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**RADIATIVE TRANSFER IN OXY-FIRED FURNACES AND IMPACT OF
COAL PROPERTIES**

TECHNICAL NOTE 27

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ABSTRACT

In oxy-fuel combustion, fuel is combusted in oxygen rather than air and the oxygen stream is diluted by recycled flue gas that is CO₂-rich to control temperature. The furnace gases have much higher levels of CO₂ and H₂O, influencing the emissivity and consequently radiative heat transfer in these systems.

Simple furnace models and computational fluid dynamic (CFD) models are essential tools in the design of oxyfuel boilers. However, certain models used in existing CFD codes such as Weighted Sum of Gray Gas Model (WSGGM) need further development in such a gas environment.

The report describes two models for estimating the emissivity of gaseous medium. Firstly, it demonstrates that the radiative heat transfer characteristics are quite different in oxyfuel combustion and air combustion, due to the different concentrations and ratios of CO₂ and H₂O. The study demonstrates that the standard WSGGM model described in the literature [1] and currently used in CFD codes such as FLUENT is not adequate in these situations. Therefore, the emissivity model WSGGM needs to be adapted to the different environment with higher partial pressures and different ratios of the gases. It is shown that the WSGGM can be modified by introducing an extra gray gas component in the model to predict the local absorption coefficient and model coefficients suitable for the oxyfuel gas environment. The introduction of fourth gray gas improves the estimates of emissivities using WSGGM for large oxy-fired furnaces.

Predictions of furnace performance are made with a well-stirred heat transfer model. The sensitivity of coal properties for furnace heat transfer is quantified for a 420 MWe furnace, with differences in emissivities calculated, with ash content shown to be significant, and the total emissivities ranging from 0.59 to 0.64. For these coals, to match heat transfer for a retrofitted furnace a 1% difference is required in the O₂ volume fraction through the burners. The effect of coal properties is greater for larger furnaces, so that the operation for oxy-firing will need greater adjustment for large furnaces.

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1. INTRODUCTION

Radiation is the principal mode of heat transfer in furnaces combusting fossil fuels. The main combustion products that actively participate in radiative heat transfer are:

- Carbon dioxide
- Water vapour and
- Particulate matter such as char, soot and fly ash particles

The behaviour of particulate matter has been modelled previously using Mie theory. The radiatively active gases have also been modelled successfully using a 3 gray-gas model. However, the model coefficients that are commonly used were developed by Smith et al [1] for certain ratios of CO₂/H₂O (1 and 2) and a total optical path length (geometrical path length multiplied by partial pressure of CO₂ and H₂O) less than 10atm-m.

The radiative properties of combustion gases produced in coal combustion systems for air-firing and oxy-firing differ in two ways

- Total partial pressure of radiating gases – $p_{H_2O} + p_{CO_2}$; air fired combustors vary from 0.2 to 0.25, where as for oxy-firing vary from 0.75 to 0.95.
- Ratio of the partial pressures of the radiating gases – p_{H_2O} / p_{CO_2} . The ratio is 0.2 to 0.8 for air firing but can be much lower if moisture is removed before recycling the flue gas in oxy-firing.

The Wide Band Model (WBM) and Narrow band models [2] are used for estimating radiative properties. However, the radiation by gases in computational fluid dynamics (CFD) models is modelled by a simpler engineering model that approximates the gases by a number of gray gases and a clear gas also known as Weighted Sum of Gray Gas Model (WSGGM). This report describes, the differences in the emissivities for different optical path lengths using the WBM. Then the differences between emissivities estimated using the standard WSGGM, which is currently used by FLUENT, and the WBM are quantified.

2. THEORY OF RADIATIVE TRANSFER

The total emissivity for combustion gases is estimated from Hottel's charts [3] in which the total emissivity is presented as a function of temperature, pressure and concentration of gases, and geometric path length of the system. New charts have also been prepared by Leckner [4] and Ludwig and co-workers [5] based on the integration of spectral data. Also, the scaling rules given by Edwards and Matavosian [6] are used to predict the gas emissivity at different pressures with charts prepared using experimental data extended in range using wide band models or narrow band models [3].

2.1 Wide Band Model

It is known that triatomic gas is not continuous but is concentrated in spectral bands of certain wavelengths as shown in Table 1. It is therefore possible to define wide-band absorptivity and/or emissivity models. Accurate prediction of radiative properties requires line-by-line calculations; however, these calculations are not practical for most engineering purposes. Empirical models are therefore derived from experiments results of band absorption. These models are called Wide-band models, including the exponential wide-band model by Edwards and Menard as also explained in [7].

Table 1: Principal bands for H₂O and CO₂

Gases	Principal Bands (μm)	Weaker Bands (μm)
H ₂ O	2.7, 6.3, 20	1.1, 1.38, 1.4, 1.9
CO ₂	2.7, 4.3, 15	1.4, 1.6, 2.0, 4.8, 5.2, 9.4, 10.4

The Wide Band Model can predict the total absorption or emission from a band. Total band absorptance is therefore calculated based on wide band correlation parameters for CO₂ and H₂O as tabulated in [7].

For radiation heat transfer calculations in combustion systems, the total band emission or absorptance is the basic property needed for the analysis. The total emissivity is defined as the portion of total emitted radiation over a path that is not attenuated by self-absorption divided by the maximum possible emission and considering only emission within the gas,

$$\varepsilon = \sum_{i=1}^N \left(\frac{\pi I_{b\eta_0}}{\sigma T^4} \right) \int_{\Delta\eta_{band}} (1 - e^{-k_{\eta} X}) d\eta = \sum_{i=1}^N \left(\frac{\pi I_{b\eta_0}}{\sigma T^4} \right) A_i \quad (2.1)$$

Where,

ε = Total emissivity (-)

$I_{b\eta_0}$ = Intensity of radiation (w.m⁻².cm)

σ = Stefan Boltzmann constant (w.m⁻².K⁻⁴)

T = Gas Temperature (K)

k_{η} = Absorption coefficient (cm⁻¹)

X = Path length (atm-m)

A_i = Band absorptance of single band (cm⁻¹)

N = Number of bands

From Table 1, H₂O and CO₂ share a common band, at a wavelength of 2.7 μm. The total absorption for the 2.7 μm overlap region cannot accurately be represented simply by summing the absorption by individual bands of H₂O and CO₂. This is because the absorption in a region of overlapped band is always less than the absorption

calculated by considering the contributions of individual non-overlapping bands. A complete overlap model would result in the effective emissivity as:

$$\varepsilon_{H_2O+CO_2} = \varepsilon_{H_2O} + \varepsilon_{CO_2} - \varepsilon_{CO_2} \cdot \varepsilon_{H_2O} \quad (2.2)$$

However, in reality, only a part of the band overlaps. Figure 1 shows the schematic overlap in width and the absorbance strength of the 2.7 μm band. The emissivity of a band is considered equal to the area of the region indicated. The total absorption for the 2.7 μm band would then be the addition of overlap and no-overlap region. Other bands are non-overlapping and thus can be added. Thus the total emissivity of H₂O and CO₂ bands including other bands of Table 1 is given by:

$$\varepsilon_{H_2O+CO_2} = \varepsilon_{H_2O} + \varepsilon_{CO_2} - BA_{H_2O} * BA_{CO_2} * (BW_{CO_2} / BW_{H_2O}) \quad (2.3)$$

