub>2</sub>	21,950	44	0,499	14,750	1,287	0,8457	0,6573	0,1884
SO <sub>2</sub>	0,162	64	0,003	0,089	1,252	0,6448	0,5150	0,1298
H <sub>2</sub> O	5,686	18	0,316	9,340	1,269	2,1800	1,7190	0,4615
N <sub>2</sub>	69,170	28	2,470	73,020	1,399	1,0400	0,7436	0,2964
O <sub>2</sub>	3,030	32	0,095	2,810	1,394	0,9182	0,6586	0,2596
	----- 100,0	29,55	<---3,384	----- 100,0	----- 1,361	----- 1,058	----- 0,7771	----- 0,2807

The flue gas properties are determined from the following thermodynamic relationships for a perfect gas:

$$n = c_p / c_v \quad \text{and} \quad R = c_p - c_v$$

The molecular mass of the wet flue gas:  $1/3,384 \times 100$

$$M = 29,55 \text{ kg/mole}$$

Universal gas constant  $\underline{R} = 8,314 \text{ kJ/moleK}$

The specific gas constant for wet flue gas:

$$R = 280,7 \text{ J/kgK}$$

The  $c_p$  value for wet flue gas:

$$c_p = 1,058 \text{ kJ/kgK}$$

The  $c_v$  value for wet flue gas:

$$c_v = 0,7771 \text{ kJ/kgK}$$

The polytropic expansion coefficient for wet flue gas:

$$n = 1,361$$

It should also be noted that the difference between the ratio gravimetric : volumetric for any gas component and the flue gas mixture is equal to the ratio of the molecular mass of the gas component : molecular mass of the total flue gas mixture.

Thus: to convert from volumetric (normally the mode the gas analysis instrument operates in) to gravimetric (normally the mode required in the calculations) multiply by the ratio  $M_{gas}/M_{mixture}$ .

In wet flue gas e.g. the ratio for oxygen of gravimetric : volumetric percentage is 3,030 : 2,807 = 1,08. The ratio of  $M_{\text{oxygen}}$  :  $M_{\text{mixture}}$  is 31.998 : 29.55 = 1.08. This difference is also significant and should be taken into account in calculations.

Similarly, the dry flue gas analysis:

GAS	GRAV ANAL (kg/100kg)	MOLE MASS (kg/mole)	MOLES (/100kg)	VOL ANAL %mole	n	$c_p$ kJ/kgK	$c_v$ kJ/kgK	R kJ/kgK
CO <sub>2</sub>	23,270	44	0,529	16,270	1,287	0,8457	0,6573	0,1884
SO <sub>2</sub>	0,172	64	0,003	0,092	1,252	0,6448	0,5150	0,1298
N <sub>2</sub>	73,340	28	2,619	80,560	1,399	1,0400	0,7436	0,2964
O <sub>2</sub>	3,213	32	0,100	3,076	1,394	0,9182	0,6586	0,2596
	100,0	30,76	<---3,251	100,0	1,375	0,9902	0,7204	0,2703

The flue gas properties here are also determined from the following thermodynamic relationships for a perfect gas:

$$n = c_p / c_v \quad \text{and} \quad R = c_p - c_v$$

The molecular mass of the dry flue gas:  $1/3,251 \times 100$

$$M = 30,76 \text{ kg/mole}$$

Universal gas constant  $R = 8,314 \text{ kJ/moleK}$

and the specific gas constant for dry flue gas:

$$R = 270,3 \text{ J/kgK}$$

Thus  $c_p$  for dry flue gas:

$$c_p = 0,9902 \text{ kJ/kgK}$$

Thus  $c_v$  for dry flue gas:

$$c_v = 0,7204 \text{ kJ/kgK}$$

Thus the polytropic expansion coefficient for dry flue gas:

$$n = 1,375$$

In the case of the dry flue gas too, it should be noted that the difference between the ratio gravimetric : volumetric for any gas component and the flue gas mixture is equal to the ratio of the molecular mass of the gas component : molecular mass of the total flue gas mixture.

Thus: to convert from volumetric to gravimetric for both wet and dry flue gas, multiply by the ratio  $M_{\text{gas}}/M_{\text{mixture}}$ . In dry flue gas e.g. the ratio for oxygen of gravimetric : volumetric percentage is 3,213 : 3,076 = 1,04. The ratio of  $M_{\text{oxygen}} : M_{\text{mixture}}$  is 32.00 : 30.76 = 1.04. This difference is also significant and should be taken into account in calculations.

### A.3.2: Air in-leakage compensation on dfg temperature

The air in-leakage via the air heater seals can have a deceiving effect on the dry flue gas loss calculation, since the back-end temperature will appear lower with higher leakage due to the dilution effect of the colder air leaking in. STEP calculates the actual dry flue gas loss according to:

$$Q = m \times c_p \times (T_{out} - T_{in})$$

Although the mass flow of flue gas will increase due to the leakage, the STEP formula will not correctly be influenced, since the O<sub>2</sub>% is normally not measured before and after the air heaters. Even if it is, as done correctly during these tests, the STEP formulae can not detect the additional mass flow, as calculated by the iterative methods discussed in Chapter 6. Therefore, a compensating formula had is to be derived:

Let O<sub>2</sub>% (gravimetric) in flue gas before A/HTRS = x

Let O<sub>2</sub>% (gravimetric) in flue gas after A/HTRS = z

O<sub>2</sub>% (gravimetric) in air (leaking in via A/HTRS) = k

Leakage fraction (gravimetric) kg<sub>air</sub>/kg<sub>gas</sub> = y

Let the mass flow of flue gas before A/HTRS = G

Let the mass flow of flue gas after A/HTRS = M

Let the mass flow of air leaking into A/HTRS = L

then:  $G + L = M$

and  $G(x/100) + L(k/100) = M(z/100)$

thus:  $xG + kL = zM$

For L/G in terms of M:

$$L = \frac{zM - xG}{k}$$

$$L = \frac{zM - x(M - L)}{k}$$

$$L = \frac{zM - xM - xL}{k}$$

$$kL - xL = zM - xM$$

$$L(k - x) = M(z - x)$$

Thus:  $L = \frac{M(z - x)}{k - x}$

$$G = \frac{zM - kL}{x}$$

$$G = \frac{zM - k(M - G)}{x}$$

$$G = \frac{zM - kM - kG}{x}$$

$$xG - kG = zM - kM$$

$$G(x - k) = M(z - k)$$

$$\text{Thus: } G = \frac{M(z - k)}{x - k}$$

$$\text{Now: } \frac{L}{G} = \frac{M(z - x)}{(k - x)} \times \frac{(x - k)}{M(z - k)}$$

$$\frac{L}{G} = \frac{(z - x)}{(k - x)} \times \frac{(k - x)}{(k - z)}$$

$$\frac{L}{G} = \frac{(z - x)}{(k - z)}$$

For L/M in terms of G:

$$L = \frac{zM - xG}{k}$$

$$L = \frac{z(G + L) - xG}{k}$$

$$L = \frac{zG + zL - xG}{k}$$

$$kL - zL = zG - xG$$

$$L(k - z) = G(z - x)$$

$$\text{Thus: } L = \frac{G(z - x)}{k - z}$$

$$M = \frac{xG - kL}{z}$$

$$M = \frac{xG + k(M - G)}{z}$$

$$M = \frac{xG + kM - kG}{z}$$

$$zM - kM = xG - kG$$

$$M(z - k) = G(x - k)$$

$$\text{Thus: } M = \frac{G(x - k)}{z - k}$$

$$\text{Now: } \frac{L}{M} = \frac{G(z - x)}{(k - z)} \times \frac{(z - k)}{G(x - k)}$$

$$\frac{L}{M} = \frac{(z - x)}{(k - z)} \times \frac{(k - z)}{(k - x)}$$



$$\frac{L}{M} = \frac{(z - x)}{(k - x)}$$

The above two formulae proved to be more accurate than the generally used formula by 1 - 2% :

$$\% \text{ Excess air} = \frac{\text{O}_2 \text{ \% after A/HTR} \times 100}{20,95 - \text{O}_2 \text{ \% after A/HTR}}$$

This is due to the fact that volumetric values for oxygen are used, but the excess air is normally required as a mass for calculations.

