Fluidised Bed Combustion: A Novel Technology for the Combustion of Low Grade Fuels

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ABSTRACT

Large quantities of wastes are produced in Kenya from industrial and agricultural activities, which could be used as source of energy. Currently only a small percentage of these wastes are utilised for energy purposes. This is attributed to the physical and chemical properties of the wastes, which make their firing in conventional furnaces difficult. A firing technology, which is increasingly becoming popular for the combustion of fuels with difficult combustion properties, is fluidised bed combustion (FBC). In the current paper, the special features of FBC have been reviewed and their advantages as compared to conventional firing systems highlighted. This has been achieved using the experiences from large-scale FBC systems as well as experimental results a semi-pilot scale fluidised bed test facility, 100 mm diameter and 9 m high. It is shown that fluidised bed furnaces have the ability to burn low quality fuels and wastes, in addition to low maintenance cost. FBC also exhibits high heat transfer coefficient. The combustion of low quality fuels can take place at high combustion efficiency and it is possible to reduce the emissions of NO_x, N_2O, CO and SO_2 to acceptable levels using standard emission reduction techniques.

1.0 INTRODUCTION

One of the constraints Kenya faces in its effort to become a Newly Industrialised Country by the year 2020, is inadequate supply of energy. In the recent time, we have witnessed severe power shortfall and consequently power rationing which has affected the operation of many industries. The problem of supplying adequate energy will need to be addressed in order to attain the planned industrialisation. One of the possible solutions is to intensify the application of steam power plants. As source of energy, coal, wastes from agricultural and industrial activities as well as wood and peat can be used. In this way, the sources of energy can be diversified and this could help reduce the over-dependence on hydro-power. Coal, for example, can be imported cheaply from the neighbouring southern African countries, whereas agricultural and industrial wastes are abundantly available in Kenya and their current level of usage for energy purposes is very low.

There are two problems, which are normally associated with the combustion of solid fuels in conventional furnaces. The first problem concerns the emissions of gaseous pollutants such as SO_2, NO_x and N_2O, as well as unburned pollutants such as CO and hydrocarbons. These pollutants are responsible for various environmental problems. For example, SO_2 and NO_x cause acid rain, which is associated with environmental problems such as lake-acidification and forest destruction, whereas NO_x and N_2O are known to lead to the destruction of Ozone layer (Mann et al. 1992). The emissions of SO_2, NO_x and N_2O depend on the contents of sulphur and nitrogen in the fuel (Lee and Chun, 1993, Hampartsoumian and Gibbs, 1984). Whereas, the emissions of unburned pollutants depend on the way the firing process is carried out, as well as the type and configuration of the furnaces (Nussbaumer, 1997). In the developed countries (and sooner or later in the developing countries), very strict emission limits exist. Meeting these limits generally requires a greater plant investment. It is no wonder that today, environmental requirements have joined cost reduction as a primary consideration in the design and operation of coal-fired power plants. The second problem associated with the combustion of solid fuels is attributed to their physical and chemical compositions, particularly for low quality coals as well as agricultural and industrial wastes. Most of these materials are characterised by high contents of moisture, ash and volatile matter as well as low bulk densities. High combustion efficiency and low emissions may be difficult to achieve during the combustion of these materials in conventional furnaces.

One of the most promising technologies, which can handle fuels with poor combustion characteristics, is fluidised bed combustion system (FBC). It has the ability to burn efficiently low quality fuels and also enable attainment of minimum emissions at low operation cost.

Detailed information concerning fluidisation technology can be found elsewhere, for example, in Werther (1983) and Kunii and Levenspiel (1991). Fluidisation occurs when a fixed bed of particulate solids resting on a grid plate is brought into a liquid-like state by an upward flowing gas or liquid. This occurs when the fluid's superficial velocity exceeds a certain limiting value called, minimum fluidisation velocity, U_{mf}. Normally fluidised bed combustion plants are operated at superficial velocities higher than U_{mf}. The excess gas-flow, $U-U_{mf}$, leads to the presence of practically solid-free bubbles which rise through the bed and generate significant solid mixing which is a very important feature of bubbling fluidised beds. At much higher gas velocities, a situation is reached whereby the particles are drawn from the bed and lifted in a relatively diluted phase upward and is returned to the bed via a cyclone what is referred to as circulating fluidised bed.

