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DESCRIPTION OF THE MARK II ATMOSPHERIC FLUIDIZED BED COMBUSTOR AT THE CANADIAN COMBUSTION RESEARCH LABORATORY

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DESCRIPTION OF THE MARK II ATMOSPHERIC FLUIDIZED BED COMBUSTOR AT THE CANADIAN COMBUSTION RESEARCH LABORATORY

by

D.R. Hector**, D.L.Desai**, F.D. Friedrich* and E.J. Anthony*

ABSTRACT

The facilities for fluidized bed research at the Canadian Combustion Research Laboratory at CANMET's Bells Corners Complex near Ottawa have been improved recently by the development of a pilot-scale combustor suitable for testing a wide variety of solid fuels. The major features of the new facility are a 380 mm x 400 mm Atmospheric Fluidized Bed Combustor (AFBC) with variable in-bed cooling, capability of feeding a variety of fuel sizes both in-bed and over-bed, sulphur sorbent injection, and fines recycle. The combustor and its auxiliary equipment are described in detail and CCRL's current capabilities for AFBC research are outlined.

The facility was brought to the point of operability in March 1981, although elements of the gas clean-up system are not yet in service. Preliminary testing using Klimax lignite from Saskatchewan demonstrated satisfactory performance of the combustor. The R & D program planned for the next few years will expand on previous research conducted on a smaller AFBC at CCRL, and is designed to provide information necessary for the design of full-scale fludized bed combustion.

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INTRODUCTION

About 1975 the Canadian Combustion Research Laboratory (CCRL) began a program of research and development on atmospheric fluidized-bed combustion (AFBC), and erected a small pilot-scale combustor, known as the Mark I combustor. This had an inside diameter of 240 mm and subsequently was used for several studies of fuel performance (1,2,3). However, its configuration and small size placed severe restrictions on the range of variables which could be explored, and some of its major drawbacks are listed below.

1. Heat input rate was restricted to about 400 MJ/H, rather too small for reliable extrapolation of results to industrial-size units.
2. The combustor design incorporated an Inconel liner which had a service life of only 100 to 200 h.
3. The combustor was circular in section, which was not typical of full-scale equipment, and probing of the bed and freeboard regions.
4. There was no in-bed cooling. This made it difficult to control bed temperature and impossible to measure bed-to-tube heat transfer rates.

As both the potential applications of FBC technology to the Canadian energy picture and the need for supporting R & D became apparent, a decision was made to support the development of a larger, more versatile pilot-scale combustor at (CCRL), and the new facility "Mark II" described in this report is the result. Its main features are as follows:

1. The combustor is approximately square in section, (380 mm x 400 mm) and fabricated from refactory brick. This allowed fairly simple construction and substantially more latitude in providing for the insertion of probes.
2. The cross-sectional area, and therefore the maximum heat input rate, is approximately three times greater than the Mark I combustor. Reliability in extrapolating results to full-scale is thus increased, although operating costs are still modest.
3. Provision has been made whereby anywhere from 0 to 48 water-cooled tubes can be inserted in the bed. Thus bed heat extraction can be matched to the requirements of a wide variety of fuels, in-bed heat transfer rates can be measured, and corrosion/erosion mechanisms in the bed can be studied.

4. Solid fuel in a variety of sizes up to 50 mm can be fed, either over the bed or directly into it.
5. Sulphur sorbents such as limestone can be fed into the bed at variable rates through a separate feed system. This circumvents the need to premix sulphur sorbents with the fuel.
6. Fly ash trapped by a primary cyclone system can be reinjected into the bed to improve the efficiency of carbon combustion and limestone utilization.

With the Mark II fluidized-bed combustor now in place and commissioned, (CCRL) is in an excellent position to conduct research on the full range of Canadian solid fuels which may be utilized by this technology, and the base of information required for the design and implementation of full-scale FBC systems.

DESCRIPTION OF THE 380 mm x 400 mm PILOT-SCALE AFBC

General Description

The Mark II pilot-scale AFBC facility consists of a combustor with a variable number of in-bed water-cooled tubes, a freeboard section with cooling coils at the top, a cyclone dust collector with means for fly ash recycle, a gas-to-air heat exchanger downstream of the dust collector, a baghouse, and a stack. To this are added fuel and sulphur sorbent feed systems, blowers to provide air for combustion and cooling, an induced draft fan, and comprehensive instrumentation.

