CSIR/MSM/EP/EXP/2005/0035/A

CO-FIRING COAL AND BIOMASS IN A FLUIDISED BED BOILER

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Keywords: Fluidised bed, Combustion, Incineration, Biomass, Waste, Energy, Boiler

ABSTRACT

It is generally accepted that global warming is a reality, and that anthropogenic CO_2 emissions are the cause of the warming. One method to reduce the effective CO_2 release from boilers is to replace some of the coal with biomass, as combustion of biomass is "CO_2 Neutral".

The CSIR was approached by one of its licensees, International Combustion (Africa) Ltd (ICAL), to design the fluidised bed combustion (FBC) zone for a biomass waste and coal co-fired boiler. This boiler had been requested by a multi-national food company based in Estcourt, Kwa-Zulu Natal, South Africa.

Two design requirements emerged from the clients needs: Additional plant steam and disposal of 12 t/h of coffee grounds sludge containing up to 87% water.

The dual purpose of the FB posed a considerable challenge. Coffee sludge, although combustible, contains insufficient energy to evaporate its own water and maintain the fluidised bed at operating temperature (900 °C). Coal therefore had to be co-fired as a support fuel. Further, additional fuel was required in order to produce the full rated capacity of 26 t/h steam.

A great deal of calculation and test work was carried out to optimise the combustion zone of the FBC, particularly to maximise the amount of coffee grounds that could be disposed of. The boiler was successfully commissioned, and has been performing as per design parameters for a number of years.

INTRODUCTION

The CSIR has been involved in the design of FBCs since 1976, when a small $0.25m^2$ test facility was erected. Work really began in earnest in 1984, when the National Fluidised Bed

Combustion (NFBC) boiler was commissioned. This facility, situated at the CSIR's pilot plant terrain in Pretoria West, was designed to produce 12 t/h steam while utilising "waste" coal. ("Discards", "Duff" and slurries.)

During the course of the 5 year test campaign on the NFBC, which was funded by the Department of Minerals and Energy and later the National Energy Council, the CSIR developed a great deal of experience in the field of FBC, and in particular the use of low grade fuels in FBCs.

The CSIR (as FBC technology supplier) and one of it's licensees, International Combustion Africa Ltd. (ICAL) (as main contractor), were awarded the contract to supply a fluidised bed coffee grounds incinerator for a multi-national food company based in Estcourt, Kwa-Zulu Natal, South Africa.

This paper describes the design (including test work) of this fluidised bed incinerator and boiler.

METHODOLOGY

There were four distinct phases in the investigation of the combustion of the coffee grounds, namely:

i) Theoretical studies
ii) Small scale combustion trials (including pumping trials)
iii) Nozzle performance trials
iv) Large scale combustion trials (including further pumping trials).

These phases are covered in greater detail below.

Theoretical Studies

The first step was to draw up a composite fuel table, where the relative feed rates and the analysis of each fuel was used to generate the analysis of a hypothetical fuel.

Table 1 shows an example. Initially the efficiency selected in this table is an estimation, based on experience with other high moisture content fuels. The analysis thus generated is then used as part of the data input in a heat and mass balance over an FBC boiler. From this balance the validity of the assumed thermal efficiency is evaluated. An iterative process followed, until a valid thermal efficiency was found.

The thermal balance over the boiler based on Table 1 is shown in Table 2A.

Having established that the feed rate of coal and sludge are sufficient to produce the required amount of steam, the next step was to perform a similar balance over the bed area. This was necessary because it must be known at what excess air level must the bed be run in order to maintain it at the required temperature (900 °C to 1000 °C). It could also be that the feed rates calculated result in an “impossible” situation, with insufficient heat being supplied (from combustion) to cover the heat losses (the major losses being heat to moisture in fuel and heat to flue gases).

A spreadsheet was constructed to perform the calculations over the entire system and the bed alone. Many “what if” scenarios were run to optimise the design and increase confidence levels in the ability of the system to be robust enough to operate well with this low-grade fuel.

Small-scale Combustion Trials

The next step was to carry out combustion trials in a small FBC rig, in order to check how close to reality the theoretical figures were. Obviously the absolute mass rates determined in the theoretical studies could not be achieved. The goal was rather to achieve the coffee grounds to coal ratio at the correct excess air level. This was a critical step, as if there was a significant deviation from theoretical behaviour, a borderline case may become impossible. It was also essential to establish how much combustion occurs in the bed, and how much drying occurs in the bed. This has a direct impact on the design of the bed because, if the actual heat balance over the bed showed that there was excess heat, then in-bed heat transfer surfaces may have needed to be installed. If, however, there was insufficient heat, then in-bed heat transfer cannot be included and, in fact, some method must be found to reduce heat losses from the bed, for example pre-drying of the sludge.

For these trials a 0.25 m^2 test facility with no in-bed heat transfer surfaces was employed. A flow diagram of this facility can be seen in Figure 1.

After optimising the coffee grounds to coal ratio, a test run was undertaken and the data used to develop an actual thermal balance over the bed. An example is given in Table 2C. Deviations from theoretical behaviour were investigated, reasons postulated and solutions proposed.