Compared with conventional firing system, the principle position of FBC is therefore, between a grate and pulverised coal firing (Figure 1). The grate system of coal combustion consists of a fixed bed of large coal particles supported on a grate. As the combustion air passes upwards through the coal bed, the coal particles burn in a stationary position and the ash formed falls into the ash pit. In FBC systems, coal particles are introduced in a hot bed of inert particles of coal, ash, sand and limestone under fluidisation. Through contacts with the hot bed particles, the coal particles are rapidly heated up, devolatilised and burnt. In pulverised fuel combustion, the coal is pulverised to fine particles ($d_p < 75\ \mu m$) and then carried in suspension to arrays of large burners firing into the combustion chamber.

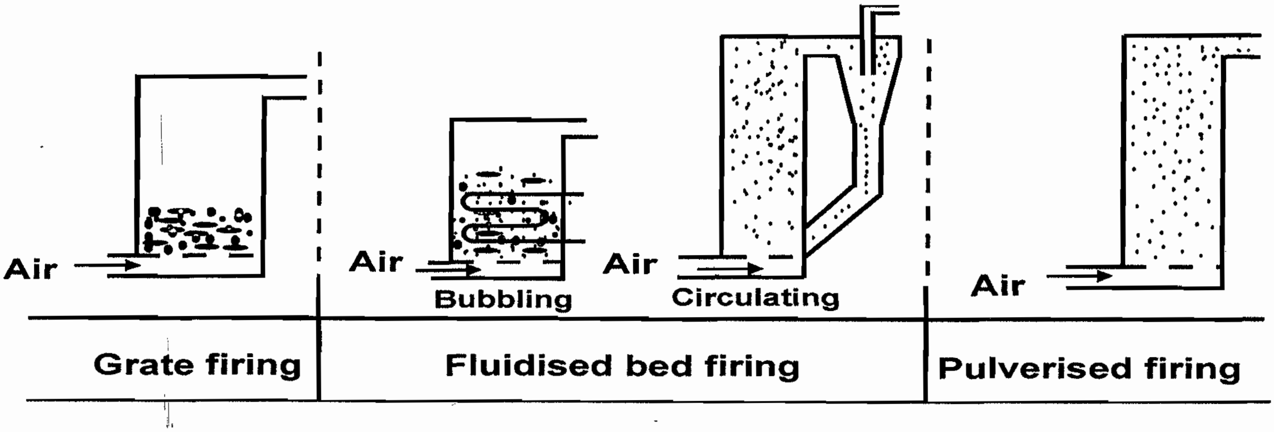

Fig. 1 Principle position of fluidised bed combustion system (Sinn, 1987)

Compared with the conventional firing systems, FBC offers several advantages. These include ability to burn low quality fuel and wastes, low maintenance cost of the furnace, cost effective method of flue gas desulphurisation, low emissions of NO_x and high heat transfer rates (Hembach, 1992).

2.0 OBJECTIVES AND METHODOLOGY

The objectives of the present paper are to review the special features of FBC systems which makes it more appropriate for the combustion of wastes than the conventional furnaces. This has been achieved through literature review, evaluation of the experience from laboratory-scale and large-scale combustion systems. In addition to this, data from the author's own experiments in a semi-pilot scale test facility at the Technical University of Hamburg-Harburg, has been used. The flow diagram of the test facility is shown in Figure 2.