Where

BA = Band absorption

BW = Band width

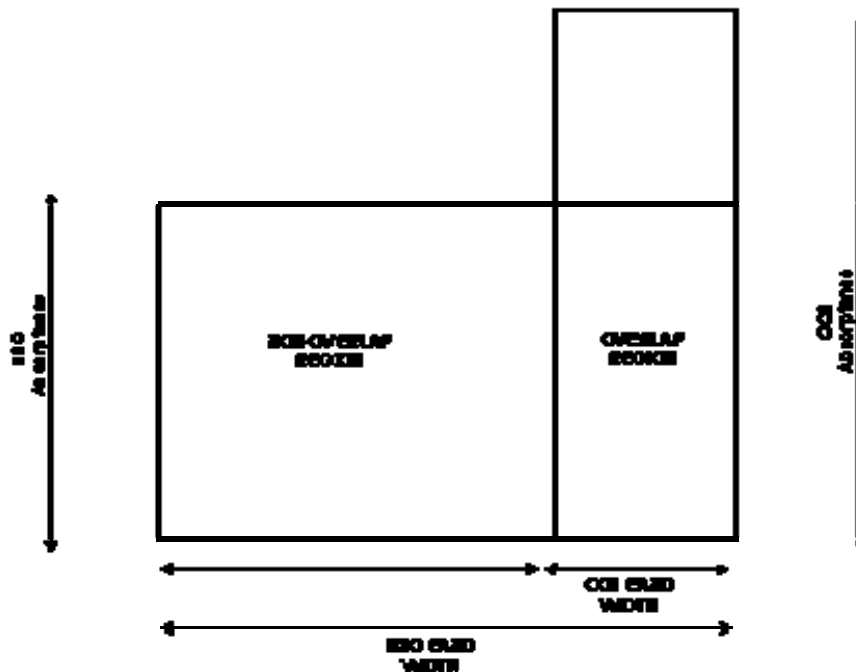


Figure 1: Overlapping absorption band for H₂O and CO₂ at 2.7 μm band region.

2.2 Weighted Sum of Gray Gas Model (WSGGM)

In CFD models, curve-fitted correlations are used, with multiple gray gas models which assume that the medium consists of a number of fictitious gray gases. The emissivity of the medium is taken as a function of optical path length - defined by the product of partial pressures (atm) of CO₂ and H₂O and path length - for a given ratio of CO₂ and H₂O. Therefore, the radiative property models can be used as continuous expressions where, the spectral and band absorptivities are first integrated over the entire spectrum for a given temperature and pressure to obtain total absorptivity and

emissivity curves. The polynomial expressions are curve-fitted at different temperature and pressures using regression techniques.

The curve-fitted expressions are arranged to represent the sum of total emissivity or absorptivity of clear and gray gases. These are known as the “weighted sum-of-gray-gases” (WSGGM) models and given as [1]. The nature of gray gases is such that the emissivity of these components approaches a value of unity with an increase in partial pressure of geometric path length of the system. However, the contribution of each gray gas is represented as a polynomial in temperatures in such a way that the total emissivity is given by the following equation:

$$\varepsilon = \sum_{i=0}^I a_i(T) [1 - e^{-k_i PS}] \quad (2.4)$$

Where

a_i = Emissivity weighting factor for i^{th} gray gas at T

$[1 - e^{-k_i PS}]$ = i^{th} gray gas emissivity with absorption coefficient, (k_i)

P = Sum of the partial pressures of the absorbing gases (atm)

PS = Partial pressure-path length product (atm-m)

k_i = Absorption coefficient of i -th gray gas (atm-m)⁻¹

I = total number of gray gases

For the clear gas, the absorption coefficient for $i = 0$ is zero for considering the transparent windows in the spectrum. All the models are restricted to the total pressure of one atmosphere and for gas radiation along a homogeneous path, i.e. uniform temperature and pressure.

$$a_i = b_{i,0} + \sum_{j=1}^J b_{i,j} T^j \quad (2.5)$$

Where

$b_{i,j}$ = Coefficients for the J^{th} order polynomial in temperature for emissivity

Smith et al [1] present the polynomial coefficients and absorption coefficients for different ratios of partial pressure of water vapour p_{H_2O} to partial pressure of carbon-dioxide (p_{CO_2}) for ($p_{H_2O} / p_{CO_2} = 1$ & 2).

Table 2 gives the coefficients for $P_w/P_c = 1$.

Table 2: Polynomial coefficients for a 3-gray gas model for H₂O and CO₂ mixture with $P_w/P_c = 1$. [1]

Gray gas, i	Absorption coefficient, (k_i)	$b_{\varepsilon, j=1}^* 10^1$	$b_{\varepsilon, j=2}^* 10^4$	$b_{\varepsilon, j=3}^* 10^7$	$b_{\varepsilon, j=4}^* 10^{11}$
1	0.4303	5.150	-2.303	0.9779	-1.494
2	7.055	0.7749	3.399	-2.297	3.770
3	178.1	1.907	-1.824	0.5608	-0.5122

3. EMISSIVITY COMPARISONS FOR AIR AND OXY-FIRING

The emissivities for air-fired and oxy-fired systems at 1500K are estimated for various beam lengths using WBM and are presented in Figure 2. The ratio of partial pressures (p_{H_2O} / p_{CO_2}) of 0.5 is assumed for both the cases and the sum of partial pressures in the two cases is assumed to be 0.24 for air firing and 0.96 oxy-firing, respectively. This sum of partial pressures has been assumed for all air-fired and oxy-fired cases in this paper. The difference in emissivities for two cases can be 25% for large boilers (large geometric path lengths) and 40% for smaller furnaces. This difference is due to the increased partial pressures of the radiatively active gases. The ratio of partial pressures (p_{H_2O} / p_{CO_2}) for oxy-firing can vary from 0.1 to 0.9 depending on type of fuel and condensation of moisture in recycled flue gas. Figure 3 shows the effect of the ratio of partial pressures (p_{H_2O} / p_{CO_2}) in oxy-firing case. The optical path length is defined as the product of the geometric path length and the sum of total partial pressures ($p_{H_2O} + p_{CO_2}$).

3.1 WBM and WSGGM Comparison

Emissivity correlations using the constants of the standard WSGGM [1] are used in FLUENT and other CFD codes. Figure 4 shows the comparison between the emissivities obtained by WSGGM and WBM. The contribution of each gray gas at higher optical paths becomes constant – these gray gas bands become opaque and beyond certain distances there is no further increase in emissivity or absorptance. The WBM, on the contrary does not show such behaviour, there is a continued increase in emissivity due to broadening of bands as the optical path increases. It can also be interpreted as if there are some weak lines of absorptance within the band the contribution from which becomes significant at higher optical path lengths.

Figure 4 shows that the Smith's constants are not adequate even for an air-fired system for geometric path lengths larger than 10-25m. At higher optical path lengths, there are differences between the WBM and WSGGM. These differences are much larger for oxy-firing systems even at a path length of 2-4m. This demonstrates the need for an extra gray gas for larger combustion systems, in particular for oxy-firing systems.

3.2 Modified WSGGM

The difference in emissivity estimated from WBM and WSGGM (3 Gray gas and 1 Clear Gas) for oxy-firing was curve-fitted for another gray gas with an absorption coefficient of an order of magnitude less than that of other gray gases in the model such that its effect is significant only at higher geometric path lengths. The same set was used for air-fired system.

It should be noted that the absorption coefficients of the first three gray gases were the same as those of Smith et al [1] given in Table 2. Further, for larger oxy-firing systems, one may need a number of sets of the WSGGM coefficients for different ratios of partial pressures (p_{H_2O} / p_{CO_2}).