The amount of air in-leakage is now available as a fraction of the gas before or the mixture after the air heaters, as a function of the gravimetric O<sub>2</sub>% before and after the air heaters. In both cases the value of k = 23.15. The advantage here is that the in-leakage will be available in kg/s, but an iterative method is necessary as discussed in A.3.4. Although the oxygen percentages are available as volumetric values (see Appendix B), the conversion to gravimetric is done as explained in A.3.1.

The primary reason for this calculation can now be pursued:

To calculate what the actual temperature of the flue gas would have been, had there been no air-in-leakage.

$$\text{Heat given off by gas} = \text{heat absorbed by air}$$

(This is not due to the heat exchange of the A/HTR between gas and air, but the gas on the A/HTR outlet and the in-leaking air.)

Let the final temperature after the air heaters of the mixture be  $T_f$  and let the air temperature before the air heaters be  $T_a$ , then:

$$m_g c_{pg} (T_g - T_f) = m_a c_{pa} (T_f - T_a)$$

$$m_g c_{pg} T_g - m_g c_{pg} T_f = m_a c_{pa} (T_f - T_a)$$

$$T_g = (m_a c_{pa} (T_f - T_a) + m_g c_{pg} T_f) / m_g c_{pg}$$

$$T_g = (m_a c_{pa} (T_f - T_a)) / m_g c_{pg} + T_f$$

$$\text{but } m_a/m_g = L/G \text{ (as above)}$$

$$\text{and } L/G = \frac{(O_2\%_{\text{after A/HTR}} - O_2\%_{\text{before A/HTR}})}{(23,15 - O_2\%_{\text{after A/HTR}})}$$

Thus, if the  $O_2\%$  (gravimetric) and temperature after the A/HTR, the  $O_2\%$  (gravimetric) before the A/HTR and the FD inlet air temperature are known ( $c_{pg} = 0,9902 \text{ J/kgK}$  is known from the tables above and  $c_{pa} = 1,004 \text{ J/kgK}$ ), the equation may be solved for  $T_g$ , i.e. what the temperature of the flue gas would have been had there been no air in-leakage (dilution). This value is used as input into the STEP after the dfg loss formula has been changed according to the above.

### A.3.3 Theoretical air vs. Stoichiometric air

In the calculations of this project there is a need to distinguish between theoretical air and stoichiometric air for the sake of terminology and calculation. Stoichiometric air is defined here as the air quantity needed for combustion of the coal as calculated in Sample calculation A.1. from the chemical equations as basis. The accuracy thereof is dependant on the coal mass flow. This entity is normally the parameter that produces accuracy problems, not so much from the volumetric feeder side (Sample calculation A.5) as from the coal density and sample representativeness. The theory in Chapter 6 justifies a need for this air quantity to be equal to that calculated back from the oxygen and excess air side. The latter is very representative and the above formulae now enables a derivative thereof. It was shown above how these two formulae were derived:

$$\frac{L}{M} = \frac{(z - x)}{(k - x)}$$

and

$$\frac{L}{G} = \frac{(z - x)}{(k - z)}$$

The latter formula can now be used to derive an equation to determine the theoretical air if applied to the circumstances in the furnace immediately after combustion. If the air in-leakage (L) is seen as the excess air "leaking" into the theoretical air (G), the oxygen content "z" will be the resulting gravimetric percentage due to this

amount of total combustion air. The oxygen content "x" will be the amount before the excess air was added, i.e. that corresponding to the theoretical air, which must be zero. The value k = 23.15 for the gravimetric percentage of oxygen in atmospheric air. The equation above then becomes:

$$\frac{\text{Excess air}}{\text{Theoretical air}} = \frac{z}{(23.15 - z)}$$

but: Theoretical air + Excess air = Combustion air

Thus: Excess air = Combustion air - Theoretical air

$$\frac{\text{Combustion air} - \text{Theoretical air}}{\text{Theoretical air}} = \frac{z}{(23.15 - z)}$$

$$\text{Combustion air} = \frac{z}{(23.15 - z)} \times (\text{Theoretical air}) + \text{Theoretical air}$$

$$\text{Combustion air} = \left(1 + \frac{z}{(23.15 - z)}\right) \times (\text{Theoretical air})$$

Thus:

$$\text{Theoretical air} = \frac{\text{Combustion air}}{\left(1 + \frac{z}{23.15 - z}\right)}$$

This equation can also be expressed as:

$$\text{Theoretical air} = \frac{\text{Total measured Air Flow} - \text{Air heater leakage}}{\left(1 + \frac{z}{23.15 - z}\right)}$$

The Combustion air also = Total measured Air Flow - Air heater leakage when Figure A.4 is viewed. The above equation is the one mentioned previously that produces more realistic values from which theoretical and excess air can be derived, than the approximate traditional equation below:

$$\% \text{ Excess air} = \frac{\text{O}_2 \% \text{ after A/HTR} \times 100}{20,95 - \text{O}_2 \% \text{ after A/HTR}}$$