The details of this plant has been presented elsewhere (e.g. Werther et al. 1995a-b, Ogada and

Werther, 1996). The combustor has a diameter of 100 mm and a height of 9.3 m. The dimensions of the unit have been chosen this way so as to ensure that the mean gas residence times may be adjusted to be similar to those normally applied in large-scale plants. As bed material, quartz sand with mean sizes of 0.55 mm was used. The required combustor temperature is maintained through electrical heating of the walls of the combustor. During both heating up and experiment, axial profiles of temperature as well as pressure drops in the combustor are automatically recorded. The unit is equipped with the necessary facilities to feed wet sludge as well as solid, liquid and gaseous fuels. Gas samples can be taken at different points of the combustor. The experimental set-up for gas-sampling and analysis is shown in Figure 3. The sample is withdrawn from the center-line of the combustor, dried and by means of a gas pump is supplied to gas analysers. Flue gas components such as O_2, CO_2, CO, NO, N_2O and SO_2 are measured on-line and stored in a computer.

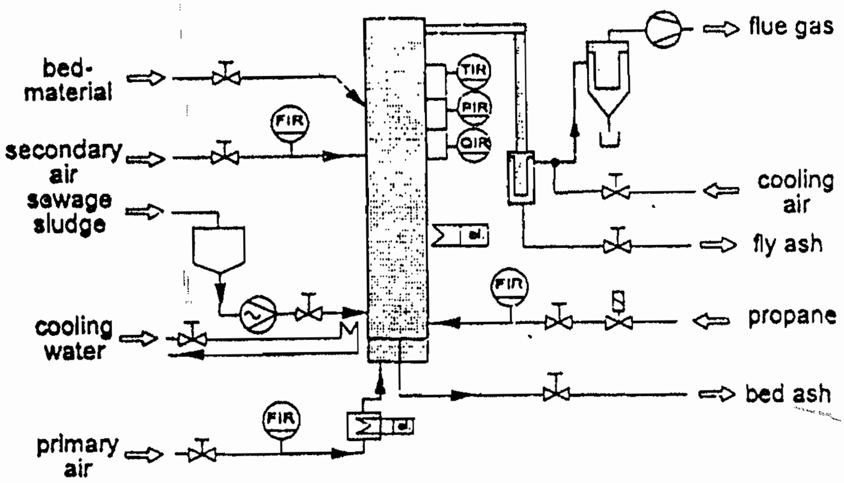

Fig. 2 Flow diagram of the stationary fluidised bed combustor

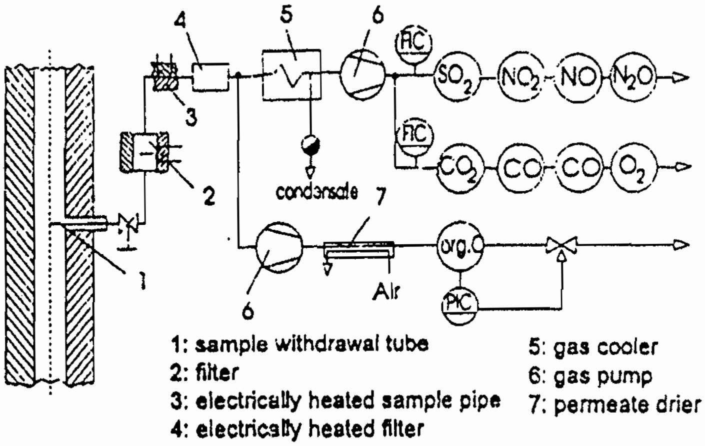

Fig. 3 Experimental set-up for gas sampling and analysis

3.0 RESULTS AND DISCUSSIONS

3.1. Ability to burn low quality fuel and wastes

An important characteristic of FBC is its ability to burn low quality fuels and wastes. This is due to several factors. The content of solid fuel in the hot bed is normally around 1 wt.-% and the bed materials also offer large surface area for heat transfer. There is also very intimate solid-solid and solid-gas mixing in the bed resulting into high turbulence and uniform bed temperatures. These factors provide virtually complete combustion of any type of fuel at relatively low excess air ratios. The large inventory of hot inert bed material acts as a thermal flywheel so that major variations in the fuel composition are stabilised by the large heat reservoir, which prevents sudden temperature changes. It is therefore possible to burn any type of fuel including those with high contents of ash, moisture and volatiles such as, peat, biomass, municipal and industrial wastes (Mullen, 1992).