Figure 5 shows predictions for the WSGGM with 4 gray gases and 1 clear gas. The introduction of an extra gray gas model has shown a good improvement on the estimates of emissivity for large air-fired systems. The estimates for oxy-firing systems also improved significantly. At higher optical paths the estimates of emissivity from the modified WSGGM are within 10% of those estimated using the Wide Band Model.

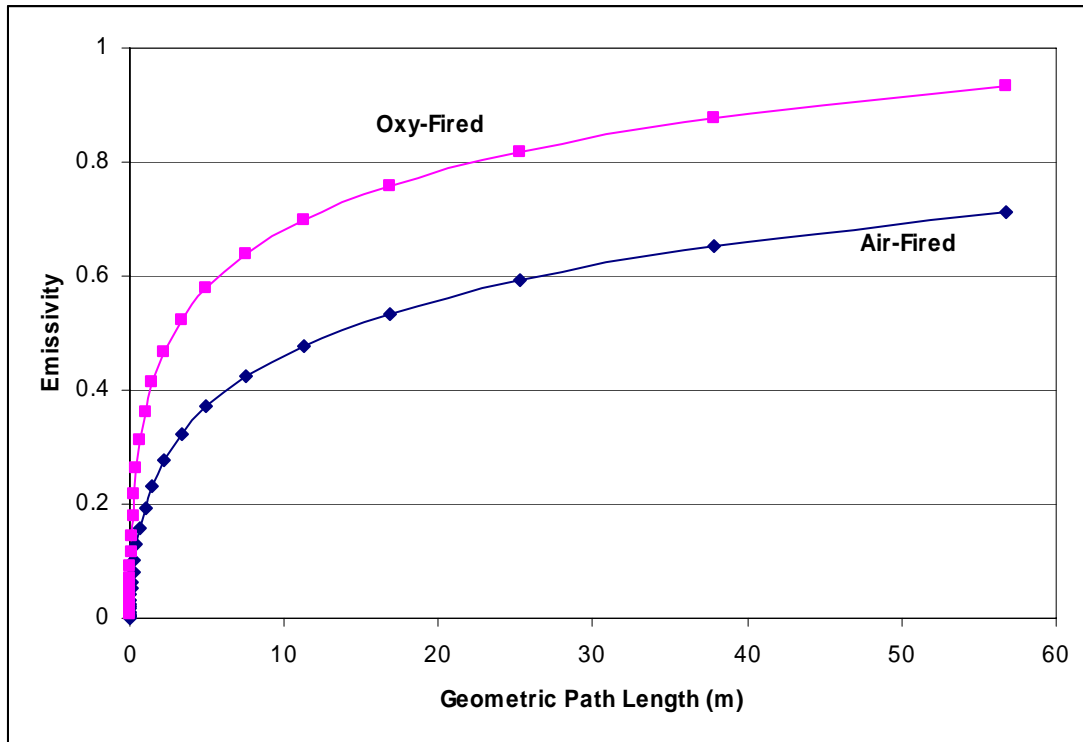


Figure 2: Difference in emissivities for air-fired and oxy-fired systems at 1500K estimated by using Wide Band Model.

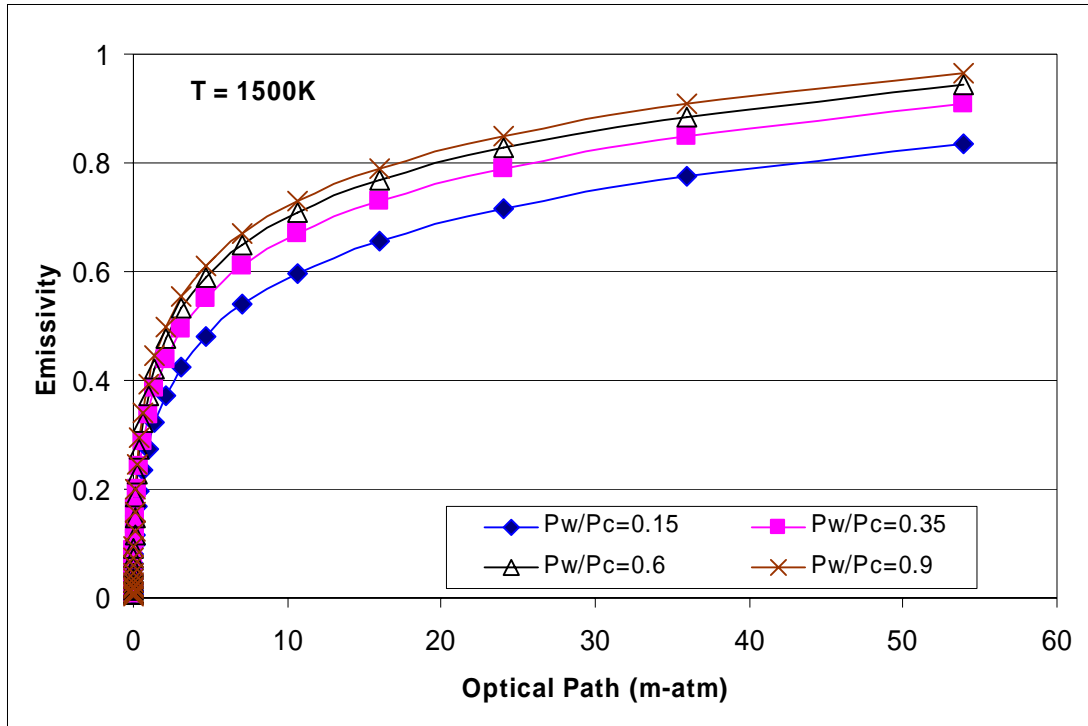


Figure 3: Effect of ratio of partial pressures on emissivities for oxy-fired systems at 1500K estimated by using Wide Band Model.

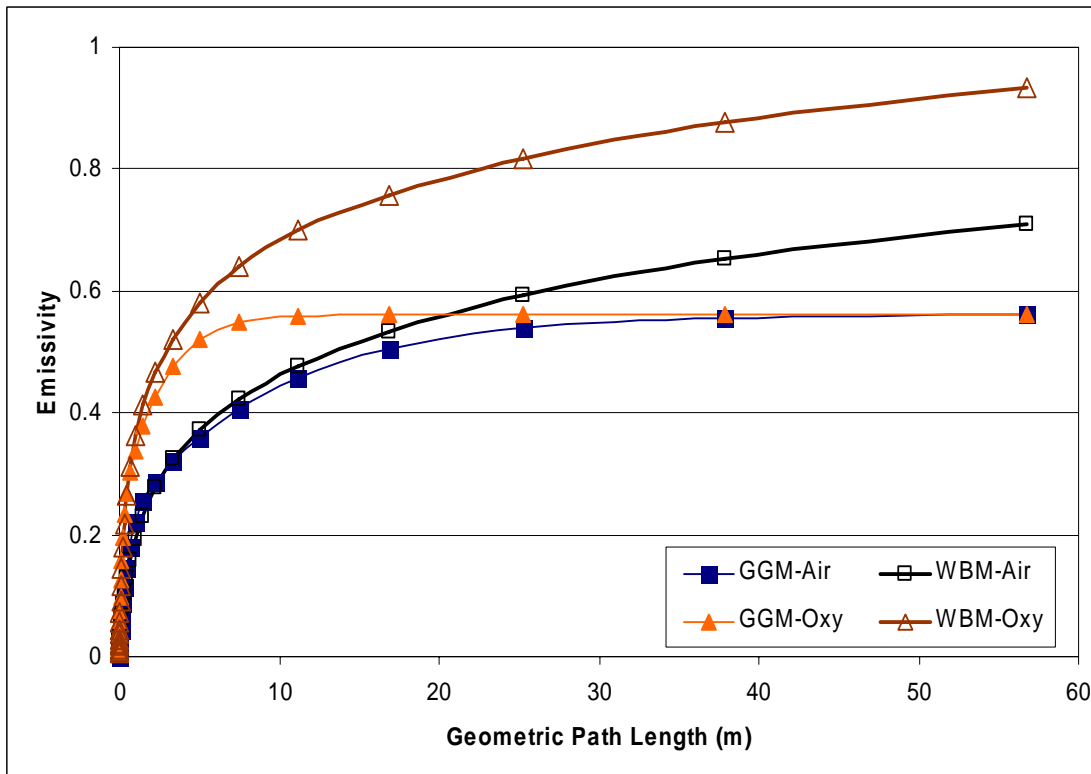


Figure 4: Comparison of emissivities at 1500K for air-fired and oxy-fired systems estimated from WSGGM (with three gray gases and Smith's (1) constants for $P_w/P_c = 1$) and WBM for $P_w/P_c = 0.5$.