Nozzle Performance Trials

Trials were carried out at the client’s premises and at the CSIR in order to determine what design of nozzle would be required to achieve dispersion of the coffee grounds sludge into a fluidised bed.

Parameters which were investigated were:

- The effect of annular compressed air
- The effect of directly injected compressed air
- The effect of a deflector at the nozzle outlet
- Required area of the nozzle to avoid blockage by chicory lumps present in the sludge. (Up to 15mm.)

Large-scale Combustion Trials

As a final test of assumptions made during Steps 2.1 and 2.2, a test run was carried out on the NFBC.

RESULTS

Theoretical Studies

As explained in Section 2, an iterative process was followed in order to determine what mass of coal is required, in theory, in order to combust the 12 t/h of coffee grounds (which contain 85% water) and raise 26 t/h of steam. The most arduous condition, disposing of all the coffee grounds while only steaming at 21 t/h, also had to be met.

Table 1, the example used earlier, is actually the composite fuel which was arrived at the end of this iterative process. Likewise, Tables 2A and 2B show the theoretical thermal balances over the boiler and the bed respectively. These tables show that, in theory, the required amount of steam can be generated by firing a composite fuel consisting of 5.03 times as much coffee grounds as coal. They also show that (again, in theory), the bed will be stable because there is sufficient heat liberated within the bed (from combustion of the fuel) to cover the heat losses from the bed.

Some points should be made here in connection with the theoretical studies.

a. They were based on a system employing no heat transfer surfaces within the bed. The results validate this, as there is a minimal amount of excess heat available in the bed. If heat transfer surfaces were present, then additional heat would need to be generated within the bed.
b. They are based on the assumption that all of the fuel dries and burns within the bed. (Although the spreadsheet was also run many times with re-calculated feed to the bed and freeboard to simulate the effect of the location of drying and combustion).
c. They are based on a fluidised-bed operating temperature of 900 ^{o}C to 1000 ^{o}C.

Small-scale Combustion Trials

These were undertaken in order to establish if a fluidised bed could be run stably while firing it with a coffee ground sludge/coal mixture in the ratio of 5.03:1, the ratio determined in the previous theoretical studies.

It was at first attempted to pump the sludge into the test rig. However, various pumps (including double diaphragm, centrifugal and Mono) were tried with no success. In any event, the nozzle which would be required in order to maintain reasonable velocities would be approximately 7 mm in diameter. This would almost certainly have blocked. It was decided therefore to feed the sludge through an auger, with the coal being fed through a separate auger.

The bed temperature was controlled by a PID controller acting on the speed of the coal feed screw. The sludge feed rate was controlled by hand, with the sludge feed rate being calculated from the screw RPM. The procedure was as follows:

- The bed was fluidised, and a diesel burner was used to bring the bed temperature up to 600 ºC.
- Coal was fed, and the temperature brought up to 700 ºC, when the burner was cut off.
- The bed temperature was further increased to 900 ºC by coal addition, and the system was left to run to "thermally soak" the refractory lining.
- The coffee ground sludge was introduced slowly, using a slow screw RPM and intermittent feeding.
- The bed cooled down, as would be expected, causing the coal feed rate to increase.
- The oxygen content of the off gases was noted.
- The coffee grounds rate was slowly increased, until the oxygen content of the off gases was in the region of 5% to 6%. This corresponds to an excess air level of approximately 30% to 40%, which is the same as would be expected from a conventionally-fired FBC unit. Note: In this case direct formation of steam in the bed (from vaporisation of the water in the sludge) is providing the cooling (and therefore consuming the coal and oxygen to counteract this cooling) that in-bed heat transfer surfaces would do in a conventional FBC boiler.

The unit was run for a period of approximately four hours, during which time readings were taken of all pertinent data. The data was used to generate a heat and mass balance over the bed.

The highest coffee ground to coal ratio which was achieved was 4.2:1. The thermal balance over the bed resulting from this run is given in Table 2C. The figure "heat in fuel" is simply the total mass of coal and sludge times the weighted gross calorific value (GCV). In order to make the balance hold, an additional figure has to be introduced, i.e. "Heat unavailable in fuel". This is the fraction of heat available in the fuel which in theory should be evolved in the bed, but in practice is not. It is approximately 7% of the total heat. If the assumption is made that this "loss" of heat arose solely from a fraction of the coffee grounds burning above the bed instead of in the bed, then it can be calculated that 20.1% of the available heat in the coffee grounds was not evolved in the bed. It is for this reason that it was not possible to reach a ratio of 5:1. This obviously has implications for the design of the planned boiler's combustion zone. Further, if the worst case is taken, i.e. a ratio of 6:1 when the boiler is producing only 21 t/h steam, a negative heat loss is seen (Table 2D). This implies that more heat would be lost from the bed than could be generated in it, resulting in loss of bed temperature and, eventually, loss of ignition.