Several large-scale fluidised bed combustion plants are operating and burning low quality fuels and materials like sludge, municipal solid wastes, paper sludge, sawdust, bark and agricultural wastes. For example, in Japan, some 53 fluidised bed incinerators of sewage sludge were reported operating in 1992 (Imoto et al., 1992) and in 1995 over 100 FBC units were firing municipal and other solid and liquid wastes (Wheeler et al., 1995). Recently, a 220 t/h circulating fluidised bed (CFB) boiler, for co-firing paper sludge with coal was commissioned in China (Xiaodong et al. 1997). At the Golbey Paper Mill, France, is the EcoEnergy bubbling fluidised bed combustion boiler co-firing bark and sawdust with paper mill sludge. The boiler was commissioned in 1993 and produces 35 t/h saturated steam at 26 bar (Vayda et al. 1993). In South Africa, a boiler was recently commissioned to burn coffee sludge with 85 % moisture content (North and Eleftheriades, 1997). Amongst the agricultural residues, which are currently being fired in large-scale, are rice stalks and wheat straws. In Punjab, India, a 10 MW fluidised bed combustion plant firing 100 % rice stalk, in baled form, has been operating since 1995 (Muthukrishnan et al., 1995), whereas, in Grenaa, Denmark, a 80 MWth boiler co-firing coal and wheat straw is operating (Trebbi et al. 1992). In all these plants, sufficient combustion efficiencies were achieved.

The experience from large-scale FBC systems agree with the data obtained in laboratory-scale test units. High burn-out efficiencies and low CO emissions were achieved during the of difficult fuels such as anthracite, brown coal, peat and sewage sludge. For example, Figures 4 and 5 show the carbon contents of filter ash and CO emissions (Ogada, 1991, Werther et al. 1995a) obtained during the combustion of brown coal and sewage sludge with moisture contents of 36 and 76 %, respectively, from the semi-pilot scale combustor. Whereas, Table 1 shows the char contents in the bed obtained during the combustion of coals of various reactivities in a laboratory-scale FBC (D'Amore et al., 1981).

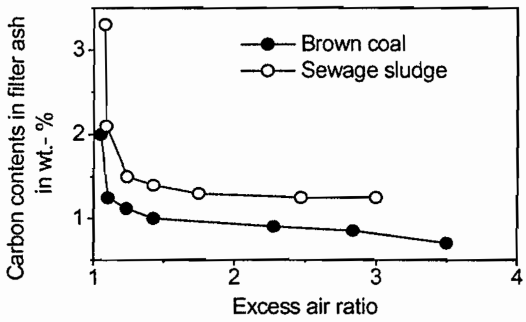

Fig. 4 Carbon contents of the filter ash as a function of excess air ratio (Ogada, 1991)

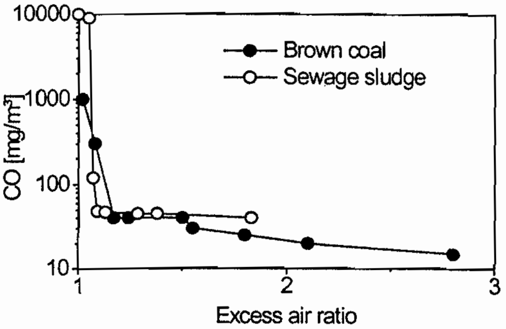

Fig. 5 CO emissions as a function of air ratios (Werther et al. 1995a)

Both filter ash and the bed ash were sampled during a steady state, quenched and cooled in an inert atmosphere of nitrogen and thereafter the carbon content determined by heating in a furnace until constant weight. The results show that under normal combustion temperature of 850 - 900°C, a char burn-out efficiency of more than 95 % and CO emissions less than 100 mg/m³ are realisable even at very low excess air ratios. A carbon content in the bed of less than 5% can also be achieved with most coals.