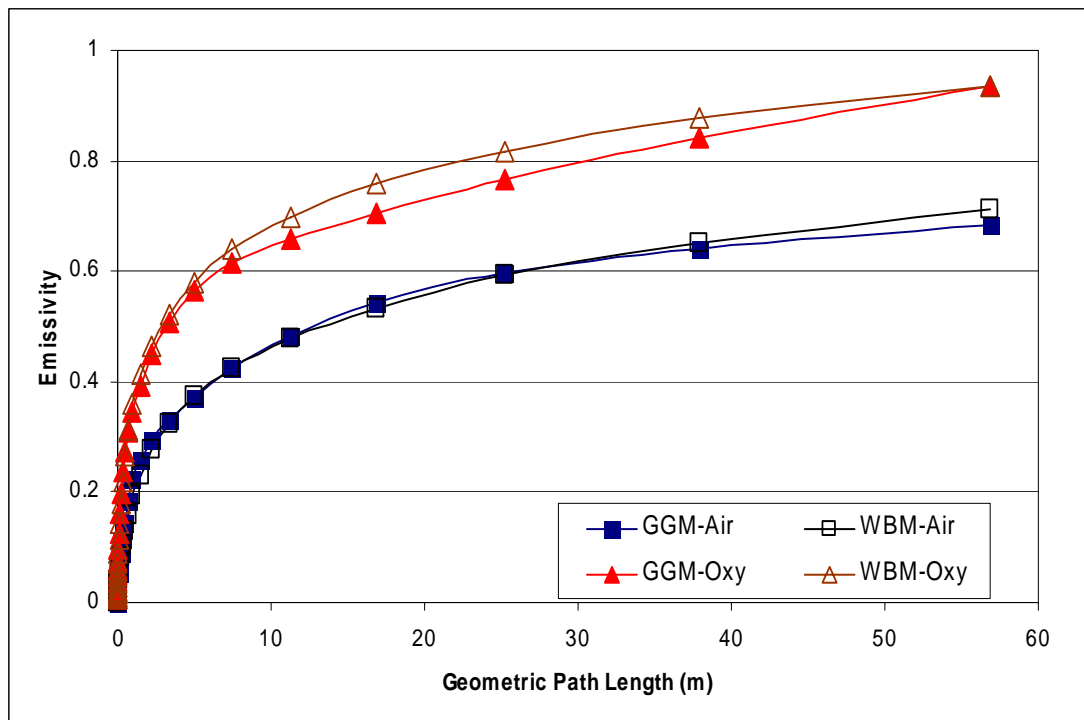
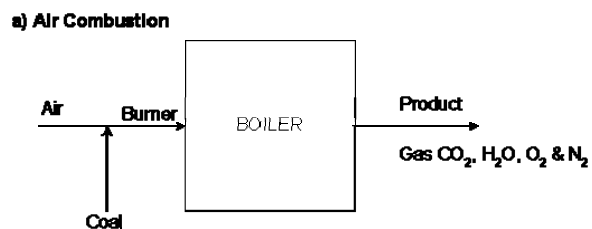


Figure 5: The comparison of WBM with WSGGM after introduction of a fourth gray gas into the WSGGM model.

4. PREDICTIONS OF RADIATIVE HEAT TRANSFER USING THE WELL-MIXED FURNACE MODEL

4.1 Furnaces and Coal Considered

Figure 6 shows a boiler schematic for an air-fired system converted to an oxy-fuel system by combustion with a) air, b) Wet-recycle of flue gas (CO_2 , H_2O , O_2) and c) Dry-recycle of flue gas (CO_2 , O_2).



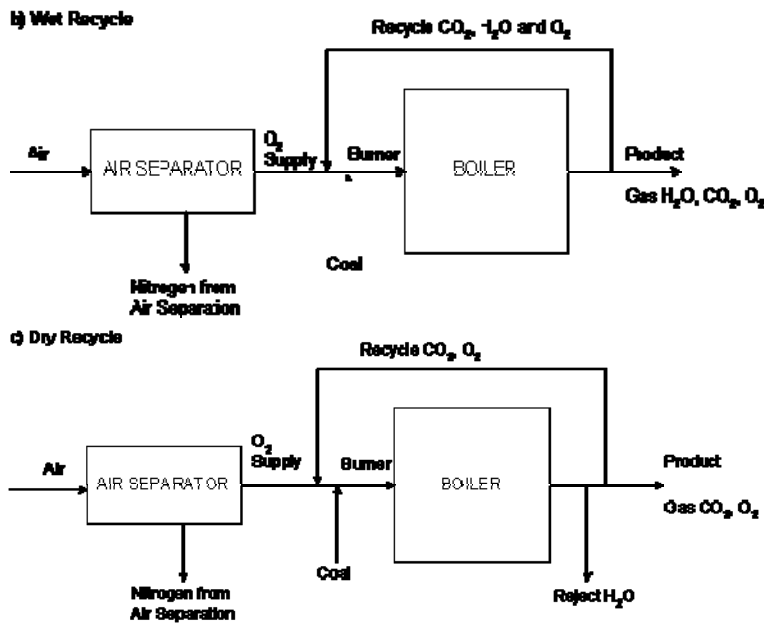


Figure 6: Boiler schematic: a) Air combustion b) Wet recycle (Oxy-Wet) c) Dry recycle (Oxy-Dry)

Three furnaces (F-A, F-B, F-C) of different sizes and thermal outputs are considered for this study. F-A is a pilot scale coal-testing furnace, F-B is a retrofit demonstration scale, F-C is a large scale furnace. Table 3 shows furnace details. An Australian coal is considered with analysis as shown in Table 4. The coal feed temperature is 298°K, the pressure is 1 atm, and air/oxygen preheat temperature is 493 °K with 20% excess, as used in previous studies [5].