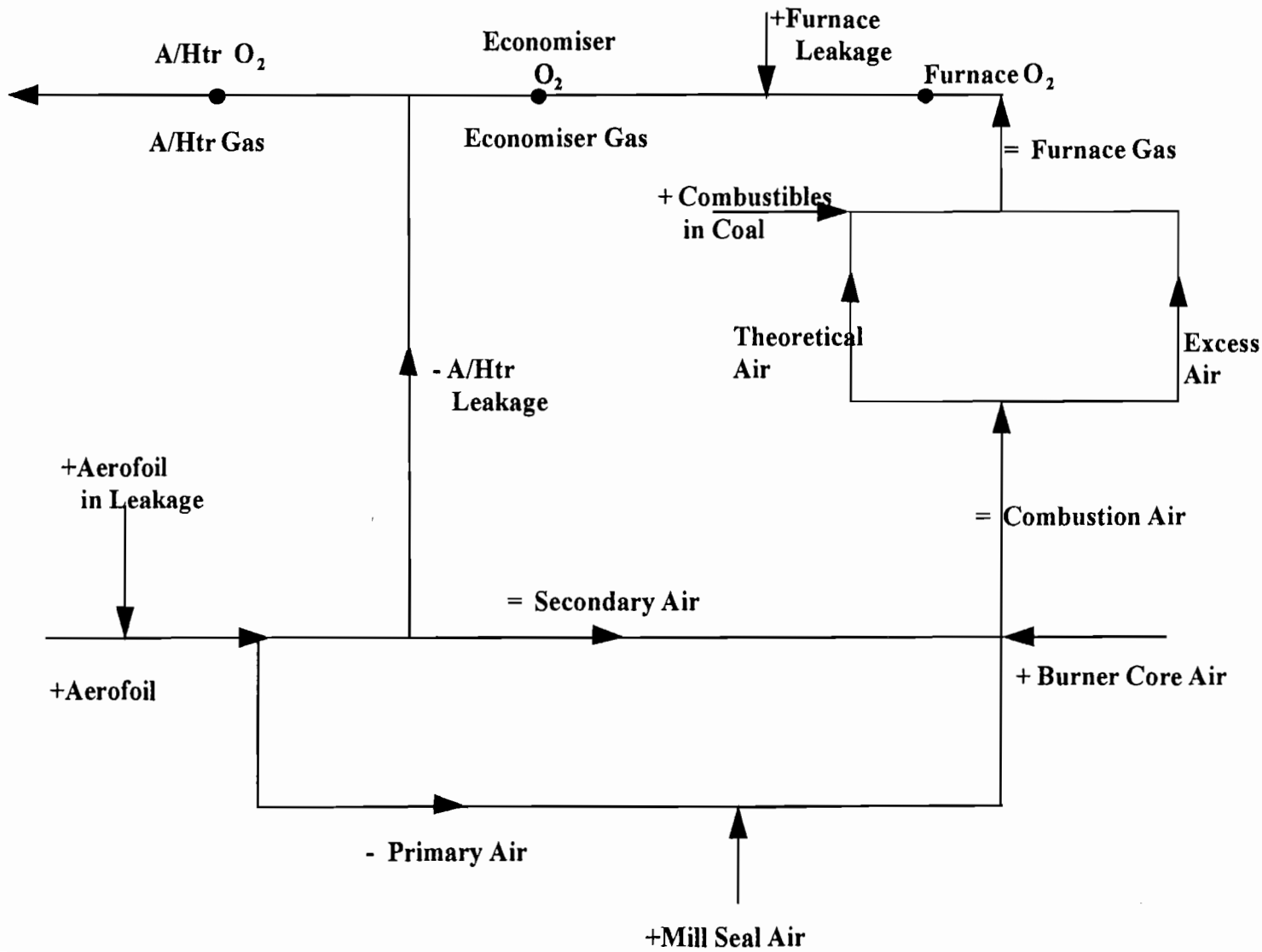


Figure A.4: AIR FLOW AND AIR HEATER LEAKAGE

A.3.4: Air Heater Leakage iteration

Air heater leakage is obtained from the formulae derived in A.3.2:

$$\frac{L}{M} = \frac{(z - x)}{(k - x)}$$

and

$$\frac{L}{G} = \frac{(z - x)}{(k - z)}$$

from which is derived (in A.3.3):

$$\text{Theoretical air} = \frac{\text{Combustion air}}{\left(1 + \frac{z}{23.15 - z}\right)}$$

and

$$\text{Theoretical air} = \frac{\text{Total measured Air Flow} - \text{Air heater leakage}}{\left(1 + \frac{z}{23.15 - z}\right)}$$

which can be verified from Figure A.4. It can be seen that since air heater leakage is at first part of combustion air and finally again part of air heater gas, an exact solution is not possible, but an

iteration is required. The iteration logic can be followed from Figure A.4 and Table A.1 in the following sequential order below: (The parameters have alphabetical row numbers, those underscored are varying with iterations until the values have converged.)

- The total air flow measured by the aerofoils (Sample calculation A.2) Plus the in-leakage at the aerofoil casing is the first addition to the mass flow. The in-leakage is detected at the circumference of the rectangular joint between the steel casing of the aerofoil and the concrete of the duct. The flow rate is determined with a vane anemometer traverse, determining the average velocities through the areas and the measuring of the rectangular areas at different boiler loads. The minimum amounted to 1.8 kg/s and the maximum was 4.2 kg/s. A linear regression formula was derived to add the appropriate proportion of in-leakage to the aerofoil flow rate. For a specific test, this flow rate is a constant value, as indicated in row (a) of Table A.1.

- Next the primary air flow is subtracted in (b), just to be added again in (f), having no effect on the total.

- The air heater leakage is then subtracted in (c). It is calculated as indicated in Table A.1 by the formula based on:

$$\frac{L}{G} = \frac{(z - x)}{(23.15 - z)}$$



Table A.1: ITERATION FOR DETERMINING AIR HEATER LEAKAGE

	<u>Parameter</u>	<u>Formula or type</u>	<u>Iteration 1</u>	<u>Iteration 2</u>	<u>Iteration 3</u>
a	+ Aerofoil + in-leakage	Measured value (constant)	constant	constant	constant
b	- Primary air	Process value (constant)	constant	constant	constant
c	- A/HTR leakage	$\frac{o(s-p)}{(23.15-s)}$	0	$\frac{o_1(s_1-p_1)}{(23.15-s_1)}$	$\frac{o_2(s_2-p_2)}{(23.15-s_2)}$
d	= Secondary air	$a-b-c$	do. (changing value)	do. (changing value)	do. (changing value)
e	+ Mill seal air	Measured value (constant)	constant	constant	constant
f	+ Primary air	Process value (constant)	constant	constant	constant
g	+ Burner core air	Measured value (constant)	constant	constant	constant
h	Combustion air	$a-c+e+g$	do. (changing value)	do. (changing value)	do. (changing value)
i	Theoretical air	$\frac{h}{[1+m/(23.15-m)]}$	do. (changing value)	do. (changing value)	do. (changing value)
j	Excess air	$\frac{h-i}{i}$	do. (changing value)	do. (changing value)	do. (changing value)
k	+ Coal Combustibles	From dry-ash free coal	constant	constant	constant
l	Furnace gas	$h+k$	do. (changing value)	do. (changing value)	do. (changing value)
m	Furnace O <sub>2</sub>	$p-[n/l*(23.15-p)]$	do. (changing value)	do. (changing value)	do. (changing value)
n	+ Furnace in-leakage	Pre-determined value	constant	constant	constant
o	Economiser gas	$l+n$	do. (changing value)	do. (changing value)	do. (changing value)
p	Economiser O <sub>2</sub>	Measured value (constant)	constant	constant	constant
q	+ A/HTR leakage	$\frac{o(s-p)}{(23.15-s)}$	$\frac{o_1(s_1-p_1)}{(23.15-s_1)}$	$\frac{o_2(s_2-p_2)}{(23.15-s_2)}$	$\frac{o_3(s_3-p_3)}{(23.15-s_3)}$
r	= A/HTR gas	$o+q$	do. (changing value)	do. (changing value)	do. (changing value)
s	A/HTR O <sub>2</sub>	Measured value (constant)	constant	constant	constant

and utilising the economiser gas (o), the A/HTR O<sub>2</sub> (s) and the economiser O<sub>2</sub> (p).

- The secondary air (d) is the resulting flow thus far.

- The mill seal air (e) and burner core air (g) are pre-determined values. The burner core air in-leakage is a constant value (11.93 kg/s) irrespective of the load and the amount of mills in service, since it is only dependant on the differential pressure between atmosphere and furnace pressure, measured with a vane anemometer during testing. (The ID fans strive to maintain constant furnace pressure.) The seal air was tested by vane anemometer and pitot traverse with an average of 3.657 kg/s/mill in service.

- The balance then produces the combustion air (h), which varies as the A/HTR leakage changes with converging iterations.

- The combustion air comprises the theoretical (i) and excess (j) air. Theoretical air is obtained from the formula:

$$\text{Theoretical air} = \frac{\text{Combustion air}}{\left(1 + \frac{z}{23.15 - z}\right)}$$

and utilises the furnace O<sub>2</sub> (m) for the value of "z". The excess air (j) is simply the difference between the combustion and theoretical

air.

- The coal combustibles (k), which adds to the gasses formed from the chemical equations, are simply the mass of the coal burnt for the test minus the moisture, hydrogen and ash.

- The addition of these coal combustibles to the combustion air amounts to the furnace gas (l).

- The furnace O<sub>2</sub> is back-solved from the above derived formula:

$$\frac{L}{G} = \frac{(z - x)}{(23.15 - z)}$$

where:

x = furnace O<sub>2</sub> (m)

L = furnace in-leakage (n)

G = Furnace gas (l)

z = economiser O<sub>2</sub> (p)

Take note that this value will be gravimetric and dry. See Appendix B for an explanation of which O<sub>2</sub> measurements are wet or dry, gravimetric or volumetric etc., by instrumentation and analysers. The gas component values are all transformed to dry gravimetric for calculations. The answers and results from iterations etc. will thus be the same.

- The furnace in-leakage (n) is pre-determined by the iterative calculation methods discussed in Chapter 6 and verified afterwards by practical tests involving pitot traverses to calculate gas and air flow differences. This value eventually amounted to a constant 35 kg/s, as can be seen in Appendices F, G and H.

- The economiser gas mass flow (o) is the sum of the furnace gas and furnace in-leakage.

- The economiser O<sub>2</sub> % is a volumetric wet measured value, transformed to gravimetric dry.

- The A/HTR leakage (q) again joins the gas stream and is calculated in the same way as in (c) above. The reason why it appears twice is to accomplish the iterative procedure explained below.