Table 1: Comparison of char carbon loading in the bed for fuels of different reactivities (D'Amore et al. 1981)

Fuel type	Fixed carbon in %	Excess air ratio	Temperature in °C	Carbon load in the bed in %
Valdarno lignite	46	1.12	850	0.05
Bituminous coal	60	1.12	850	1.00
Coke	81	1.17	850	4.85
Graphite coke	87	1.1	850	14.38
Graphite coke	98	1.03	900	21.42

3.2 Low maintenance cost of the furnace

A major maintenance cost for most furnaces is the repair and replacement of the refractory. In FBC units, the large inventory of the bed material eliminates thermal shocks and resultant damage to the refractory. Furthermore, there are no moving parts in the hot zone. These factors result into low maintenance cost. A number of fluidised bed furnaces (incinerators) have been in operation for over 20 years with no major replacement of the refractory (Mullen, 1992).

3.3 Cost effective method of flue gas desulphurisation

In most countries an SO_2-reduction of 85% or more is normally required for the control of SO_2. In conventional firing system, SO2 limits are achieved through removal downstream after the furnace using expensive Flue Gas Desulphurisation (FGD) system. In the case of fluidised bed, the cost of desulphurisation is significantly reduced, through in-bed SO_2-capture using CaO (limestone). The limestone is continuously fed directly into the hot bed parallel to coal feeding. The limestone decompose and CaO formed react with SO_2 forming $CaSO_4$, according to the reaction,

$$CaO + SO_2 + \frac{1}{2} O_2 \Rightarrow CaSO_4$$

Several authors have tested the techniques of SO_2- capture in fluidised bed test rigs (Lyngfelt and Leckner, 1993, Dennis and Hayhurst, 1987 and Anthony et al., 1991). The technique operates well in the presence of good solid-gas contact and a temperature of 800-900°C. At temperatures above 900°C, the $CaSO_4$ formed decomposes back into $CaO + SO_2$. A Ca/S molar ratio of 2-3 is sufficient to provide a significant SO2 - capture. For example, Anthony et al. (1991) obtained an in-bed SO_2- reduction from 6220 ppm to less than 560 ppm (an SO_2-reduction of around 91 %) at a Ca/S ratio of around 3 during the combustion of a high sulphur maritime coal in a pilot scale and industrial fluidised bed boilers.

3.4. Emission of nitrogen dioxide

The NO_x formed from any firing system normally consists of two components namely; thermal-NO_x and fuel-NO_x (Zelkowski, 1986). Thermal NO_x is formed due to the oxidation of the nitrogen in the air whereas fuel-NO_x is formed due to the combustion of the nitrogen contained in the fuel. The level of thermal NO depends very much on the combustion temperatures such that at temperatures above 1200°C, typical of pulverised combustion system, thermal-NO_x becomes significant and can account of up to 40 % of the NO_x emissions

(Cooke and Pragnell, 1990). At the normal operation temperatures of fluidised bed combustion plants of 800-900°C, thermal NO_x is negligible and thus lower emissions of NO_x are normally achieved. For example, Fig.6 shows the typical uncontrolled NO_x emissions performance of the various firing technologies using British coals. It is seen that the circulating fluidised bed system has the lowest NO_x emission levels. Whereas, the uncontrolled NO_x emissions do not show clearly the advantages of FBC over the other types of furnaces, the application of NO_x-reduction techniques is easier in FBC.