The only way to overcome this situation is to partially dry the coffee grounds before they reach the bed, thus lowering the "heat lost due to moisture in fuel" component and bringing the balance back to a favourable state. The easiest way to achieve this drying is to allow some of the water to flash off in the freeboard. Also shown in Table 2D is a thermal balance over the small scale FB in which the heat lost to moisture in fuel component has artificially been reduced in order to make the balance hold. This shows that 31.7 MJh^{-1} of heat must be supplied to the fuel in the freeboard in order to drive off sufficient water to enable the bed to operate at 900 ºC. This is equivalent to 7.77 kgh^{-1} water. The coffee grounds originally contained 58.5 kgh^{-1} of water, i.e. 13.3% of the water in the coffee grounds must be flashed off in the freeboard in order that the bed can maintain temperature when firing at a ratio of 6:1.

In order to test the feasibility of this, a further test was carried out. Small pellets (approximately 5mm diameter) were subjected to a 900 ºC environment for 2 seconds (this being the time that they will, on average, spend in the freeboard). In excess of 18% of the water was removed, showing that the required 13.3% should be achievable. Further, if for some reason more drying is required (for example, if the water content of the fuel should rise) this can be achieved by angling the sludge injection nozzles upwards in order to increase the residence time of the particles in the freeboard.

Such a small amount of water being driven off in the freeboard should not seriously affect the temperature profile there. However, if the process is taken to the extreme, i.e. if all of the coffee grounds are dried and burnt in the freeboard, this will result in a chilling of the gases by almost 300 ºC which will have implications on combustion characteristics and downstream heat transfer surfaces. It is for this reason that suspension firing, as is sometimes employed with bagasse and wood waste, is not feasible.

Nozzle Performance Trials

The first nozzle to be tested was a concentric tube type with annular air, shown in Figure 2. Trials at the client's premises in Estcourt and at the CSIR showed that the sludge could be fired through a nozzle as small as 20mm diameter, provided the reduction from the 75mm line was gradual. However, the degree of dispersion achieved was minimal, even when annular air was employed. Direct injection of air into the sludge line proved much more successful, and the sludge could be fired for several meters with a spread of approximately 2 to 3 metres. The sludge was broken up into particles approximately 5mm in size. Interestingly, the particles appeared to have undergone some drying, even though the ambient air temperature was only about 20 ºC. Placing a deflection plate in the path of the sludge greatly increased dispersion, and a spread of 6 to 10 metres was achieved.

Both these features, i.e. direct air injection and deflector plate, were employed in the nozzle which was built for the trials in the NFBC, although the pipe itself was of a larger diameter (40mm). Cold trials with the nozzle showed that the dispersion achieved with the smaller nozzle could also be achieved with the larger nozzle.

Large-scale Combustion Trials

In order to further prove the ability of in-flight flash evaporation to swing the thermal balance to a favourable state, trials were carried out in the NFBC facility. A side view of the NFBC can be seen in Figure 3. The operating parameters can be seen in Table 3.

The NFBC is of a membrane wall construction, and therefore has cooling surfaces in the bed area. For the purposes of this test, the NFBC was set up to simulate a "hot gas generator", or un-cooled furnace as closely as possible. This was achieved by isolating the bubble caps around the periphery of the bed, thereby creating a stagnant slumped zone between the bed and the membrane wall. This limits heat transfer to the wall to a great extent, but it does not remove it altogether. Prior to firing the coffee grounds, trials were carried out to determine what heat was still being removed from the bed by the membrane walls, in order that this figure could be included in thermal balances over the bed when firing the coffee grounds.

The most difficult aspect of the trials proved to be the pumping of the sludge. Earlier trials had shown that a 50mm double diaphragm pump should be able to handle it, however, when running for periods in excess of 10 minutes a solid cake formed in the chamber which prevented further pumping, and in fact caused one of the pistons in the pump to shatter. The coffee grounds were acting as their own filtration medium, and de-watered themselves.

Another pump was tried (a lobe type, supplied by Mono), which successfully circulated the solids from and back to the 8m^3 storage tank. Unfortunately, an unforeseen problem occurred when firing the sludge to the boiler. The pump would run for periods of up to 30 minutes but would then block. It transpired that what was happening was that, due to the fairly high suction head of the pump, the sludge was again filtering itself and water was preferentially being drawn from the tank. This did not matter when the sludge was being re-circulated, but when it was being fired into the boiler, the remaining sludge in the tank gradually became thicker, resulting in the pump blocking. Due to time pressures, however, it was decided to proceed with this pump and cope with these blockages as best as possible.

It should be noted that these pumping problems would not arise with the planned boiler, as it has already been proven at the client's site that a wide throat auger fed Mono pump can pump the sludge successfully. The problem was simply that such a pump was not available for the trials at the pilot plant in Pretoria West.

To determine what drying took place in the freeboard, a thermal balance was again generated for the bed. After including the factors mentioned and evaluated earlier (i.e. "heat unavailable in fuel" and "heat to in-bed tubes"), a negative heat loss was seen. Since by definition the system did balance (as indicated by the fact that the bed temperature remained stable) it must be that the heat losses from the bed were not as great as would occur if all the coffee grounds dried in the bed. This energy "saving" can be equated to approximately 30% of the water being flashed off in the freeboard rather than the bed.