- The A/HTR gas (r) is the sum of the economiser gas (o) and the A/HTR leakage (q).

- The A/HTR O<sub>2</sub> is a volumetric wet measured value, converted to gravimetric dry for calculation.

The iteration operates as follows when the columns and specifically rows (c) and (q) in Table A.1 are viewed:

A value of zero is initially entered into row (c) of Iteration column 1 for the A/HTR leakage value. The above formulae will calculate a first iteration value for A/HTR leakage by going through the process explained above and place that value in row (q). All the other parameters that should change (underscored) will automatically be recalculated.

This first estimation for A/HTR leakage in row (q) column 1, will then be placed into row (c) of column 2, as a starting value by a macro written into the spreadsheet. The second iterative value for A/HTR leakage will then be calculated by the procedure and formulae described above in row (q), column 2.

This second estimation for A/HTR leakage in row (q) column 2, will then be placed into row (c) of column 3, as a starting value. The third iterative value for A/HTR leakage will then be calculated by the procedure and formulae and shown in row (q). The iteration is repeated until all the values, especially the A/HTR leakage have converged to an accepted degree of significant figures.

The answer of air heater leakage is now in terms of kg/s air flow, not as a fraction of the gas before or the mixture after the heater.

#### A.4: BOILER FEED WATER FLOW

This example uses the values for the H/550/28/9h00 test. The data is an extraction of the report: Feed water Flow rate calculations<sup>(23)</sup>, specially compiled for these tests. (The amount of significant figures are as per digital instrument output. The final answer is rounded off to 5 significant figures.)

Determine the Static pressure working range:

Static output (averaged) = 11.9695 mA  
Static output zero = 4.015 mA  
Calibrated static output zero = 4.003 mA

Thus,

Actual static output =  $11.9695 + (4.003 - 4.015)$   
= 11.9575 mA


From calibration Table A.2, interpolate the actual static pressure:

$$\begin{aligned} \text{Static pressure} &= (11.9575 - 11.5740) / (13.088 - 11.5740) \\ &\quad \times (23481.57 - 19569.31) + 19569.31 \\ &= 20560.295 \text{ kPa} \end{aligned}$$

Thus,

Static pressure working range is between 19000 and 22000 kPa


Table A.2: CALIBRATION CERTIFICATE: GAUGE PRESSURE TRANSMITTER



NCS

ESKOM - TECHNOLOGY, RESEARCH AND INVESTIGATIONS

CERTIFICATE OF CALIBRATION No. : 0692P056  
FOR A GAUGE PRESSURE TRANSMITTER



ESKOM

TRI REFERENCE No. : A1  
TRI CALIBRATION No. : 19

MANUFACTURER & TYPE : Rosemount 1151GP  
SERIAL NUMBER : 152636  
INSTRUMENT RANGE : 0 to 41369 kPa

CALIBRATED FOR : ESKOM -T.R.I./ Performance & Metrology

CALIBRATION PROCEDURE : PC-02-02  
REFERENCE EQUIPMENT : Budenberg 280D Pressure Balance S/N 9004  
Fluke 8600A DMM S/N 2365133


DATE OF CALIBRATION : 29/06/92  
LABORATORY TEMPERATURE : 21.7 °C

True Pressure (kPa)	Transmitter Output (mA)		
	Rising	Falling	Average
0.00	3.996	4.010	4.0030
3913.37	5.506	5.525	5.5155
7827.37	7.022	7.037	7.0295
11741.69	8.537	8.550	8.5435
15655.77	10.053	10.066	10.0595
19569.31	11.568	11.580	11.5740
23481.57	13.083	13.093	13.0880
27395.04	14.599	14.606	14.6025
31308.62	16.112	16.122	16.1170
35222.15	17.623	17.633	17.6280
39135.39	19.139	19.139	19.1390

UNCERTAINTY - The uncertainty of measurement is :  $\pm 0.1\%$  FS  
estimated for a confidence level of 95 % .

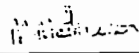
VALIDITY OF CERTIFICATE : 12 months

COMMENTS : Calibrated with diaphragm in a vertical plane.No load resistance applied.Excitation voltage = 24 VDC.

CALIBRATED BY : W De Vries 

CHECKED BY : M Mathieson

HEAD OF LABORATORY



Determine the differential pressure:

Differential output (averaged) = 9.07731 mA

Differential output zero = 3.896 mA

For a static pressure of 19000 kPa:

Calibrated differential output zero = 4.012 mA

Thus:

Actual differential output = 9.07731 + (4.012 - 3.896)  
= 9.19331 mA

From calibration Table A.3 interpolate actual differential pressure.

Actual differential pressure = (9.19331 - 7.5290) / (9.2865 - 7.5290)  
x (59.88 - 39.92) + 39.92  
= 58.8216 kPa

For a static pressure of 22000 kPa:

Calibrated differential output zero = 4.0105 mA

Thus:

Actual differential output = 9.07731 + (4.0105 - 3.896)  
= 9.19181 mA



Table A.3: CALIBRATION TABLE: DIFFERENTIAL PRESSURE TRANSDUCER

Rec nr : 57                      HP DIFFERENTIAL PRESSURE TRANSDUCER  
 Static pressure no. 3  
 DEVICE : DPHP12              NO. PTS : 10                      STATIC PRESSURE: 19000                      kPa

Number	Pressure kPa	mA output	mV output R=20 Ohms
1	0.00	4.0120	80.2400
2	19.96	5.7710	115.4200
3	39.92	7.5290	150.5800
4	59.88	9.2865	185.7300
5	79.84	11.0440	220.8800
6	99.80	12.8035	256.0700
7	119.76	14.5635	291.2700
8	139.71	16.3280	326.5600
9	159.67	18.0940	361.8800
10	179.63	19.8680	397.3600

Calibration table for differential pressure transducer at static pressure of 19000 kPa

Rec nr : 58                      HP DIFFERENTIAL PRESSURE TRANSDUCER  
 Static pressure no. 4  
 DEVICE : DPHP12              NO. PTS : 10                      STATIC PRESSURE: 22000                      kPa

Number	Pressure kPa	mA output	mV output R=20 Ohms
1	0.00	4.0105	80.2100
2	19.96	5.7640	115.2800
3	39.92	7.5165	150.3300
4	59.88	9.2680	185.3600
5	79.84	11.0195	220.3900
6	99.80	12.7730	255.4600
7	119.76	14.5305	290.6100
8	139.71	16.2880	325.7600
9	159.67	18.0470	360.9400
10	179.63	19.8140	396.2800

Calibration table for differential pressure transducer at static pressure of 22000 kPa

From calibration Table A.3 interpolate actual differential pressure.

$$\begin{aligned}\text{Actual differential pressure} &= (9.19181 - 7.5165) / (9.2680 - 7.5165) \\ &\quad \times (59.88 - 39.92) + 39.92 \\ &= 59.0117 \text{ kPa}\end{aligned}$$

The next step is to interpolate to find the actual differential pressure at the calculated static pressure.

$$\begin{aligned}\text{Differential pressure (H)} &= (20560.295 - 19000) / (22000 - 19000) \\ &\quad \times (59.0117 - 58.8216) + 58.8216 \\ &= 58.92047 \text{ kPa} \\ &= 6008.2164 \text{ mm H}_2\text{O}\end{aligned}$$

Determine the feedwater density:

$$\begin{aligned}\text{Feed water temperature} &= 155.7 \text{ }^\circ\text{C} \\ \text{Static pressure} &= 20560.295 \text{ kPa} \\ &= 205.603 \text{ bar}\end{aligned}$$

From steam tables<sup>(18)</sup> interpolate specific volume for those conditions.

$$\begin{aligned}\text{At 200 bar, the specific volume} &= (155.7 - 150) / (160 - 150) \\ &\quad \times (0.0010836 - 0.0010779) + 0.001077 \\ &= 0.001083999 \text{ m}^3/\text{kg}\end{aligned}$$

$$\begin{aligned}
 \text{At 210 bar, the specific volume} &= (155.7 - 150) / (160 - 150) \\
 &\quad \times (0.0010879 - 0.0010773) + 0.0010773 \\
 &= 0.001199465 \text{ m}^3/\text{kg}
 \end{aligned}$$