Table 3: Furnace details [5] [6]

Furnace Details	F-A	F-B	F-C
Unit Output (MWe)	0.2	30	420
Coal feeding rate (kg/s)	0.0095	5.45	54.17
Furnace volume (m ³)	1.1	670.3	12031.9
Total furnace wall area (m ²)	7.04	501.6	3482.8
Wall fraction	0.09	0.96	0.96
Effective furnace wall area (m ²)	0.63	481.1	3349.8
Mean Beam Length (m)	0.52	4.68	12.1
Wall Temperature (°K)	773	673	673
Wall emissivity	0.7	0.7	0.7

Table 4: Coal input details [5]

Coal property	
HHV _{daf}	29.50 MJ/kg
Proximate analysis	(%ar) (as received)
Moisture	12.0
Ash	21.1
Volatile Matter (VM)	23.43
Fixed Carbon (FC)	44.10
Ultimate analysis	(%ar) (as received)
C	53.42
H	2.67
N	0.72
S	0.17
O	10.57

In the combustion zone of the furnace, heat associated with coal (fuel) is liberated during its oxidation. The adiabatic flame temperature (also called as theoretical flame temperature) is estimated assuming that heat generated during combustion is completely transferred to the combustion products without heat loss [7]. These calculations are purely stoichiometric and thus furnace independent. The coefficients for the temperature dependent specific heat capacity of gases are taken from literature [8]. Two parameters are commonly used to characterise the oxygen level for the oxy-fired case is the O₂ fraction at the burner inlet or alternatively the recycle ratio, defined as the ratio of recycled flue gas to the total flue gas throughput in the furnace. Table 5 shows the flue gas volumes and O₂ partial pressure (fraction) in the flue gas which result in similar adiabatic flame temperatures for 20% excess O₂.

Table 5: Flue gas volumes and O₂ partial pressure (fraction) for air, oxy-dry and oxy-wet for F-B at similar adiabatic flame temperatures and 20 % excess air/O₂

	Air Case	Oxy-Dry	Oxy-Wet
Adiabatic flame temperature (°K)	2197	2197	2197
Flue gas volume (kmol)	5693.2	3490.2	4300.7
Recycle ratio of flue gas (-)	-	1.40	1.96
O ₂ fraction in flue gas (v/v)	0.033	0.157	0.129

Table 6: Flue gas compositions for the F-B, for the computed adiabatic flame temperature and 20 % excess O₂ (conditions similar to Table 3)

	Air case	Oxy-Dry	Oxy-Wet
	Mol %	Mol %	Mol %
CO ₂	15.3	73.1	60.07
H ₂ O	6.9	11.2	27.0
O ₂	3.3	15.7	12.9
N ₂	74.5	-	-
Total (kmol)	5693.2	3490.2	4300.7

In oxy-firing, the concentrations of CO₂ and H₂O are higher compared to air-fired case which resulting in higher emissivity values as shown in Figure 7.

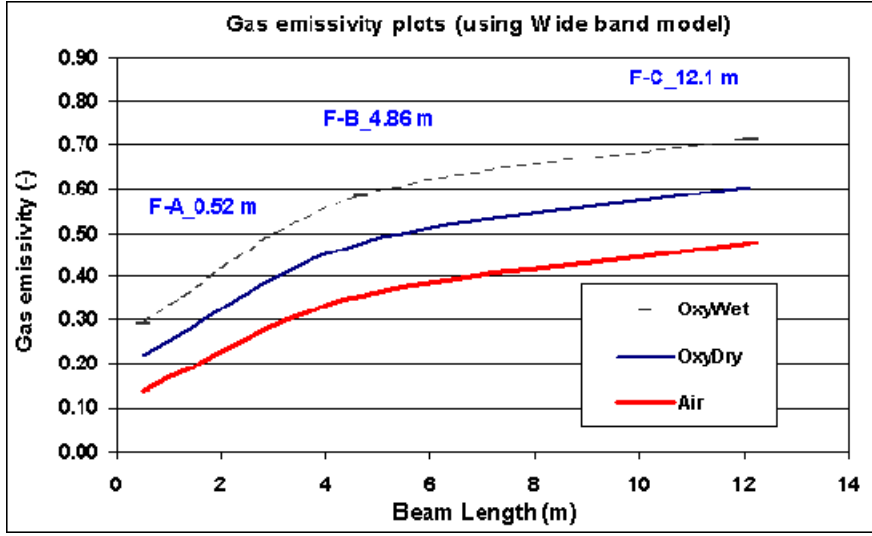


Figure 7: Gas emissivity for Air, Oxy-dry and Oxy-wet cases using Wide Band Model

During coal combustion in furnaces, fine ash particles are carried in the combustion gases. These particles can have a strong contribution on radiative heat transfer. A detailed knowledge of the factors influencing ash radiation is necessary. Factors include the ash concentration, particle size distribution of cloud and the complex refractive index and absorption index [11]. A simplified engineering approach is used here to estimate the emissivity of a particulate cloud. First, the emissivity of a cloud of black particles (ϵ_B) is calculated using a simple model [12] and then a correction factor for ash particle cloud absorption efficiency (Q_{abs}) (of 0.2) is used to estimate ash particle cloud emissivity (ϵ_{ash}) as suggested by Gupta and Wall [11]. Average projected area (a) of 180 m²/kg of ash is used, with

$$\epsilon_B = 1 - e^{-(a/v)L} \quad (4.1)$$

$$\epsilon_{ash} = 1 - e^{-Q_{abs}(a/v)L} \quad (4.2)$$

The total emissivity due to joint emission from gas and particulate ash is given by the following equation [12]. The results are in Table 7, and the combined emissivity plots for the three cases are shown in Figure 8.

$$\epsilon_{Comb} = \epsilon_g + \epsilon_{ash} - (\epsilon_g)(\epsilon_{ash})$$

Table 7: Emissivity results

Ash particle			
Size (μm)	15		
Density (kg/m ³)	2200		
Furnace	F-A	F-B	F-C
Mean beam length (m)	0.52	4.68	12.1
Ash emissivity, ϵ_{ash} (-)			
Air	0.0276	0.2225	0.4783
Oxy-Dry	0.0457	0.3443	0.6630
Oxy-Wet	0.0372	0.2876	0.5851

Gas emissivity, ε_g (-)				
Air	0.138	0.355	0.476	
Oxy-Dry	0.2201	0.476	0.607	
Oxy-Wet	0.2915	0.582	0.713	
Combined emissivity, ε_{Comb} (-)				
Air	0.162	0.499	0.726	
Oxy-Dry	0.256	0.656	0.868	
Oxy-Wet	0.318	0.702	0.881	

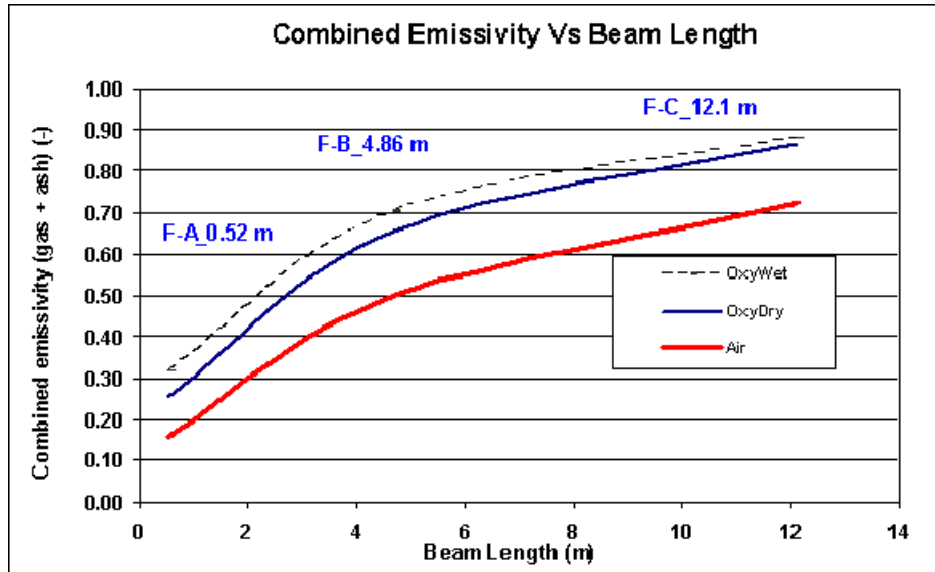


Figure 8: Combined emissivity (Gas + Ash) for Air, Oxy-dry and Oxy-wet cases

4.2 Model

An engineering approach is made by representing the furnace by a single volume of gas zone surrounded by furnace walls with a single value assigned to the composition and temperature of the radiating gas - referred to as the Single Zone Model or Well-Stirred Combustion Chamber Model [13]. The model assumptions are that the gas furnace gases can be assigned a single mean temperature (T_g), temperature variations in the gas are ignored, the gas is gray and the surface of the heat sink, of area (A_T), is gray and can be assigned a single temperature (T_1).

