CLEAN COMBUSTION OF COAL. MINIMIZATION OF ENVIRONMENTAL POLLUTION EFFECTS.

Gloria Villaflor, Rubens Pocoví, Jorge Velasco y Eduardo Bisonard

Instituto de Beneficio de Minerales (IN BE MI) – Facultad de Ingeniería
Consejo de Investigación – INIQUI– Universidad Nacional de Salta – CONICET
Buenos Aires 177 – 4400 – Salta – Argentina
Tel: 54-87-255412 – Fax: 54-87-255451 – Email: inbemi@unsa.edu.ar

ABSTRACT

The coal combustion in fluidized bed combustor is being highly studied because it is an interesting alternative to minimize the environmental pollution.

If the coal is burned mixed with limestone, an important part of the sulfur dioxide produced by the combustion reactions is fixed as calcium sulfate. Bed temperature control allows the minimization of nitrogen oxides emission. Dust emission is minimized by cleaning the combustion gases in high efficiency cyclones, filters or electrostatic separators.

Combustion of carbon from Río Turbio (Santa Cruz Province, Argentine) in fluidized bed is studied in this paper.

Sulfur retention in the residual solids is expressed as a function of the relation Ca/S in the reactor feed.

A computer program has been developed to carry on the required calculations to design and/or control the operation of the fluidized bed combustor. It gives the air required for the complete combustion, the quantity and composition of the combustion gases and efficiencies of combustion reactions, limestone calcination and sulfur retention. It can also check out the fluidization conditions.

INTRODUCTION

When coal and other fossil fuels are burned to produce thermal energy, a great number of pollutants are emitted into the atmosphere. These include carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), hydrocarbons and organic compounds produced by an incomplete combustion, and particulate matter as smoke and ashes. The most important contaminants among the above mentioned, due to their global emissions and maximum admissible concentration levels are the SO_2 and NO_x. They produce very serious environmental problems through mechanisms of photo-oxidation reactions, affecting human health, causing visibility degradation, material corrosion and the harmful acid rains. The NO_x reacts with ozone and contributes to the ozone layer destruction (Wark and Warner, 1997; De Nevers 1998). The carbon dioxide, produced by complete combustion of the carbon, is not considered as a pollutant but the continuos increase in its production produces an increase in the mean earth temperature (greenhouse effect).

The fuels generally used to produce energy in power plants and industrial processes are natural gas, fuel oil and coal. The order in which they have been mentioned corresponds to the increasing level of contamination they produce by their combustion. Because the earth coal reserves are much higher than the corresponding to natural gas and crude oil, it is very important to study the clean combustion of coal to minimize the environmental pollution produced when coal is burned in conventional installations. The combustion in fluidized bed reactors is an important alternative to get this goal (Montes and Otero, 1997).

Coal combustion in fluidized beds permits the SO_2 and NO_x emissions minimization and the use of high overall efficiency systems to recover the produced dust (Calbo García, 1991; Tillman, 1991).

As it was said, the SO_2 produced by the coal sulfur content can be fixed mixing the coal with limestone. Then the SO_2 is retained as calcium sulfate, which is discharged with the combustion residual ashes. This reaction of sulfur fixing is helped by the high turbulence of the fluidized bed reactors (Armesto et al., 1993).

The NO_x emissions are minimized working at temperatures lower than 900°C, because only above this temperature level the NO_x formation begins to be important. Bed temperature is controlled with heat exchangers placed into the combustion reactor, where water is used as cooling fluid, producing high pressure steam (absorbing the vaporization heat).

The combustion process produces ashes (residual solids) that are discharged from the bed and combustion gases that are sent to cyclones and filters to obtain clean gases.