It should be noted that the chief aim of these trials was to maximise the drying in the freeboard, and a great deal of dispersion (by air injection and a deflector plate) was employed. Physical inspection of the furnace after the tests revealed that the degree of dispersion was actually too great, and some coffee grounds had impinged on the tubes. This had to be avoided in the planned boiler. There are two beneficial factors which indicate that this should be easily achieved.

1. The planned boiler furnace is much larger than the NFBC furnace (28m^2 vs 9m^2).
2. The degree of drying achieved in the NFBC was much greater than actually required (30% vs 13.3%), indicating that a lesser degree of dispersion can be employed.

CONCLUSIONS FROM THE THEORETICAL STUDIES AND TESTWORK

It is necessary to fire the coffee grounds (with a moisture content of 85%) at a rate five times greater than coal in order to generate 26 t/h steam while utilizing the entire 12 t/h of coffee grounds. Further, it is theoretically possible to fire such a composite fuel in an un-cooled fluidised bed (i.e. one with no in-bed heat transfer surfaces) while maintaining a reasonable excess air level.

The worst case situation is when the boiler is producing only 21 t/h steam while still being fed with the full 12 t/h of coffee grounds. In this case, the coffee grounds to coal ratio must be 6:1.

In small-scale trials, however, it proved to be impossible even to reach a ratio of 5:1, with 4.2:1 being the best achieved. This was due to the fact that, although the coffee grounds did dry in the bed, not all of the heat from combustion was released in the bed (approximately 20% over-bed). This situation had to be avoided in the planned boiler as it would lead to less than optimal efficiencies and possibly venting of steam. It is very difficult, if not impossible, to alter the burning characteristics of the fuel, so in order to obtain a ratio of 5 or 6:1, it is necessary to partially dry the coffee grounds before they enter the bed. Calculations show that just over 13% of the water must be removed in order that a ratio of 6:1 can be achieved.

Trials carried out in a muffle oven, where 5mm diameter sludge particles were subjected to a 900 °C environment for two seconds (the mean residence time in the freeboard), showed that in excess of 18% of the water in the fuel could be removed in this time, establishing that in-flight flash evaporation is able to reduce the fuel moisture content by the required amount.
It should be stressed that this drying is required in order that an <u>un-cooled</u> bed can be operated satisfactorily. Inclusion of in-bed heat transfer surfaces is therefore precluded, as this would have a negative effect on an already adverse heat balance over the bed.

Further drying of the feed in the freeboard, even if physically possible, would lead to another problem, namely excessive cooling of the off gases. If all the coffee grounds were to be dried and burnt in the freeboard, the gases would be cooled by almost 300 °C, assuming no significant radiation to the furnace walls. This lowering of the gas temperature would lead to excessively large heat transfer surfaces in order to recover the heat from the gases. It would also result in poor combustion characteristics in the freeboard.

Trails carried out in a large FBC boiler, the NFBC, confirmed that drying of the fuel can be achieved by dispersing it into the freeboard. In fact, it would appear that a relatively low level of dispersion can be employed in order to achieve the required drying. The degree of drying can be controlled by altering the dispersion and/or the angle of injection. (When the nozzle angle was changed from horizontal to approximately 30° above horizontal, the bed temperature rose immediately.)

A further observation from the NFBC trials was that cooling of the gases in the freeboard must be avoided. The volatile matter arising from the coffee grounds requires a hot environment in order to fully combust. If this is not achieved the result will be that the volatiles may condense out on down-stream heat transfer surfaces. It is for this reason that the freeboard zone of the actual plant was refractory lined, and was not a water wall type of construction. This refractory lining was also intended to aid in the drying of the coffee grounds. To further ensure that all the volatiles are fully combusted, a large freeboard volume was selected, with the refractory lined zone being in the order of 4 to 5 metres in height.

In order to optimise the amount of coffee grounds which could be incinerated a sophisticated yet user-friendly control system was installed in order to avoid the operator having to constantly perform heat balance calculations. An “operability map” was generated, and incorporated in the control logic, that essentially lets the operator ask the plant to do anything he wants, and will only over-rule him if he is asking it to do something impossible or unsafe. This operability map can be seen as Figure 4. The upper line in Figure 4 is a consequence of the fact that the maximum allowable coffee grounds injection rate is a function of the steaming rate. An additional point of interest on Figure 4 is the lower line. The FD fans are specified to deliver sufficient air to operate the boiler at full load when burning coffee grounds. The boiler cannot be operated at full load without sludge injection, as to do so would have meant unnecessarily over sizing of the FD fans. Therefore, to increase the steaming rate above 70% of the maximum continuous rating (MCR) in the absence of coffee grounds, water may have to be injected as a substitute. Due to the incorporation of the operability map the control system automatically limits the sludge injection rate as the load falls, and also detects if there is a sludge deficiency as the load increases and an appropriate amount of water is injected.