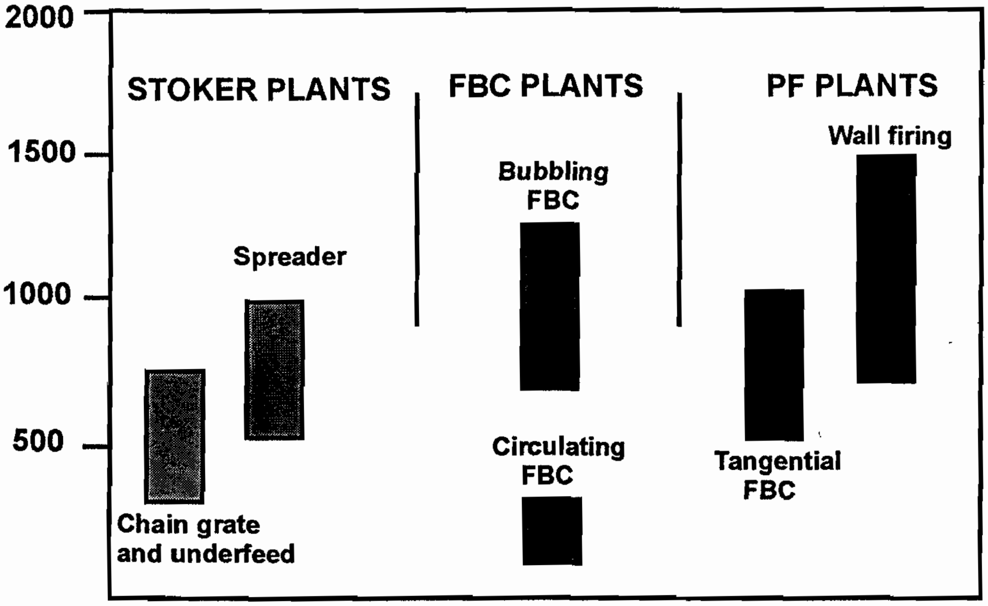

Fig.6(a). A typical uncontrolled emissions of NO_x performance of various firing technologies using British coals (Cooke and Pragnell, 1990).

One technique of reducing NO_x is the use of aqueous ammonia and urea whereby ammonia radicals (NH_i) reduces NO to N_2 according to the equations given below;

$$6NO + 4NH_3 \Rightarrow 5N_2 + 6H_20$$

$$4NO + 4NH_3 + O_2 \Rightarrow 4N_2 + 6H_20$$

Depending on the temperatures of operations and applications, this NO_x-reduction technique can be carried out at higher temperatures of around 800-950°C - called thermal reduction of NO_x (or thermal $DeNO_x$). The technique can also be applied at a lower temperature of 300 - 400°C whereby the NO_x reduction takes place with the help of a catalyst (Selective Catalytic Reduction of NO_x -SCR), commonly vanadium pentoxide. Thermal $DeNO_x$ is cheaper to apply than SCR because the latter requires expensive catalyst and an extra unit in which the reaction takes place whereas for the former, aqueous ammonia is injected directly in the furnace. Because of high temperature of operation of pulverised firing systems, thermal DeNO$_x$ can not be applied since higher temperatures favours the oxidation of NH$_3$ to NO and more NO would be formed instead, according to the equation given below.

$$4NH_3 + 5O_2 \quad \Rightarrow \quad 5NO + 6H_20$$

Measurements from both laboratory and large-scale fluidised bed combustion plants have proved the suitability of the thermal DeNO$_x$ techniques to FBC technology (e.g. Lee and Chun, 1993, Valk et al., 1989, Khan and Gibbs, 1991, Salam et al. (1989), Ogada, 1995). For example, Ogada (1995) injected NH$_3$ and urea during single stage combustion of dry sewage sludge in a bubbling fluidised bed. The reagents were introduced at a height of 4.3 m in the freeboard and the samples were drawn after a residence time of 2 s in the plant. The stoichiometric molar ratio, (β_{NH3}, defined as the molar quantity of ammonia injected per unit molar quantity of the NO in the flue gas. This was achieved by increasing the molar quantity of the ammonia or urea whereas the combustion condition remained constant. The results (Figure 6) show a reduction of NO$_x$ from around 750 to less than 200 mg/m^3 was achieved by using a stoichiometric ratio of 1-2.5.