MASS BALANCE

The mass balance of the fluidized bed combustion process is made according to the following considerations:

- Air is used to carry on the combustion reactions and as fluidizer gas.
- NO_x are not formed from air nitrogen oxidation, due the low temperature level used in the fluidized bed. But from the point of view of environmental pollution it is important to check out the NO_x formation, even if it is very low.
- Limestone mixed with the coal to be burned is fed to fix an important part of SO_2 formed as $CaSO_4$. The chemical reactions are:

Sulfur combustion

$$S(s) + O_2(g) \rightleftarrows SO_2(g) \qquad (1)$$

Limestone calcination

$$CaCO_3(s) \rightleftarrows CaO(s) + CO_2(g) \qquad (2)$$

SO_2 fixation

$$SO_2(g) + CaO(s) + \tfrac{1}{2}O_2(g) \rightleftarrows CaSO_4(s) \qquad (3)$$

In fact, limestone is formed by $CaCO_3$ and impurities as $MgCO_3$, inert components and moisture.

- The quantity of limestone fed is a function of the coal sulfur content. It is calculated from the molar relation:

$$R_{lime} = \frac{\text{Ca moles}}{\text{S moles}} \qquad (4)$$

- The residual solid discharged from the fluidized bed is formed by: $CaSO_4$, $CaCO_3$, CaO, $MgCO_3$, MgO, C (not burned) and inert components of the coal and limestone.
- The dust concentration in the combustion gases depends of the overall efficiency of cyclones and filter.

EFFICIENCIES

Conversion coal efficiency

It is defined as the quantity of coal burned related to the quantity of coal fed to the reactor. It is calculated from the unburned carbon present in the residual solid discharged from the reactor:

$$E_{conv} = \frac{\text{C burned}}{\text{C fed}} = 1 - \left(\frac{\text{C unburned}}{\text{C fed}}\right)$$

$$E_{conv} = 1 - \sum^{i} \frac{m_{di}\left(C_{Tdi} - C_{lime\,di}\right)}{C} \qquad (5)$$

where:

$m_{di} = W_{di} / W_f$

m_{di}: mass fractions in the solid discharges

being i = b (bed discharge), i = cf (cyclones and filter discharges)

W_{di} : mass flow in the discharges (kg/h)

W_f : mass flow in the feed (kg/h)

C_{Ti}: weight fraction of total carbon in solid discharge

$C_{lime\ i}$ = weight fraction of carbon in the uncalcined limestone

Complete combustion efficiency

It is the amount of coal carbon burned to CO_2, related to the total coal carbon burned. It is calculated from the concentration of CO in the combustion gases:

$$E_{cc} = \frac{CO_2\text{ produced}}{\text{C burned}} = 1 - \frac{\text{CO produced}}{\text{C burned}} \qquad (6)$$

Limestone calcination efficiency

It is the relation between the calcined limestone and the fed limestone.

The uncalcined limestone and unreacted CaO are discharged with the residual solids and the recovery dust equipments. The limestone fed depends on relation (4) used.

$$E_{D\,lime} = \frac{\text{calcined limestone}}{\text{fed limestone}}$$

$$E_{D\,lime} = 1 - \left(\frac{\text{uncalcined limestone}}{\text{fed limestone}}\right)$$

$$E_{D\,lime} = 1 - 0.8\frac{Ca_{lime}}{R_{lime}\,S}\sum^{i}\frac{m_{di}\,C_{lime\,i}}{C_{lime}} \qquad (7)$$

Sulfur retention efficiency

It is the relation between the amount of sulfur retained by the limestone (as $CaSO_4$) and the amount of coal sulfur.

It is calculated from the amount of SO_2 in the combustion gases.

$$E_{RS} = \frac{SO_2 \text{ retained}}{SO_2 \text{ produced}} = 1 - \frac{SO_2 \text{ unretained}}{SO_2 \text{ produced}} \qquad (8)$$

AIR REQUIRED FOR COMBUSTION

The minimum amount of air required for the complete combustion, Wa_{min} (kg air/kg coal), is calculated from the data of an elemental coal analysis. It is calculated from the combustion reactions (Dubbel, 1979), limestone calcination and SO_2 fixing. Considering dry air (23.2 wt% of oxigen), Wa_{min} is expressed as a function of the coal composition.

$$Wa_{min} = \frac{1}{0.232}\left[1.33\left(E_{cc}+1\right)C + 8\,H + \left(1 + \frac{E_{RS}}{2}\right)S - O\right]E_{conv} \qquad (9)$$

Minimum air volume Va_{min} (m^3_N/kg) is calculated with a specific volume of 0.773 m^3_N/kg (0°C, 760 mmHg).