Thus,

$$\begin{aligned}
 \text{At 205.603 bar, the specific volume} &= (205.603 - 200) / (210 - 200) \\
 &\quad \times (0.001083342 - 0.001200744) + 0.001200744 \\
 &= 0.0010836309 \text{ m}^3/\text{kg}
 \end{aligned}$$

Thus,

$$\begin{aligned}
 \text{Feed water density} &= 1 / 0.0010836309 \\
 &= 922.82345 \text{ kg/m}^3
 \end{aligned}$$

Calculate the feed water flow rate:

$$\text{Feed water flow rate (Q)} = 0.01252 \times c \times d_c \times E \times \sqrt{H} \times \sqrt{\text{density}}$$

Where,

$$\begin{aligned}
 c &= \text{discharge coefficient (constant from m vs c graph, } 4d^2/D^2) \\
 &= 0.6063
 \end{aligned}$$

$$m = d^2 / D^2$$

$$\begin{aligned}
 D &= \text{internal diameter of feed water pipe} \\
 &= 422.191 \text{ mm}
 \end{aligned}$$

d = orifice internal diameter

$$= 280.007 \text{ mm}$$

Temperature correction =  $[1 + 0.0000126 \times (T - 20)]^2$

T = temperature at orifice (°C)

Corrected diameter,  $d_c = d^2 \times \text{temperature correction}$

$$E = 1 / \sqrt{(1 - m^2)}$$

$$= 1.11351$$

Feed water flow rate (Q) =  $0.01252 \times 0.6063 \times (280,007)^2$   
 $\times (1 + 0.0000126 \times (155.7 - 20))^2 \times 1.11351 \times \sqrt{(6008.2146)}$   
 $\times \sqrt{(922.8235)}$

$$= 1565812.26 \text{ kg/h}$$

$$= \underline{434.95 \text{ kg/s}}$$

A.5: COAL VOLUMETRIC FEEDER INTEGRATOR

Table A.4 shows the feeder bar profile and the values in the table refer. The area of the feeder profile must first be determined:

profile area = Large rectangle - two small triangles

$$A = ((0,121 + 0,348 + 0,115) \times 0,1765) - (0,5 \times 0,065 \times 0,121) \\ - (0,5 \times 0,115 \times 0,0645) \\ A = 0,09544 \text{ m}^2$$

The 100% motor speed = 1260 rpm

Reduction gearbox ratio: 64,0 : 1

the feeder pulley speed = 19,6875 rpm

@ 40,21 % feeder speed, the feeder pulley speed = 7,916 rpm

For 23,75 minutes duration of test,

Tail pulley revolutions = 188

For area A, the swept volume = 15,22 m<sup>3</sup>

Previous bulk density determination of coal = 1.0115 kg/m<sup>3</sup>

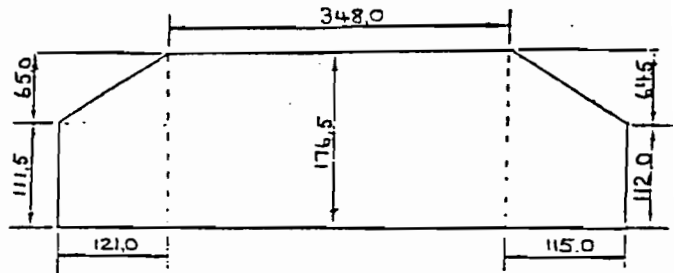
Mass = swept volume x density = 15,39 tons

Table A.4: COAL FEEDER CALIBRATION

CONSTANTS USED.

- Feeder Bar Area = 0,09544 m<sup>2</sup>
- Drive Gear Ratio = 64,0:1
- 100% Speed = 1260 rpm.
- Drive Pulley Dia. = 270 mm.
- Belt Thickness = 10 mm.

FEEDER PROFILE.



LORRY TEST RESULTS.

TEST NO.	1.	2.	3.	4.	5.	TOTAL	AVERAGE.
Target Speed %	40	35	30	32,5	30		
Revs/Time %	40,21	35,97	29,96	32,50	30,10		
Tail Pulley Revs.	188	188	188	188	188		
Test Duration min..	23,75	25,55	31,37	29,38	31,53		
Total Swept Vol m <sup>3</sup>	15,79	15,79	15,79	15,79	15,79	78,95	
Bulk Density Kg/m <sup>3</sup>	1011,5	1006,9	1015,4	1013,1	1008,7		1011,1
Vol x B/D Kg	15964,7	15895,4	16032,7	15996,4	15927,0		
Coal Mass.(Weighed) Kg.	17020,0	16700,0	17240,0	16720,0	16740,0	84420,0	
K1 (Based on Pulley Revs)	1,0661	1,0506	1,0753	1,0452	1,0510		1,0546
Coal Mass Flow Rate t/h.	43,00	37,97	32,46	34,15	31,86		
Stock Integrator Adv. m <sup>3</sup>	16	16	17	16	16	81	
K2 (Mass/(B.Dx Int Vol)).	1,0517	1,0366	0,9987	1,0315	1,0992		1,0435
K3 (Hft/Speed % x B.D)	1,0572	1,0484	1,0670	1,0372	1,0493		1,0519

A.6: REVISED OSTWALD DIAGRAM FOR MAXIMUM THEORETICAL CO<sub>2</sub><sup>++</sup>

According to sample calculation 1 it can be seen that CO<sub>2</sub> is one of the combustion products. The maximum percentage of CO<sub>2</sub> that can result from a combustion process is when the percentage excess air is zero and complete combustion takes place. This theoretical maximum amount of CO<sub>2</sub> is noted in an Ostwald diagram as CO<sub>2</sub><sup>++</sup> (see Figure A.5). This percentage CO<sub>2</sub><sup>++</sup> has a specific value for each coal analysis. It is generally calculated as follows<sup>(24)</sup>:

$$\text{CO}_2^{++} \% = \frac{20,95 C + 0,1 (H + S/8)}{C + 2,355 (H + 0,16 S + 0,04 N)}$$

where the symbols have the same meaning as the elements participating in the combustion process and the constants are derived from the stoichiometric ratios of the same. When an actual amount of O<sub>2</sub> is measured in the flue gas, a corresponding amount of CO<sub>2</sub><sup>+</sup> (called the Ostwald CO<sub>2</sub>) can be derived from the graph and when an actual amount of CO<sub>2</sub> is measured, a corresponding amount of O<sub>2</sub><sup>+</sup> (called the Ostwald O<sub>2</sub>) can be derived. The trivial cases would produce the maximum CO<sub>2</sub><sup>++</sup> at zero O<sub>2</sub> %, and 20.95 % O<sub>2</sub> (the volumetric percentage in air) would produce zero % CO<sub>2</sub>.