Another NO$_x$ reduction technique is staged combustion. Like in conventional firing system, air staging was found to be an effective method of emission reduction. It is particularly useful in bubbling fluidised bed in which apart from the control of NO$_x$, reduction of N$_2$O and CO is also possible due to increased retention time of the gaseous species in the hot region. For example, Werther et al. (1995a, 1995b) achieved significant reduction of NO$_x$, N$_2$O and CO during the combustion of dry sewage sludge (Figures 7 a-c). The bed region was maintained at around stoichiometric conditions whereas the secondary air was varied to achieve a varying excess air ratio at the outlet. Compared with the results obtained from single-stage combustion using the same sludge, it is seen that at normal operation conditions, (excess air ratios of 1.2-1.5), NO$_x$ emissions decreased significantly from 900-1300 mg/m^3 to less than 260 mg/m^3. In addition to this, N$_2$O emissions decreased from around 300 mg/m^3 to less than 100 mg/m^3 and CO emissions decreased to less than 30 mg/m^3.

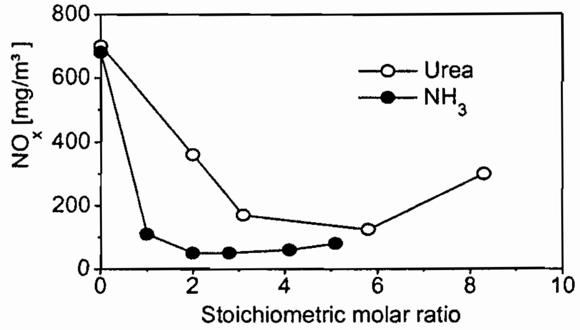

Fig. 6(b) Reduction of No_x through the injection of NH_3 and urea during combustion of dry sludge in a bubbling fluidised bed (Ogada, 1995)

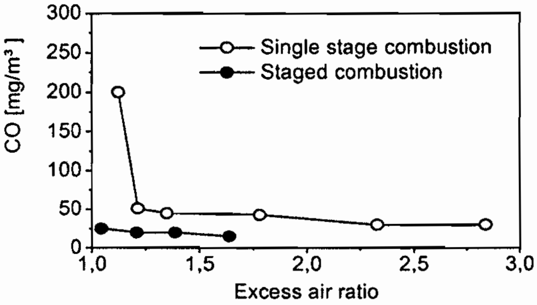

Fig. 7a Comparison of CO emissions from of staged combustion with single-stage combustion for dry sludge (Werther et al., 1995 a)

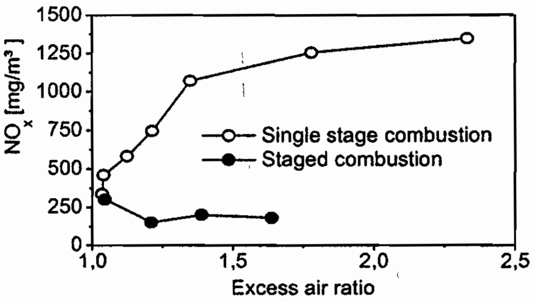

Fig. 7b Comparison of No_x emissions from staged combustion with single-stage combustion for dry sludge (Werther et al., 1995a)

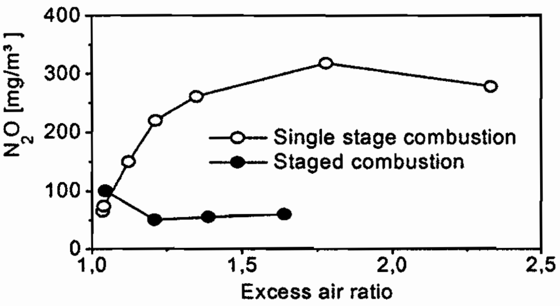

Fig. 7c. Comparison of N_2O emissions from staged combustion with single-stage combustion for dry sludge (Werther et al. 1995b)

Other researchers have also shown that further reduction can be obtained by combining thermal $DeNO_x$ with staged combustion. For example, Salam et al. (1989), starting with an NO_x concentration of around 820 mg/m^3, achieved a reduction of NO_x to 574 mg/m^3 through air staging and to less than 205 mg/m^3 through a combination of air staging and ammonia injection.