The actual air volume, Va (m^3_N/kg), is:

$Va = n\, Va_{min} \qquad n > 1$

where n is a coefficient of air excess, which depends on the kind of fuel used and of the combustion equipment used.

The wet air volume Va_f (m^3_N/kg), is calculated with a correction factor f (Dubbel, 1979):

$Va_f = f\, Va$

COMBUSTION GASES

The combustion gases volume Vg_f (m^3_N/kg), is calculated from the coal composition, n and f values, as well its composition (CO, CO_2, SO_2, H_2O, N_2, O_2) (vol%).

$$\begin{aligned} Vg_f = {} & (1.86\,C + 0.68\,(1 - E_{RS})\,S + 11.2\,H + 0.8\,N)\,E_{conv} + \\ & + 1.24\,H_2O + 2.33\,R_{lime}\,S\,E_{D\,lime}\,C_{lime}/Ca_{lime} + \\ & + 1.55\,H_2O_{lime}\,R_{lime}\,S/Ca_{lime} + (f\,n - 0.21)\,Va_{min} \qquad (10) \end{aligned}$$

FLUIDIZATION CONDITIONS VERIFICATION

From the knowledge of the air required for the coal combustion, Va_f (m^3_N/kg coal) and the coal consumption (kg/h), it is possible to calculate the air flow required for the combustion: $Q_a = Va_f\, W_f$

The superficial air velocity, defined with the bed cross-sectional area, A, is: $u_a = Q_a/A$.

The minimum fluidization velocity, u_{mf}, was calculate from the Kunii and Levenspiel equation (Kunii and Levenspiel, 1969; Villaflor et al, 1998).

$$u_{mf} = \frac{\mu}{\rho\,\phi_s\,d_p}\left[\sqrt{42.9^2\left(1-\varepsilon_{mf}\right)^2 + 0.57\,Ga\,\phi_s^3\,\varepsilon_{mf}^3} - 42.9\left(1-\varepsilon_{mf}\right)\right] \qquad (11)$$

μ : air viscosity (kg/m s)

ρ: air density (kg/m^3)

ρ_s: solid density (kg/m^3)

d_p: particle diameter (m)

ϕ_s: sphericity factor (dimensionless)

ε_{mf}: minimum fluidization porosity (dimensionless)

$Ga = \frac{d_p^3 \rho}{\mu^2}(\rho_s - \rho)g$: Galileo Number (dimensionless)

The operating fluidized bed velocity was taken as: $u_f = r\, u_{mf}$, where $r > 1$ is the fluidization relation ($r = u_f/u_{mf}$).

SO_2 PRODUCTION

The SO_2 produced and discharged with the combustion gases can be calculated from equation (1), the SO_2 specific volume and the combustion and sulfur retention efficiencies. It is:

$$\%\,SO_2 = \frac{0.68\,\left(1 - E_{RS}\right)\,S\,E_{conv}}{Vg_f} \times 100 \qquad (12)$$

EXPERIMENTAL EQUIPMENT

The combustion chamber is a 20 cm diameter fluidization column, constructed with stainless steel (Figure 1). The necessary heating to begin the combustion reaction is made by electric energy with quartz candles.

The coal and limestone are fed continuously using a screw feeder. Residual solids are removed from the column through an overflow pipe. They consist of ashes, calcium sulfate and unburned coal. The fine particles may be entrained by the gas. They are recovered with a high efficiency cyclones system.

A gas analyzer allows the measuring of the flue gas composition (O_2, SO_2, NO, NO_2, CO, CO_2 and C_xH_y), temperature and air excess used to burn the coal.