COMMISSIONING AND PERFORMANCE

The plant was commissioned during and after a scheduled Christmas shut down in 1993 by the CSIR and Alstom John Thompson. It was not an easy task to commission the system, as the client consistently had a low steam demand, in the order of 8 to 10 t/h, which was below the turn-down limit of the plant. This was partly due to the fact that the entire coffee plant had not yet been brought on line, but it also turned out to be an inherent problem, as the client had over-estimated his steam requirements. It was eventually commissioned with a fair amount of steam venting. Later in January 1994 the steam demand rose to about 14 to 18 t/h, and the plant was able to run more satisfactorily. The entire coffee grounds production was successfully incinerated during 1994, but there were continuing operational problems due to the low steam demand. The client took the opportunity of the next Christmas shutdown to request the commissioning team to return to modify the FBC to allow operation at the lower steam demand while still burning close to the design mass of coffee grounds. This involved major changes to the plant. The FD fan dampers were discarded, and air flow control was achieved by installing frequency inverters on the motors. (This resulted in considerable power cost savings rather than choking back the existing fans.) New impellers were also installed. The air distribution caps were modified, essentially by blocking off two of the twelve nozzles. In addition, all peripheral nozzles were completely blocked off, effectively reducing the bed size. It was successfully re-commissioned and has been running continuously ever since. The CSIR was awarded the South African Institution of Chemical Engineers (SAIChE) Innovation award for the plant.

THE EFFECT OF DEWATERING THE COFFEE GROUNDS

The design of the boiler was based not only on technical issues, but was also driven by economic conditions prevailing at the time, with capital being relatively expensive and energy being relatively cheap. Hence the decision not to dewater the coffee grounds, as the capital equipment required (presses and evaporators or a treatment plant for the press water) could not be justified. In 2005, with different economic conditions where capital is relatively cheap and energy is relatively expensive, a study was undertaken to look at the possible benefits of dewatering the coffee grounds and feeding them with the coal.

Table 4 shows the calculated amount of coal required to steam at different loads with varying coffee grounds moisture content. It can be seen that by dewatering the grounds from 88% moisture to 62% moisture, almost 1 ton per hour of coal can be saved. Table 5 shows the calculated boiler efficiency with the same parameters. The data at Maximum Continuous Rating (MCR) are shown graphically in Figure 5 and Figure 6.

The client is currently evaluating the option of dewatering the grounds.

TABLE 1: Composite Fuel Table

COMPONENT		COAL	COFFEE	TOTAL (Mass)	COMPOSITE FUEL
CV	MJ/kg	26.60	3.77		7.56
Rate	kg/h	2 385.00	12 000.00	14 385.00	14 385.00
C	%	67.70	10.53	2 878.42	20.01
H	%	3.40	0.71	166.59	1.16
O	%	7.00	3.64	603.15	4.19
N	%	1.60	0.01	39.41	0.27
S	%	0.00	0.03	3.74	0.03
Ash	%	14.60	0.08	357.76	2.49
H_2O	%	5.70	85.00	10 335.95	71.85

COMPONENT	kg/h	%	Mols/h	Mols O_2 Reqd	Mols Gas Formed (Incl. Comb. Air)	Mols Incl. Excess Air	Dry Gas Comp
Rate	14385.0	100.0					
$C(CO_2)$	2 878.4	20.0	239.87	225.48	225.48	225.48	14.50
$H(H_2O)$	166.0	1.2	166.59	41.65	83.29	83.29	
$O(O_2)$	603.2	4.2	37.70	-18.85	0.00	82.71	5.32
$N(N_2)$	39.4	0.3	2.81	0.00	935.83	1 247.00	80.18
$S(SO_2)$	3.7	0.0	0.12	0.12	0.12	0.12	0.01
Ash	357.8	2.5	0.00	0.00	0.00	0.00	
$H_2O(H_2O)$	10 335.9	71.9	574.22	0.00	574.22	574.22	

Total Mols O_2 Reqd. (Stoich.): 248.39
Associated Mols N_2 (Stoich): 934.42
Excess Air Level (%): 33.30
Mols Excess O_2: 82.71
Mols Excess N_2: 311.16

Mols wet: 2 212.82
Mols dry: 1 555.30
Mols Air: 1 578.48

TABLE 2A: Theoretical Thermal Balance Over FBC Boiler

	MJ/h	%
Heat in fuel	109 326.00	100.00
Heat transferred to steam (thermal efficiency	58 657.88	53.65
Heat lost in ashes	5 894.25	5.39
Heat lost due to moisture in fuel	28 456.35	26.03
Heat lost due to hydrogen in fuel	4 274.39	3.93
Heat lost in dry flue gases	7 953.58	7.28
Heat lost due to humidity of air	58.28	5.33
Overall accountability	105 294.70	96.31
Therefore radiation, convection and unaccounted losses =	4 031.28	3.69

TABLE 2B: Theoretical Thermal Balance over Fluidised Bed

	MJ/h	%
Heat in fuel	109 326.00	100.00
Heat lost in ashes	6 116.28	5.59
Heat lost due to moisture in fuel	43 000.16	39.33
Heat lost due to hydrogen in fuel	6 458.99	5.91
Heat lost in dry flue gases	46 000.76	42.08
Heat lost due to humidity of air	340.67	0.31
Overall accountability	101 916.90	93.22
Therefore radiation, convection and unaccounted losses =	7 409.13	6.78