The geometric complexity of radiative transfer can be simplified by assuming the boundary of the furnace is a single sink and a refractory such that the view-factor to the sink surface from any point on the walls is the same as from any other point. This implies that sink and refractory are intimately mixed.

Heat transfer from the flame to the heat absorption surface is given by [13],

$$Q = (\overline{GS}_1)_R \sigma (T_g^4 - T_1^4) \quad (4.3)$$

Where, total the exchange area is

$$(\overline{GS}_1)_R = \frac{A_T}{\frac{1}{\varepsilon_{Comb}} + \frac{1}{(C_s \varepsilon_1)} - 1}$$

To calculate exit gas temperature (T_g) of the medium, following equations are used:

Energy Balance:

$$\frac{H_F - Q_{g \leftrightarrow 1}}{H_F} = \frac{T_g - T_0}{T_{aft} - T_0} = (1 - \eta) \quad (4.4)$$

From (4.3) and (4.4), the Control Equation is:

$$\left(\frac{Q}{H_F}\right) \frac{H_F}{\sigma(GS_1)_R} + T_1^4 = T_{aft}^4 \left[1 - \left(\frac{Q}{H_F}\right) \frac{T_{aft} - T_0}{T_{aft}}\right]$$

Where, Furnace Efficiency, $\eta = \frac{Q}{H_F}$

4.3 Predictions

From Table 5, the oxygen concentration in the flue gas is higher for oxy-case (dry and wet) as compared to the air case. Therefore, to reduce the oxygen concentration in the flue gas (to the same levels as the air case), the furnace can be operated with lower excess oxygen in the feed. Table 8 gives the new % excess O_2 required in the feed to achieve similar O_2 partial pressure (fraction) in the flue gas. From the computed results, this implies a significant reduction in energy for the air separation units [2].

Based on these results, Figure 9 gives the O_2 fraction required at the burner inlet to achieve similar adiabatic flame temperature as air case. The literature on combustion parameters used in other studies is shown in Table 8.

Table 8: Estimates of % reduction in O_2 production compared to the 20% excess O_2 firing

	Oxy-Dry	Oxy-Wet
% Excess O_2 for oxy-fuel	3.5 %	4.6 %
% reduction in O_2 supplied compared to 20% excess O_2	13.75 %	12.80 %

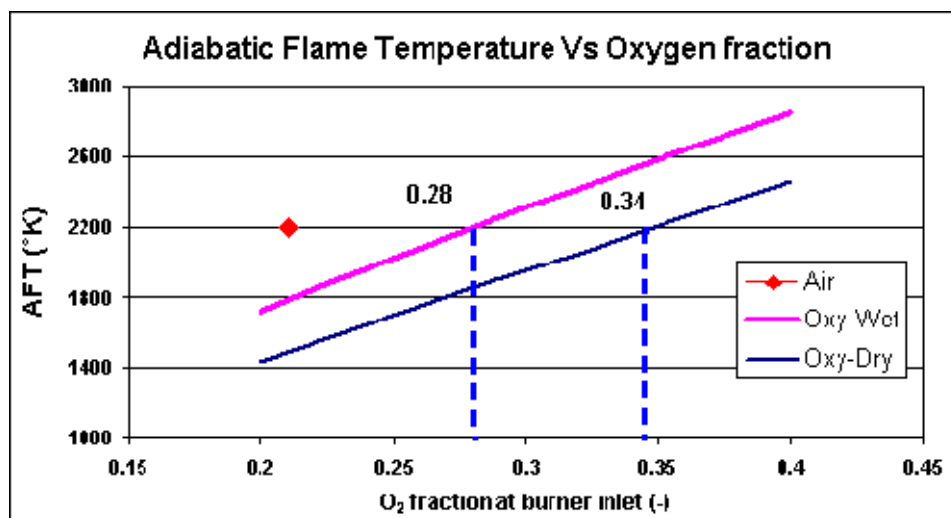


Figure 9: Plot of O_2 partial pressure (fractions) required at burner inlet to achieve similar adiabatic flame temperature as the air-case for Air, Oxy-dry and Oxy-wet cases for the % excess air/oxygen feed results of Table 8.

For the same O_2 fraction in the flue gas (0.033 v/v), the oxygen concentration at the burner inlet is calculated for oxy-dry recycle (O_2/CO_2) and oxy-wet recycle ($O_2/CO_2/H_2O$) cases to achieve similar furnace heat transfer (as for the air case). Fig 10 gives the resultant furnace heat transfer. Even lower excess air levels can be expected for satisfactory burnout due to the higher oxygen levels in the furnace flue gases, but reactivity experiments are necessary for this assumption. Results for other furnaces showing O_2 fraction required to achieve similar furnace heat transfer as the air case are given in Table 9. Also, for similar furnace heat transfer, indicative flue gas volumes (kmol) for three furnaces are given in Table 10.

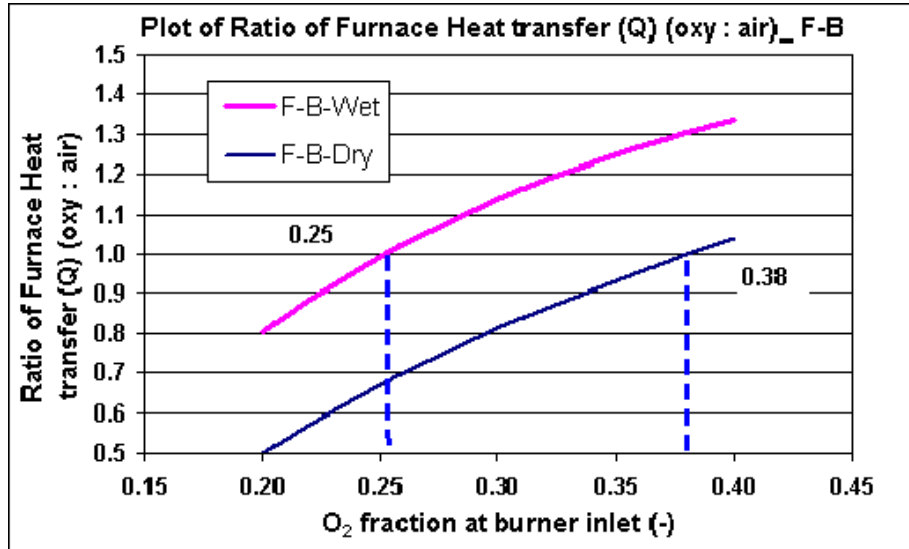


Figure 10: Plot of ratio of furnace heat transfer (Q) (oxy : air) for F-B for same % O_2 partial pressure (fraction) in the flue gas

Table 9: Oxygen fraction required at the burner inlet for similar furnace heat transfer (as air-case) for three furnaces

Furnace	Air Case	Oxy-Dry	Oxy-Wet
F-A	0.21	0.39	0.26
F-B	0.21	0.38	0.25
F-C	0.21	0.39	0.26

Table 10: Furnace flue gas volume (kmol) for similar heat transfer (as air-case) for three furnaces

Flue gas (kmol)	Air (kmol)	Oxy-Dry (kmol)	Oxy-Wet (kmol)
Furnace	(kmol)	(kmol)	(kmol)
F-A	9.97	5.3	7.8
F-B	5693.2	3057.9	4641.7
F-C	56631.9	29874.1	43952.3

From the well-mixed combustion model, furnace flue gas temperatures (T_g) are calculated. Table 11 shows an indicative temperature decrease (dT) of exit flue gas, when compared to the air case. The lower temperatures indicate that low fusion

temperature coals will suit Oxy-Fuel technology. Convective pass heat transfer will depend on the transport properties of flue gas (viscosity, thermal conductivity, density, specific heat and also the gas velocity). A detailed analysis of these factors is needed to determine the convective heat transfer achieved.