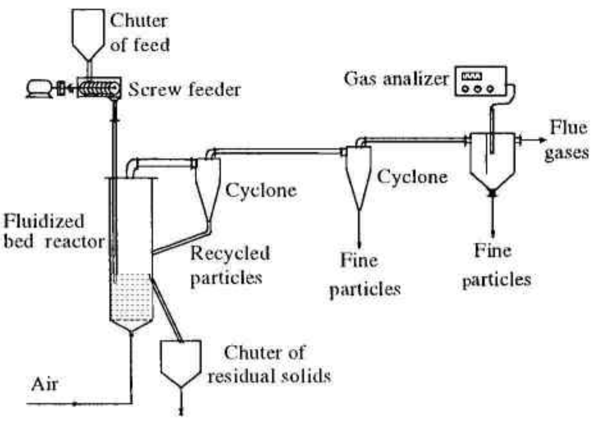

Figure 1: Fluidized bed for combustion experiments and sulfur fixing

RESULTS

Some of the experimental results, obtained in combustion and sulfur retention tests are shows in Tables I, II and III.

The tests were carried out using lime for the sulfur fixing as $CaSO_4$, and different relations $R_{lime} = Ca/S$ were also used.

Compositions of coal and lime fed to the fluidization bed are given in Table I. An example of combustion gases composition is given in Table II for a test using $R_{lime} = 1$.

Results of different combustion tests, with different relations Ca/S are given in Table III.

Table I: Coal and lime composition

Coal	(%)	Lime	(%)
Carbon	61.0	CaO	71.58
Hydrogen	4.2	MgO	8.2
Sulfur	1.0	Inert	14.25
Oxygen	11.2	Water	5.97
Nitrogen	0.6		
Ashes	12.0		
Water	10.0		

Table II: Combustion gases composition

Combustion gases	vol % $R_{lime} = 0$	vol % $R_{lime} = 1$
CO_2	16.33	16.32
CO	0	0
SO_2	0.1026	0.0755
H_2O	8.96	8.99
N_2	73.71	73.72
O_2	0.9	0.9

Table III: Sulfur retention efficiency with different relations $R_{lime} = Ca/S$

R_{lime}	Fludization Air (m^3_N/h)	Combustion gases (m^3_N/h)	r	E_{RS}
1	5.56	5.93	4.83	0.257
1.5	5.40	5.76	4.69	0.404
2	5.18	5.57	4.50	0.487
3	5.36	5.73	4.66	0.688

CONCLUSIONS

- The Río Turbio coal combustion in fluidized bed reactors allows to reduce contaminative emission to the atmosphere.
- The SO_2 retention efficiencies obtained are low. This is because of the low sulfur content of the Río Turbio coal. This makes necessary to work with high Ca/S relations.
- NO_x emissions are very low, due to the low combustion temperature used ($\cong 850°C$) and the low air excess required by the combustion in fluid bed reactors.
- If the coal composition is known, the developed computer program allows to calculate: air flow required for the combustion, amount and composition of the combustion gases. The different efficiencies of the combustion process can be checked out with the computer program.
- Fluidization conditions can be calculated with the computer program.

REFERENCES

Armesto, L., Cabanillas, A. and Bahillo A., Prediction of Sorbent Behavior of Limestone, 12 International Conference on Fluidized Bed Combustion, San Diego, 1993.

Calbo García, J., Tecnologías para el uso limpio del carbón, Energía, volumen 17 (3), 89-94, 1991.

De Nevers, N. Ingeniería de control de la contaminación del aire, Mc Graw Hill, 1998.

Dubbel, H., Manual del constructor de máquinas, Editorial Labor, 1979.

Kuni and Levenspiel, Fluidization Engineering, J Willey & Sons, New York, 1969.

Montes, M. y Otero, J., Tecnologías avanzadas de generación energética a partir del carbón, Ingeniería Química, Año XXIX, N° 333, Madrid, España, Marzo 1997.

Tillman, D., The Combustion of Solids Fuels and Wastes, Academic Press, 1991.

Villaflor, G., Velasco, J., Pocoví, R. y Flores, H., Combustión de carbón en lecho fluidizado: aspectos fluidodinámicos, Información Tecnológica, Chile, V9 (1), 130 a 135, 1998.

Wark, K. y Warner, C., Contaminación del aire. Origen y control, Ed. Limusa, 1997.