TABLE 2C: Actual Thermal Balance, Small-scale FBC

	MJ/h	%
Heat in fuel	453.53	100.00
Heat unavailable from fuel	30.79	6.79
Heat lost in ashes	13.33	2.94
Heat lost due to moisture in fuel	172.99	37.92
Heat lost due to hydrogen in fuel	23.78	5.24
Heat lost in dry flue gases	198.52	43.77
Heat lost due to humidity of air	1.48	0.33
Overall accountability	440.22	97.00
Therefore radiation, convection and unaccounted losses =	13.60	3.0

TABLE 2D: Thermal Balance for Extrapolated Ratio of 6:1, Small-scale FBC

	NO DRYING		WITH DRYING	
	MJ/h	%	MJ/h	%
Heat in fuel	513.52	100.00	513.52	100.00
Heat unavailable from fuel	43.43	8.46	43.43	8.46
Heat lost in ashes	14.89	2.90	14.89	2.90
Heat lost due to moisture in fuel	241.22	46.97	209.52	40.80
Heat lost due to hydrogen in fuel	29.02	5.65	29.02	5.65
Heat lost in dry flue gases	199.78	38.90	199.78	38.90
Heat lost due to humidity of air	1.47	0.29	1.47	0.29
Overall accountability	529.82	103.17	498.11	97.00
Therefore radiation, convection and unaccounted losses =	-16.30	-3.17	15.41	3.00

TABLE 3: NFBC Boiler Operating Parameters (Basis: Duff Coal)

Steam flow (kg/h)	12 000
Steam conditions:	
Pressure (MPa)	1.5
Temperature (super heater) (°C)	255
Feed water temperature (°C)	95
Bed temperature (°C)	780 - 900
Bed dimensions (m)	3.05 x 3.05
Super heater area (m^2)	2.35
Sulphur capture (%)	80
Boiler turndown	3:1
Boiler efficiency (%)	80
Max. Freeboard velocity (m/s)	1.9
Exit. Flue-gas temperature (°C)	170

TABLE 4: Coal Feed Rate at Varying Moisture Content and Load

Coffee grounds Moisture (%)	Steam flow (tons/h)		
	16	20	26
62	1.08	1.56	2.33
75	1.25	1.75	2.50
80	1.44	1.90	2.65
88 (design)	1.90	2.41	3.10

TABLE 5: Thermal Efficiency at Varying Moisture Content and Load

Coffee grounds Moisture (%)	Steam flow (tons/h)		
	16	20	26
62	65.7	67.2	68.7
75	60.3	62.6	65.0
80	57.1	59.8	62.6
88 (design)	48.0	51.8	55.5