3.5 Higher heat transfer coefficient than in conventional furnaces

Another important characteristic of fluidised bed is a higher heat transfer coefficient to the in-built surfaces than experienced in conventional furnaces. This is because, in addition to the convective and radiative heat transfer coefficients typical in conventional furnaces, in fluidised bed, a third heat transfer mode - particle heat transfer, exists. This is the heat transfer due to the collision of the surface of the heat exchangers by the numerous hot particles of the bed materials. Furthermore, at high temperatures, the radiation terms is also enhanced due to the contribution of the bed materials.

Much information is available concerning heat transfer in FBC systems (e.g. Molerus and Mattmann, 1992, Molerus, 1992, Farag and Tsai, 1992, Grewal and Menart, 1987, Mathur and Saxena, 1987 and Kuipers et al. 1992). For example, Farag and Tsai, (1992), measured the rate of heat transfer in the freeboard of an FBC test facility of 300 mm diameter and 2 m high with a static bed height of 290 mm. It was shown that the heat transfer rate decreased from 245 W/m^2 K in the splash zone to 60 W/m^2 K at 3 mm above the bed surface (Figure 8). The higher rate of heat transfer in the bed region is attributed to decrease of solid particle concentrations axially along the combustor height. On the other hand, measurements of Mathur and Saxena, (1987) of the total and radiation heat transfer to immersed surface in a gas fluidised bed using high temperature heat transfer probe established that the total heat transfer depends on the excess gas velocity ($U-U_{mf}$), bed temperature and particle velocity. For example, increasing the bed temperature from 700 to 1000°C, the total heat transfer rate increased from around 250 to 400 W/m^2 K whereas the radiation term increased from 16 - 40 W/m^2 K for a 559 μm sand particle bed and a $U-U_{mf}$ of 0.2 m/s.

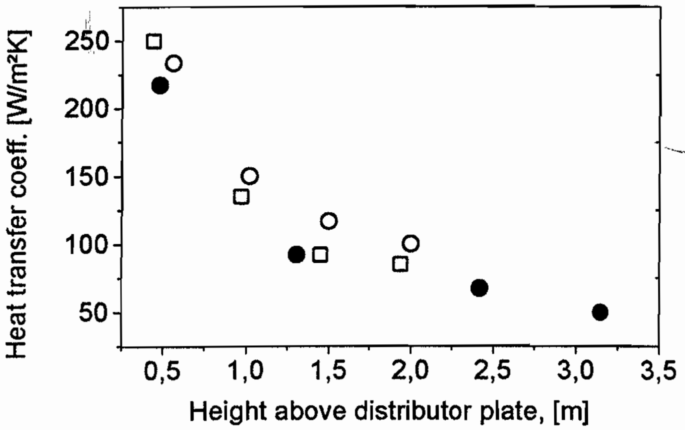

Fig. 8: Variation of overall heat transfer coefficient as a function of axial position of a fluidised bed combustor (Farag and Tsai, 1992)

4.0 CONCLUSION

With the help of experimental data as well as the experience from large-scale plants, it has been shown that FBC technology has several advantages compared to conventional furnaces. Although, the application of the FBC technology for firing various low quality fuels like agricultural and industrial wastes is not yet wide spread in Kenya, efficient combustion of these wastes are possible using FBC. The higher heat transfer in the bed indicates that large portion of the heat released during combustion can be removed using in-bed heating surfaces for steam generation. For wastes with high contents of S and N, in bed SO_2-capture as well as thermal $DeNO_x$ techniques can be used to control the emissions of SO_2 and NO_x, respectively. Whereas staged combustion, can be used to control the emissions of NO_x, N_2O and the unburned pollutants such as CO and hydrocarbons. Fluidised bed techniques should therefore be considered for the generation of process steam and power using wastes from agricultural and industrial processes in our country.

5.0 REFERENCES

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