Table 11: Indicative reduction of flue gas exit temperature for oxy-fuel compared to air firing

	Oxy-Dry	Oxy-Wet
Furnace	dT (°K)	dT (°K)
F-A	36.7	49.9
F-B	68.1	84.3
F-C	40.8	44.4

5. PREDICTIONS USING CFD MODELS

Currently, the CFD model FLUENT is being used for predictions of combustion and fluid flow in a pilot-scale furnace and a 30 MWe furnace with a geometric part length of 4.4m. From Figure 5, for furnaces of this size the existing three-gray gas model used in FLUENT should give reasonable predictions, but for larger furnaces it may not. Therefore, no evaluation of the new four-gray gas model is available at this time.

6. COAL PROPERTY IMPACTS ON FURNACE HEAT TRANSFER IN OXY-FIRING

The coal influences radiative heat transfer due to the properties of the combustion products, namely

- Carbon dioxide and water vapour, and
- Particulate matter such as char, soot and fly ash particles

Let us consider variations of these properties for a range of coals, as given in Table 12. The Australian coals were fired in the pilot-scale tests in Japan, and the lignite is that used in the 30 MWt Vattenfall plant being currently constructed.

Table 12: Different Coals Considered

Coal property	Australian local coal (Callide)	Australian export coal (Rolleston)	German lignite (Lausitz) [16]
HHV _{daf}	29.40 MJ/kg	32.25 MJ/kg	26.59 MJ/kg
Proximate analysis (% as received basis)			
Moisture	11.5	18.3	10.0
Ash	17.1	5.6	10.6
Volatile Matter (VM)	22.7	27.9	45.1
Fixed Carbon (FC)	48.7	48.2	34.2
Ultimate analysis (% daf basis)			
C	78.69	79.91	67.96
H	3.51	4.53	4.91
N	0.9	2.05	0.78
S	0.3	0.95	2.07
O	16.72	12.63	27.29

Consider coal feed rate of 100 kg/hr of as received basis, for three coals under consideration fired in a single furnace of 420 MWe output. Different coals require different stoichiometric and excess amount of air /or oxygen in the feed such that to maintain similar O₂ in the flue gas (typically 3.3 % (v/v)).

Radiation heat transfer depends of radiative properties of combustion gaseous and solid particulates (ash) generated by burning coal with different coals result in varying amounts of water vapour and carbon-dioxide being generated. Table 13 gives emissivity differences for the coals based on difference in gaseous and particulate composition evaluated at 1670 K for the mean beam length of the furnace.

Table 13: Radiative property estimates for the coals in the 420 MWe furnace

	Air-Case	Oxy-Case
Coals	Ratio (P _W / P _C)	Ratio (P _W / P _C)
Callide	0.375	0.404
Rolleston	0.541	0.548
Lignite	0.557	0.557

Air-Combustion

Coals	Emissivity (gas)	Emissivity (ash)	Emissivity (gas+ash)
Callide	0.424	0.37	0.64
Rolleston	0.449	0.12	0.52
Lignite	0.455	0.25	0.59

Oxy-Combustion

Coals	Emissivity (gas)	Emissivity (ash)	Emissivity (gas+ash)
Callide	0.659	0.45	0.81
Rolleston	0.679	0.16	0.73
Lignite	0.681	0.31	0.78

It is seen that there are differences in emissivities which are related to coal properties, with ash content being significant, and the total emissivities ranging from 0.59 to 0.64 . There is some uncertainty for this estimate, particularly related to ash sizing and optical properties. The emissivity values of Table 13 may be used to estimate the impact of heat transfer differences due to coal properties, Table 14 giving the results. The calculation determines the burner inlet O₂ levels (wet %) by matching the heat transfer for oxy-fired to air-fired case. The O₂ concentration of 3.3 % (v/v) at furnace exit is maintained by adjusting the % excess oxygen in the feed.

Table 14: Coal property impacts in oxy-firing environment

Coal Types	Callide	Rolleston	Lausitz Lignite
% excess O ₂	4.5	4.7	4.9
O ₂ fraction at the burner inlet (-)	0.27	0.26	0.265
O ₂ fraction at the furnace exit (-)	0.033	0.033	0.033
Adiabatic Flame Temperature, K	2201	2165	2164
Flue gas temperature, K	1549	1555	1569
Flue gas volume, kmol/hr	43156.6	44394.7	44213.7
Total Heat Transfer, Mw	408.3	385.6	389.4

In Table 14, the total heat input is similar and this is reflected in slight differences in adiabatic flame and gas temperatures. Gas emissivity for Rolleston coal is high because of higher concentrations of CO₂ and H₂O in the flue gas. However, the ash content is lower compared to Callide and lignite coal, which is reflected in terms of ash emissivity values. The combined influence of gas/particulate properties gives lower emissivities for Rolleston and that is reflected in the total heat absorption.

The emissivity of furnace gases depends directly on gas partial pressures, particulate concentration and the furnace size, as represented by the beam length. To achieve the same heat transfer for the oxy-firing as air-firing, the effect will be that lower amount of oxygen will be required at the burner inlet. A sensitivity analysis on oxygen requirement for two furnaces for 30 MWe and 420 MWe outputs shows slightly lower concentrations of oxygen is required for the larger furnace, as is shown on Figure 11.

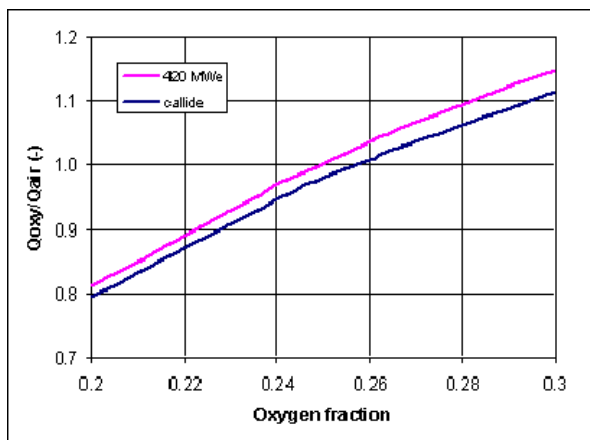


Figure 11: Ratio of furnace heat transfer for oxy-firing and air firing with oxygen volume fraction through the burners.

The effect of change in furnace size is indicated in terms of surface area available for heat exchange between gas and surface, called GS and represented by.

$$\overline{(GS_1)}_R = \frac{A_T}{\frac{1}{\epsilon_{Comb}} + \frac{1}{(C_s \epsilon_1)} - 1}$$

Large furnaces have greater surface areas available (A_T), and the gas to surface heat exchange depends on A_T and emissivity of medium. Since both these parameters are higher for 420 MWe, the GS and therefore the heat absorption will be greater. Figure 12 shows a comparison of trends for two furnaces.