There is always a fixed relationship between the percentages of O<sub>2</sub> and CO<sub>2</sub> in dry flue gas, even if excess air is present, relative to the

# MODIFIED OSTWALD DIAGRAM

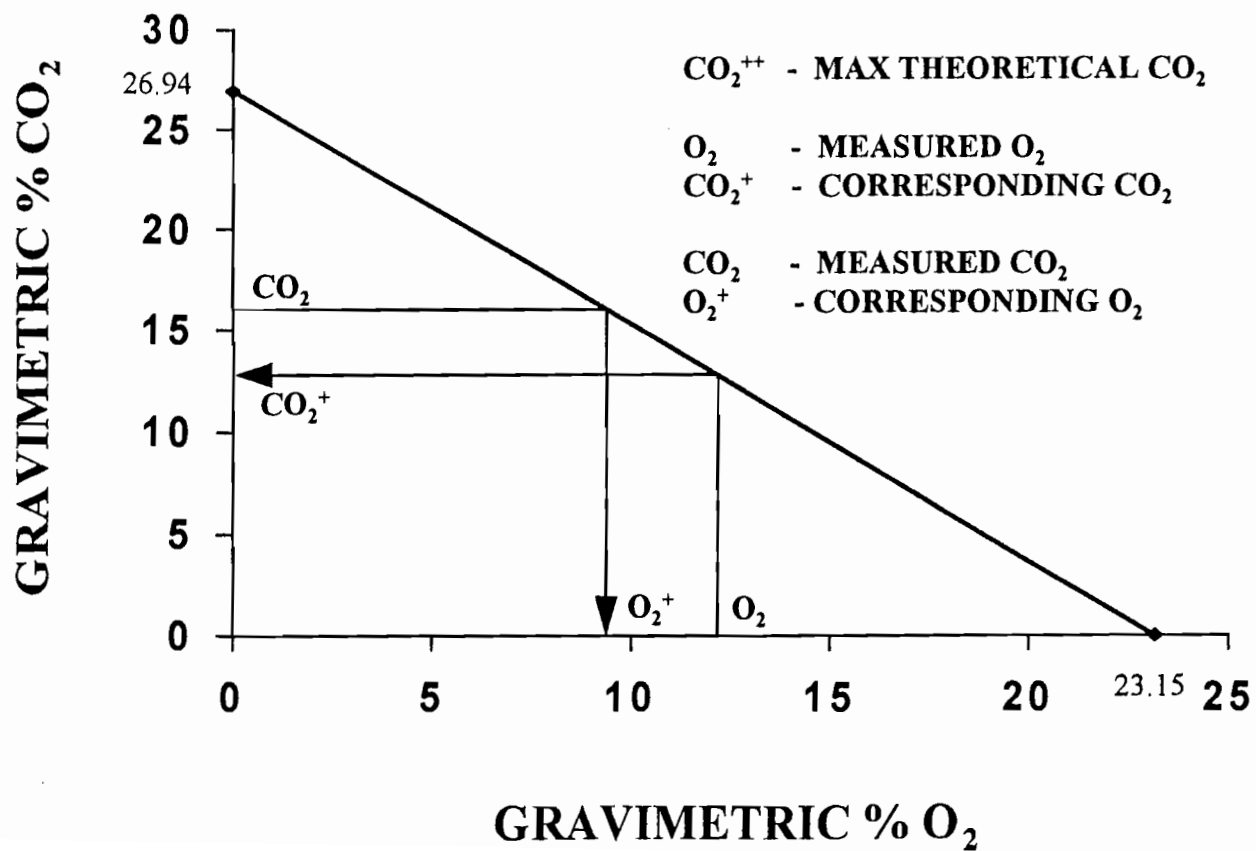


Figure A.5:

CORRECTED OSTWALD DIAGRAM



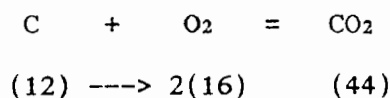
percentage CO<sub>2</sub><sup>++</sup>:

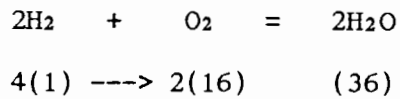
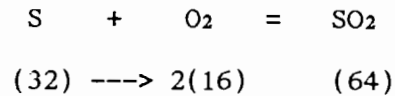
$$O_2^+ \% = \frac{20,95 (CO_2^{++} - CO_2)}{CO_2^{++}}$$

If the coal analysis is known and thus the percentage CO<sub>2</sub><sup>++</sup>, the percentage CO<sub>2</sub> can be measured and thus the percentage O<sub>2</sub><sup>+</sup> derived. This can be compared to the actual measured O<sub>2</sub> as a cross check of measurement accuracy and validity of testing.

Problems were encountered in reconciling the back-end gas analysis of the caravan with the mass-energy balance method devised in Chapter 6. It was discovered that the inaccuracies of the generally used Ostwald diagram was one of the main deficiencies. Practically the deficiencies presented as: the derived CO<sub>2</sub><sup>+</sup> from the actual back-end measured O<sub>2</sub> values by the caravan's analysers failed to correspond to the actual measured CO<sub>2</sub> by the caravan to an acceptable level, and vice versa. The specific reasons being that volumetric gas percentages derived from the Ostwald diagram were used in gravimetric gas balance formulae. It was therefore proposed to derive an Ostwald diagram on a dry gravimetric basis.

From the basic combustion equations as in Sample calculation 1:





the total dry ash free gas mass:

= CO<sub>2</sub> + SO<sub>2</sub> (dry gasses formed)

+ nitrogen in air from oxygen needed for combustion

+ nitrogen in coal

= (44/12 x C + 64/12 x S)

+ (32/12 x C + 32/4 x H + S - O<sub>2</sub>) x 76.86/23.15

+ N<sub>2</sub>

the maximum theoretical CO<sub>2</sub>:

= (44/12 x C + 64/12 x S)

for a coal analysis of: C - 38%, S - 0.5%, H - 2.5%, O<sub>2</sub> - 6%, N<sub>2</sub> - 3%,

the maximum theoretical CO<sub>2</sub> = 1.393 kg and total dry gas = 5.279 kg.

The CO<sub>2</sub><sup>++</sup> = 26.388 %

The clean air O<sub>2</sub> on the graph is then 23.15 % (instead of the 20.95 volumetric).

The  $y = mx + c$  of this gravimetric graph amounts to:

$$CO_2^+ = CO_2^{++}(1 - O_2/23.15)$$

The conversion of volumetric to gravimetric percentage is done according to the method in Sample calculation A.3.1. In the actual test calculations the carbon in the above combustion equations were reduced by the unburned carbon in ash and the more accurate molecular masses (Figure A.1) to more significant figures were used. An actual test example illustrated the following difference between the old and revised Ostwald diagrams:

Actual measured volumetric dry  $O_2$  % = 5.6 (by caravan analyser)  
= 5.973 % gravimetric dry

From the above formula, the corresponding  $CO_2^+$  = 19.579% (gravimetric)

Back calculated: = 13.349% (volumetric)

The caravan analyser measured: actual  $CO_2$  = 13.2% (volumetric)

The old volumetric Ostwald diagram and formula produced:

$$CO_2^+ = 13.9 \%$$

which is less accurate than the above 13.349 produced by the revised gravimetric diagram.

#### A.7: BACK-END GAS ANALYSIS AND MASS FLOW RECONCILIATION

The back-end gas analysis from the caravan facility was identified and utilised as a powerful tool to serve as one link in the energy and mass balance technique described in Chapter 6. The variance between the theoretical complete (Sample calculation A.1) and practical incomplete combustion also required an iteration to determine the dry flue gas mass flow more accurately. All this will be explained below by using the S/630/5.5/15h30 test as a sample calculation.

The gas components are displayed in the first column of Table A.5. Column (a) contains the volumetric percentages as measured by the caravan facility. The  $\text{NO}_x$ ,  $\text{SO}_2$  and  $\text{CO}$  is measured in ppm, but converted to percentage, which is displayed. The  $\text{N}_2$  is determined by difference.

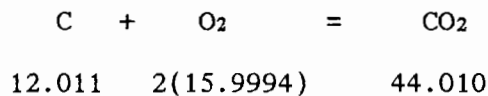
Column (b) contains the molecular mass of each component, as determined from Table A.1. Column (c) contains the product of (a) and (b) where the sum total divided by 100 gives the molecular mass of the flue gas. Column (d) produces the gravimetric percentage per 100 kg of flue gas, by dividing the value in (c) by the molecular mass of the mixture.