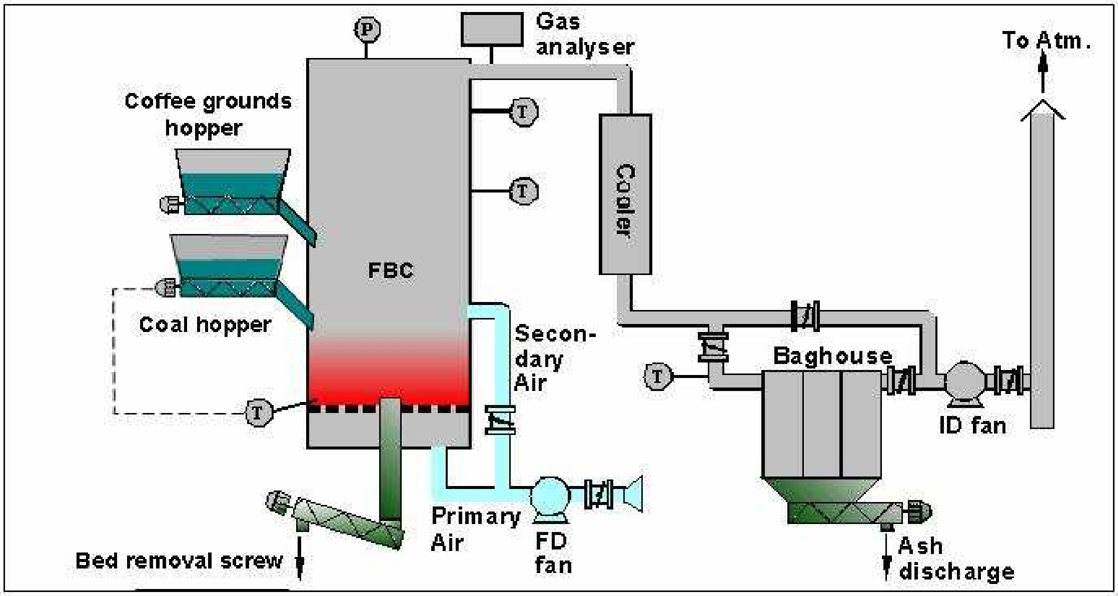

Figure 1: Pilot Plant Flowsheet

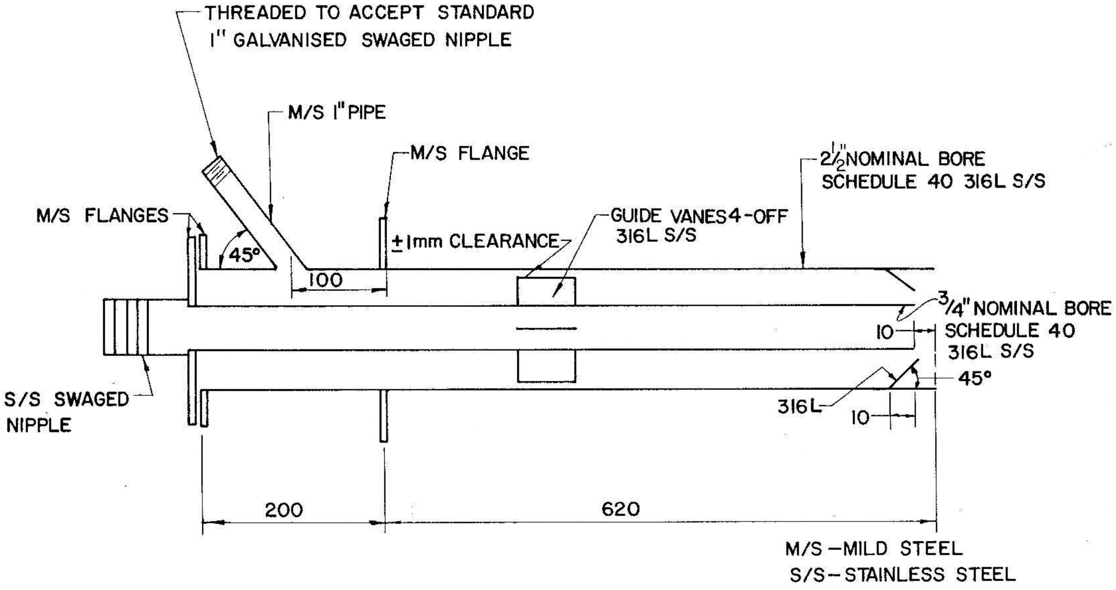

Figure 2: Coffee Grounds Injector

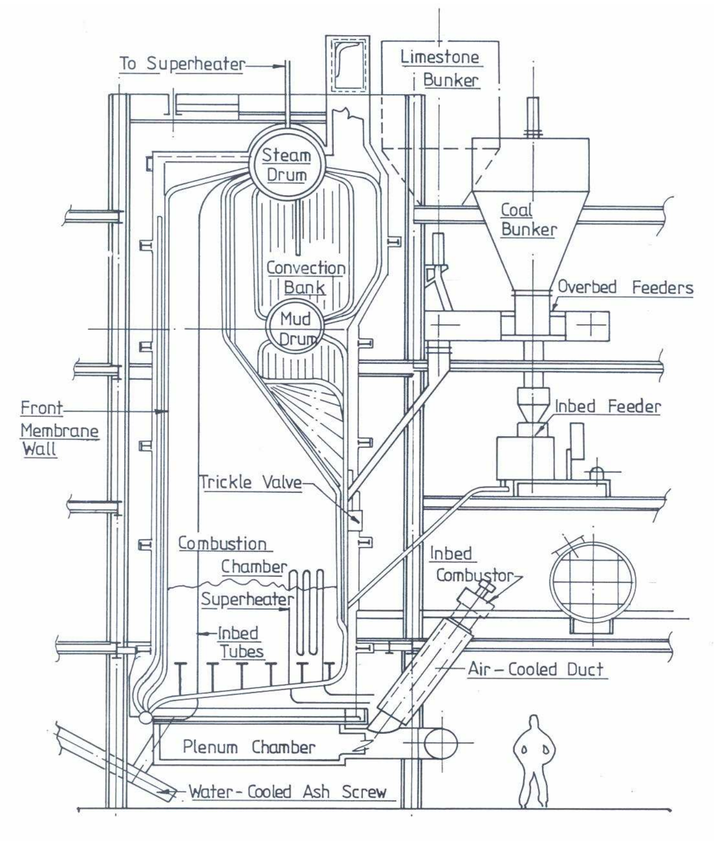

Figure 3: Sectional Side View of NFBC Boiler