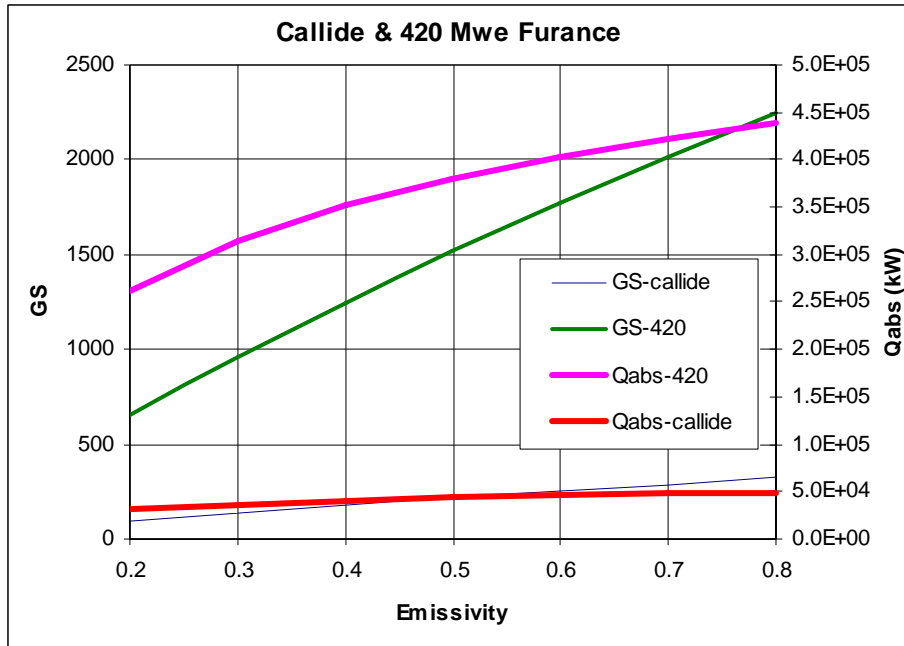


Figure 12: GS and Heat absorption trends for Callide A (30 MWt) and 420 MWe furnaces

The effect of emissivity is seen to be greater for the larger furnace, so that the operation for oxy-firing will need greater adjustment than for some furnaces.

7. CONCLUSIONS

Emissivity of gases

A. The gases determining radiative heat transfer in air-fired and oxy-fired systems differ in the partial pressures of H₂O and CO₂. The emissivity in the two systems differs primarily due to total partial pressures of H₂O and CO₂ may also differ due the ratio of partial pressures of the two gases.

B. The standard WSGGM using three gray gases used in CFD codes is not adequate for larger furnaces and in particular for oxy-fired furnaces. The introduction of a fourth gray gas improves the estimate of emissivity in these systems.

The well-stirred combustion chamber model (WSM)

C. The WSM has been shown to provide predictions of radiative heat transfer to compare air and oxy-firing.

D. In particular the WSM has predicted oxygen concentrations at the burner inlet to range from 25% - 38% (v/v) to achieve similar predicted furnace heat transfer as the air case. The use of dry or wet recycle and furnace size has an effect on the O₂ concentration requirement at burner inlet.

E. In addition the WSM has shown that for matching heat transfer, lower temperatures for the gases entering the convective section for oxy-fuel are the result of the different heat capacities of the flue gases.

Impact of coal properties on furnace heat transfer

F. Coal properties such as its heating value and ash content influence the furnace heat transfer. Higher concentrations of gases (CO₂ and H₂O) and particulate matter changes the radiative properties of gas mixture system (depends on coal types) and thus influences the furnace heat transfer.

G. The sensitivity of coal properties for furnace heat transfer is quantified for a 420 MWe furnace, with differences in emissivities calculated, with ash content shown to be significant, and the total emissivities ranging from 0.59 to 0.64. For these coals, to match heat transfer for a retrofitted furnace a 1% difference is required in the O₂ volume fraction through the burners. The effect of coal properties is greater for larger furnaces, so that the operation for oxy-firing will need greater adjustment for large furnaces.

8. NOTATION

- $a = a' / 4$, Projected area of particle (m²)
 a' = Actual surface area of particle (m²)
 a/v = Projected area of particles per unit volume of space (m²/m³)
 A_T = Total surface envelope area, (m²)
 c = Number concentration of particles (per m³ of flue gas)
 C_s = Cold or sink fraction of the total surface envelope of area, A_T , (-)
 $(\overline{GS}_1)_R$ = Total exchange area between gas and surface zone in radiative equilibrium, (m²)
 H_f = Enthalpy of stream, (kW)
 L = Path (Beam) length (m)
 p = System total pressure, (atm)
 p_g = Partial pressure of absorbing gas, (atm)
 Q = Energy flux, (kW)
 T_{aft} = Adiabatic flame temperature, (K)
 T_g = Temperature of gas, (K)
 T_1 = Temperature of furnace wall surface, (K)
 T_0 = Reference temperature, (K)
 ε_B = Black particle emissivity (-)
 ε_{ash} = Ash particle emissivity (-)
 ε_g = Gas emissivity (-)
 ε_{Comb} = Combined emissivity (gas + ash) (-)
 ε_1 = Emissivity of furnace wall surface, (-)
 σ = Stefan-Boltzmann constant = (5.67E-11 kW/m².k⁴)
 η = Furnace Efficiency (-)

9. REFERENCES

1. Smith TF, Shen ZF, Friedman JN. Evaluation of coefficients for the weighted sum of gray gases model. *J. Heat transfer*, 104, 602-608, 1982.
2. Modest, MF. Radiative heat transfer, 1993.
3. Hottel HC, Sarofim AF. Radiative transfer, vol.1. NY, USA: McGraw-Hill, Inc; 1967.
4. Leckner B. Spectral and total emissivity of water vapour and carbon dioxide. *Combustion and flame*, 19, pp. 33-48, 1972.
5. Ludwig CB, Malkmus W, Reardon JE, Thompson JA. Handbook of Infrared Radiation from Combustion Gases, NASA SP-3080, 1973.
6. Edwards DK, Matavosian R. *J. Heat Transfer*, 106, 684, 1984.
7. Edwards DK, Menard WA. Correlations for absorption by methane and carbon-dioxide gases. *Applied Optics*, 3,621, 1964.
8. CS Energy, QLD, Australia
9. ACIRL Combustion Technology Centre, ACIRL Pty Ltd
10. Field, M.A., D.W. Gill, D.W., Morgan, B.B., Hawksley, P.G.W., 'Combustion of Pulverised coal', The British Coal Utilisation Research Association, 1967
11. Turns, S.R., *An Introduction to Combustion - Concepts and applications (second edition)*, 2000
12. Gupta, R.P., Wall, T.F., 'The Optical Properties of Fly Ash in Coal Fired Furnaces', *Combustion and flame* 61:145-151, 1985
13. Perry, R.H., Green, D.W., *Perry's Chemical Engineers' Handbook (7th Edition)*, 1997
14. Hottel, H.C., A.F. Sarofim, A.F., *Radiative Transfer*, p468, 1967
15. McDonald, M.M. & Co, A Design Study of the Application of CO₂/O₂ Combustion to an Existing 300 MW Coal Fired Power Plant, Clearwater Conference, 2004
16. www.kwt.tu-cottbus.de/pages/texte/2005_results_operation_experiences.pdf