To obtain the gravimetric fraction of the gas component as a percentage of a 100 kg of coal, the amount of  $\text{CO}_2$  for complete

Table A.5: BACK-END GAS ANALYSIS

Gas component	(a)	(b)	(c = a x b)	(d = c/b*100)	(e)	(f)
	Measured Analysis Volumetric % (= mole %)	Molecular mass kg/mole	kg/100 mole	Gravimetric % kg/100kg gas	Gravimetric % kg/100kg coal THEORETICAL	Gravimetric % kg/100kg coal PRACTICAL
N <sub>2</sub>	80.774	28.013	2262.731	73.607	455.522	448.492
O <sub>2</sub>	3.013	31.999	96.414	3.136	19.410	19.110
NO <sub>x</sub>	.063	46.006	2.912	.095	.586	.376
SO <sub>2</sub>	.102	64.059	6.533	.213	1.315	1.295
CO	.047	28.010	1.328	.043	.267	.263
CO <sub>2</sub>	16.000	44.010	704.160	22.906	141.762	139.572
Flue gas	100.000	Mixture =	30.741	100.000	618.859	609.109

combustion is determined first:



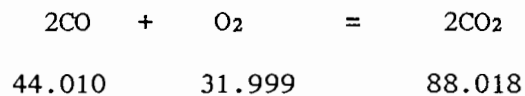
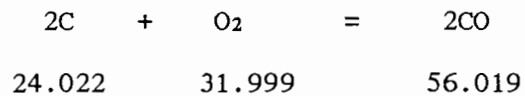
The coal analysis for this test has 38.689 % carbon on an as received basis. For a 100 kg of coal burnt,

$$38.689 \times 44.010 / 12.011 = 141.762 \text{ kg of CO}_2 \text{ is produced.}$$

This is the maximum theoretical amount of CO<sub>2</sub> that is produced.

Thus, if 22.907 % of a gas component = 141.762 kg, then 100 % of the total gas =  $141.762 / .22907 = 618.859$  kg of the total dry flue gas for each 100 kg of coal. The other gas components' quantities can now be determined if the percentage of the component in (d) of the total in (e) is taken.

If the practical case is to be evaluated, where incomplete combustion takes place, the following chemical equations are valid:



The above equations can be used to indicate incomplete combustion. The unburnt carbon is firstly subtracted from the carbon in the first equation, then the CO measured at the back-end (unburnt gas) is subtracted in the second equation. Both these entities reduce the possible amount of CO<sub>2</sub> and thus the total amount of flue gas that can be formed, since less carbon directly combusts into CO<sub>2</sub>.

From the above equations the amount of CO formed is calculated by:

$$CO = (\text{ppm CO} / 1000000 \times 100) \times (28.013 / M_{\text{mixture}}) \times (\text{flue gas} / 100 \text{ kg coal})$$

the resulting CO<sub>2</sub> can now be calculated by:

$$\text{CO}_2 = 88.019/56.019 \times [ 56.019/24.022 \times (C - \text{Cunburnt} \times \text{ash\%} /100) - \text{CO}_{(\text{as above})}]$$

with this new value of CO<sub>2</sub>, a new value of flue gas is determined as above. This requires an iteration as in Table A.6:

Table A.6: ITERATION FOR FLUE GAS, CO AND CO<sub>2</sub>

<u>Parameter</u>	<u>Formula</u>	<u>Iteration 1</u>	<u>Iteration 2</u>	<u>Iteration 3</u>
CO	as above	0	= f(flue gas <sub>(1)</sub> )	= f(flue gas <sub>(2)</sub> )
CO <sub>2</sub>	as above	= f(CO <sub>(1)</sub> )	= f(CO <sub>(2)</sub> )	= f(CO <sub>(3)</sub> )
flue gas	as above	= f(CO <sub>2(1)</sub> )	= f(CO <sub>2(2)</sub> )	= f(CO <sub>2(3)</sub> )

Firstly, the CO is calculated as a function of the flue gas in the previous column (iteration). Then the CO<sub>2</sub> is calculated as a function of the CO in the same column (iteration). The flue gas is then calculated as a function of the CO<sub>2</sub> in the same iteration, all according to the formulae derived above. Iteration 1 is started by entering zero CO formed. The resulting CO<sub>2</sub> and flue gas will be equal to the theoretical amount. The iteration is then repeated until the values converge.

These final values can be seen in column (f) of Table A.5. It can be seen that the differences are not negligible. The resulting flue gas e.g. differs from the theoretical with almost 10 kg/100 kg coal. This is necessary for the degree of accuracy needed especially to distinguish between the tests with high vs low excess air (producing high and low unburnt carbon and CO).

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A.8: CALCULATED CALORIFIC VALUE OF COAL

The calorific value (CV) of coal has always been a topic of contention. It has a significant impact on the accuracy of the thermal efficiency calculation caused by the sensitivity due to its relatively small amount of significant figures. The general simplified equation for overall thermal efficiency is (if no fuel oil is used):

$$\eta_{\text{overall}} = \frac{\text{Electrical units sent out (USO)}}{\text{coal mass flow} \times \text{CV}}$$

The USO has a relatively large amount of significant figures, even if measured in MWh, and the measuring instrumentation (CT and VT) is relatively very accurate and reliable. The amount of significant figures in the coal mass flow is also favourable, as well as the mass flow when a high quality load cell mass meter is used under the conveyor belt. Accurate mass flow becomes a more difficult task when a volumetric feeder is used, more in the determination of an accurate and representative density of coal. This problem is discussed in the calculation methods in Chapter 6. Even so, the biggest problem regarding accuracy and representativeness remains the CV.

The representivity is firstly a problem. This can largely be overcome by an accurate coal scanner which is able to cater for the

characteristics of the components of the specific coal range. This aspect is discussed in Chapter 7. After the representivity comes the issue of the bomb calorimeter. During the calculation phases discussed in Chapter 6, it was found that the CV values produced by the bomb calorimeters, from three different laboratories involved, differed on average and trend values to such an extent that unrealistic efficiencies emanated in various cases. The calculated efficiencies also exhibited such a great variance on successive reduced air flow tests that no optimum can be derived, hence the curves displaying a jagged pattern.

After contemplation and literature survey on this issue<sup>(14,25)</sup> the following arguments can be offered:

- The bomb calorimeter is an artificially ignited closed system process, not representing the actual case in the burner accurately, which would be closer represented by a flow process combustion chamber type testing method.

- It is stated<sup>(25)</sup> that the bomb is actually only suitable for testing of substances less volatile than fuel oil. This would render virtually only the carbon as a separate substance suitable for testing in a bomb regarding this argument, but rule out all volatiles and the coal as a whole.

- The bomb measures GCV since the latent energy of the moisture is recovered in the process over time. The combustion process and heat transfer in the furnace and gas passes would be closer represented by a NCV since only a portion of the super heat of the moisture is recovered, but no latent heat.

- The combustion in the bomb is a constant volume process while in the burner and furnace it would more closely be represented by a constant pressure process, thus  $NCV_p$  rather than  $GCV_v$ .

- The time consumed by ignition and combustion in the bomb is different to that in the burner and furnace, since it is triggered by an electric spark in the bomb but the ignition in the burner results from sustained exothermic heat transfer.

- Combustion in the bomb takes place under a different pressure and an artificial  $O_2$  atmosphere as opposed to the atmospheric air supply in the furnace.

- The benzoic tablet used for calibrating the bomb has a CV value roughly double that of the range of coal burnt at Lethabo, making the calibration less accurate.

The above assists in the motivation to compile a CV calculation method that would produce more consistent, representative and realistic

values of CV for the tests. Each coal sample is divided into four parts. These four parts were intended for:

- Moisture analysis
- CV determination by bomb calorimeter
- Ultimate analysis with an infra-red spectrograph
- Referee sample for future reference

The elemental analysis of the sample proved a lot more representative and realistic than the comparative values of CV determined by the bomb. It was therefore decided to derive a Dulong type formula where the specific CV value of an element was weighted with the percentage of the element in the ultimate analysis to produce an overall CV for the sample. (See Gill<sup>(14)</sup> Chapter 8, p303 - 306 and BS 1016<sup>(26)</sup> part 16.)