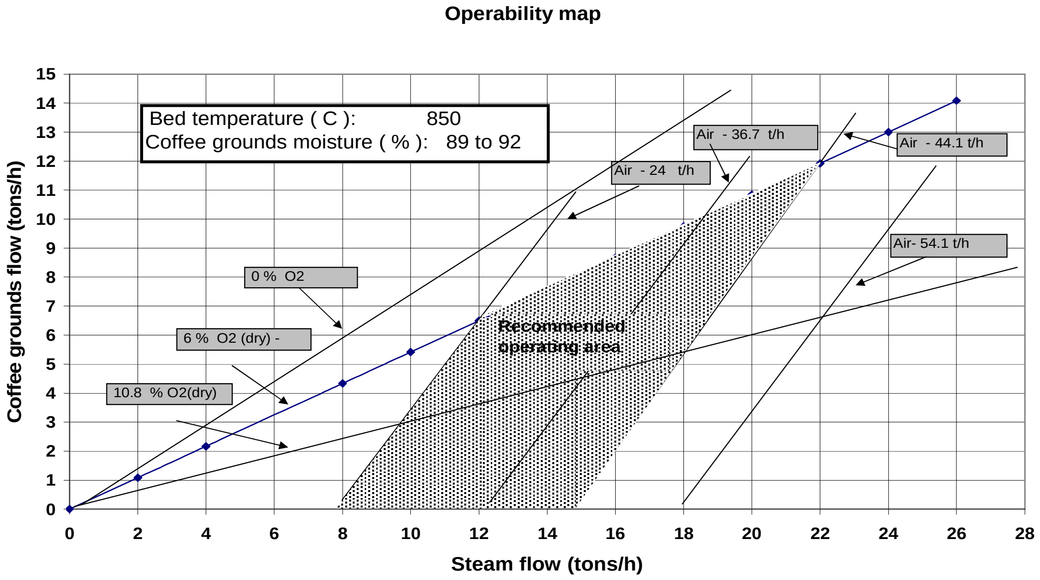

Figure 4: Operability Map

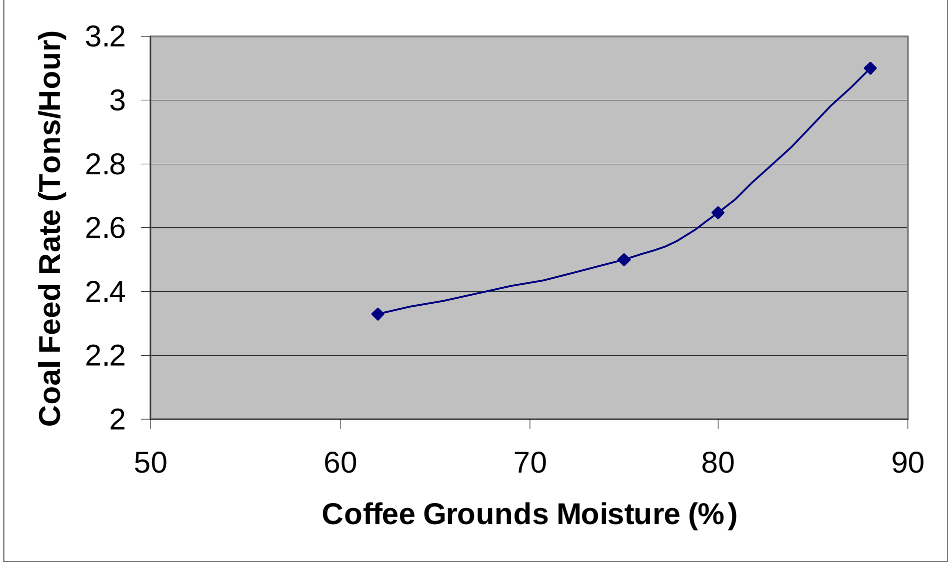

Fig. 5: Coal Feed Rate Vs Moisture at MCR

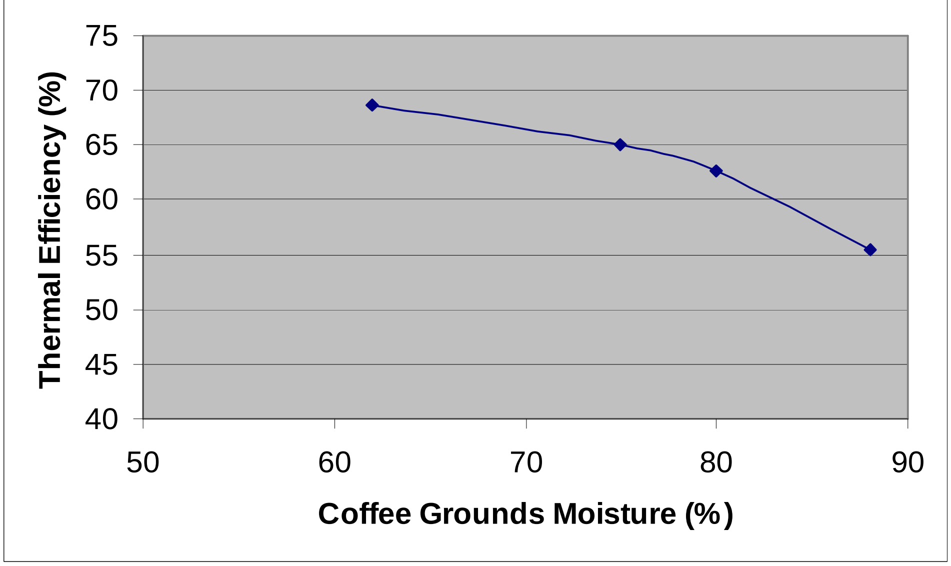

Fig. 6: Thermal Efficiency Vs Moisture at MCR