The general formula (also used in Chapter 4 and accompanying appendices C, D and E) for converting air dried to as fired CV is:

$$CV_{\text{as fired}} = CV_{\text{air dried}} \times \frac{(100 - \text{Total moisture})}{(100 - \text{Inherent moisture})}$$

The Dulong type formula used to calculate the CV of the coal from the separate CV's of its constituents is:

$$CV_{as \text{ fired}} = \frac{(C \times 33.82) + (H \times 143.050) + (S \times 9.304)}{100}$$

where 33.82, 143.050 and 9.304 are the GCV<sub>v</sub> values tested separately for the elements of Carbon, Hydrogen and Sulphur respectively, under the conditions of Gross CV, constant volume process. The reason for doing this is to utilise the more realistic values of the ultimate analysis of the coal as opposed to the direct bomb CV. The value for carbon used is the total carbon, including that in volatiles, but excluding the carbonates (in ash and CO<sub>2</sub> gaseous form), also supplied by the analysis. There is a value of 121.840 MJ/kg available for the NCV<sub>p</sub> of hydrogen, but no equivalent values for carbon and sulphur.

This formula differs from the similar one in Gill<sup>(14)</sup> in that the inherent oxygen in coal is not subtracted from the hydrogen (first divided by 8) since the way the ultimate analysis is done for these tests directly contains the free hydrogen available for combustion, and not that also contained in crystalline water.

This value of GCV<sub>v</sub> is then converted to NCV<sub>p</sub> by means of the formula given in BS 1016<sup>(26)</sup>:

$$NCV_p = GCV_v - (0.212 \times H) - (0.024 \times (\text{Total moisture} + 0.1 \times \text{Ash})) - (0.0008 \times O_2)$$

The equivalent formula in Gill differs in the factor that is multiplied by the  $O_2$  % (0.0007 instead of 0.0008). This results in a very small difference in the final answer, but 0.0008 is preferred since Gill mentions approximations introduced into his formula for the average inherent oxygen content of UK coal.

Concerning the representativeness of a specific parameter, it was found that even while the coal ordered and actually received varied in a narrow band of less than 2 MJ/kg per quality type, the individual tests showed a greater variance. The same holds for the ultimate analysis percentages of the elements. This is due to the fact that the qualities and analysis of the mass of coal supplied was given as averages of greater masses, while the sampling at the feeders during testing was less representative.

By means of experimentation in the calculation method of Chapter 6 it was found that by using the actual test value of an entity (percentage of an element, etc.) on a one to one basis, the curve of efficiencies with varying excess air (coal quality and load kept constant), had a sharper peak, showing the much wanted apex or optimum easier. Some tests however, showed a too jagged image with this criteria. If the average value of all the tests for the day of a parameter of the coal quality is used, the value seems more in line with the trend of the large batch of coal received. The curve is then smoother, showing evidence of more representivity regarding a macroscopic approach,

but often lacking the forming of an apex, being too smooth.

The mentioned experimentation showed that the best of both the above extremes produced the most favourable results. This was achieved by biasing the daily average value of a parameter with a weighting of 50% towards the specific test value.

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#### A.9: MOISTURE IN FLUE GAS

Since all the calculations involving gasses (Chapters 4, 6 and 7, as well as accompanying appendices) are based on dry ash free principles, it was necessary to calculate the moisture in flue gas. For each and every test this calculation was done in the spreadsheets of Appendices F, G and H.

- The first moisture component entering the flue gas comes from the air supplied for combustion:

$$\text{Atmospheric air moisture} = \infty \times (\text{Total aerofoil air} + \text{in-leakages})$$

where  $\infty = \text{kg}_{\text{water vapour}} / \text{kg}_{\text{air}}$  from the value as per Appendix A.2. The total aerofoil air plus the in-leakages (core air, mill seal air and aerofoil casing leakage) as per Appendix A.3.4 are used instead of the iterated combustion air. The reason for this was that the moisture in flue gas was needed where most of the flue gas measurements and analysis are made. That is where the air heater leakage has again joined up to the main stream of gas flow. The value will be accurate for A/HTR and ID discharge, with a small error at the economiser outlet.

- The moisture in coal on an as fired basis also enters the flue gas:

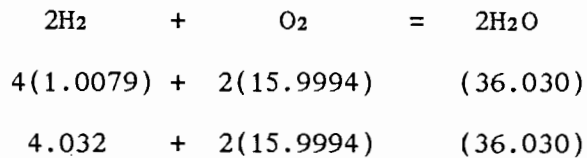
$$\text{Total moisture in coal} = \text{coal mass flow} \times \text{total moisture \%}$$



- The moisture resulting from the combustion of hydrogen:

$$\text{Moisture from combustion} = \text{mass flow of coal} \times \% \text{ hydrogen in coal} \\ (\text{as received basis}) / 100 \times 8.937$$

The factor 8.937 comes from the amount of water resulting from the combustion of the amount of hydrogen in the coal analysis:



$$\text{i.e. } 36.030 / 4.032 = 8.937$$

- The moisture originating from the ash hopper:

$$\text{Moisture from Ash hopper} = 5 - (\text{mass flow of coal} \times \text{ash \%} / 100 \\ \times 0.073 \times 0.401)$$

The total make-up water to the ash hopper is a measured average of 300 litres / minute (= 5 kg/s) and consists of:

- Potable water to the sealing trough

- Secondary CW to the hopper
- Potable water to the quenching sprays

The moisture in the bottom ash removed by the submerged scraper conveyor (SSC) must be subtracted from this figure. That is the moisture (40.1 % average as analysed by the laboratory) in the bottom ash component (7.3 %) of the total ash in the coal. The remainder of the water evaporates and rises into the flue gas.

- The fly ash contains crystalline water despite the high temperatures that it is subjected to prior to being sampled in the sampling matrix. This moisture can also be picked up in the sampler which is much cooler than the flue gas due to the fly ash being hygroscopic to an extent. The laboratory detects an average of 14.2 % moisture in fly ash during the unburnt carbon-in-ash analysis. (During the precipitator efficiency tests the fly ash : bottom ash ratio was determined as 92.7 : 7.3 %). This moisture value has to be subtracted from the above sum total:

$$\text{Moisture in fly ash} = \text{coal mass flow} \times \text{ash \%} / 100 \times 0.927 \times 0.142$$

The table below contains actual test values at 630 MW, high air flow. The values in brackets indicate the approximate percentage of the specific moisture component of the dry flue gas.

Table A.7: Moisture in flue gas

<u>Moisture origin</u>	<u>Low grade</u>	<u>Spec grade</u>	<u>High grade</u>
+ Atmospheric air moisture	4.07 (10.7)	3.98 (10.1)	4.53 (12.1)
+ Total moisture in coal	8.39 (22.1)	8.42 (22.3)	10.34 (27.6)
+ Moisture from combustion	22.01 (57.9)	22.58 (57.4)	19.92 (53.1)
+ Moisture from Ash hopper	3.60 (9.5)	3.70 (9.4)	4.23 (11.3)
- Moisture in fly ash	6.39	5.92	3.51
Total moisture in flue gas	31.67	32.80	31.26
Flue gas-Moist. corr. fact.	0.957	0.954	0.956
Average correction factor	0.958	0.953	0.954

The Flue gas moisture correction factor =

$$1 - (\text{total moisture in gas} / (\text{ID Dfg} + \text{total moisture in gas}))$$

It can be seen that the average moisture correction factor does not differ much between coal qualities and indicates that the moisture is approximately 5 % of the gas and thus not negligible. The moisture from combustion is highest and averages approximately 56%, followed by the moisture in coal (at  $\pm 24\%$ ), followed by moisture in air ( $\pm 11\%$ ), followed by moisture from the ash hopper (at  $\pm 9\%$ ). The tests were performed during a month of May in the Southern hemisphere presenting very dry air ( $\phi = 15\%$ ). Also, the lower loads are characterised by higher A/F ratios. It can thus be said that during

the summer months with relative humidities in excess of 80 % at times and especially at lower loads, the fraction of moisture from combustion air increases with the other sources decreasing proportionally. A trial calculation showed that the moisture from air exceeds the fraction of moisture from coal at times such as these.

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