The combustor and freeboard consist of 9 sections staked one upon another, bolted together by means of flanges, with the joints sealed by Fibrefrax rope gaskets and silicone caulking compound. This assembly stands approximately 4.8 m high and has outside dimensions of 0.94 m x 0.97 m. The internal cross-sectional area is constant at 0.15 m^2. Brackets at the lowest freeboard section transfer the weight of the combustor and freeboard assembly to a framework of tabular steel columns. A major advantage of this centre support system is that the windbox can be readily removed from below, giving access to the distributor plate and the entire combustor shaft, without dismantling any other part of the combustor. Figures 1 and 2 show details of this assembly.

Windbox and air distributor

The lowermost section of the combustor consists of a windbox with an air distributor fixed to the top of it. The windbox is constructed of mild steel 6.3 mm thick and is equipped with an explosion relief vent. The air distributor, which forms the floor of the combustion zone, is a steel plate 380 mm square and 9.5 mm thick, fitted with 100 bubble caps for dispersing the air uniformly into the fluidized-bed. The bubble caps are arranged in a 35 mm x 38 mm rectangular pitch, as shown in Figure 3, and those on the perimeter serve to fasten the air distributor to the windbox. The bubble caps were made from stainless steel bolts 13 mm diam. x 32 mm long by drilling an air passage 6 mm diam. up the bolt axis and drilling four 3 mm diam. air nozzles at right angles under the bolt head, as shown in Figure 4. With this configuration the bolt head serves as a shield to prevent bed material from weeping through the air passages into the windbox. The air nozzles are located about 20 mm above the plate and thus leave a layer of non-fluidized bed material which thermally insulates the plate from the high temperatures of the combustion zone.

Air for fluidization and combustion is supplied by a centrifugal blower which has sufficient capacity to provide fluidizing velocities of up to 4 m/s, at the design firing rate. The air enters the windbox via a pipework system which contains flow metering and control equipment. Pressure drop across the air distributor varies from about 150 mm to 250 mm w.g. at fluidizing velocities of 1 to 3 m/s.

Active bed zone

The active bed zone extends for about 1400 mm above the air distributor. For convenience in assembly and maintenance this was fabricated in two sections approximately 750 mm and 650 mm in height. The pressure capability of the present fluidizing air blower limits the fluidized-bed depth to about 0.75 m when silica sand in the size range of 0.85 to 1.70 mm is used as bed material, but the splash zone above the bed must also be considered part of the active bed.

Except for the bed tube retainers described later, the active bed zone is lined, with an inner course of 114 mm thick firebrick backed by two courses of 64 mm thick high density insulating brick. The brickwork is encased by a mild steel shell 6.3 mm thick and a 30 mm layer of insulating castable refractory fills the space between the brickwork and the shell. This construction is typical of the freeboard sections as well as the active bed zone, and is shown in cross-section in Figure 5.

On each of two opposite sides of the active bed zones immediately above the air distributor, is a water-cooled bed tube retainer 650 mm high, 560 mm wide and 127 mm thick. As shown in Figure 6, the retainers are each penetrated by 48 guide sleeves which have an I.D. of 35 mm and are arranged on an 81 mm triangular pitch. Each sleeve is aligned with its counterpart across the combustor, thus each pair provides a path by which a tube can be passed through the bed. The retainers are set back approximately 75 mm from the inside surface of the combustor and this space is filled, between the guide sleeves, with castable refractory which serves to minimize the heat loss to the retainers during operation.

The amount of heat which must be removed from the fluidized-bed to maintain a target bed temperature depends upon the moisture content of the fuel, the firing rate, the excess air level, the desired bed temperature and the calorific value of the fuel. While it is expected that the bed cooling requirements of the combustor can in most cases be met with less than 20 cooling tubes, the provision for 48 allows considerable flexibility in vertical and horizontal spacing. This will be useful when research is expanded beyond the measurement of heat transfer rates to studies of boiler tube corrosion in fluidized beds and the effect of immersed tubes on bubble growth.

The cooling tubes are straight sections of stainless steel pipe, 15.8 mm I.D. (½ in. nominal pipe size) approximately 381 mm long. By means of hoses they can be externally connected through flowmeters to a water supply line in series or parallel circuits as desired. To seal off the combustor where the cooling tubes pass out of the guide pipes, bushings with 'O' rings are used as shown in Figure 7. The guide sleeves can also be used as ports for measuring probes or fly ash reinjection; unused sleeves are simply capped off with a blank insert to prevent the sleeve filling up with bed material.

Fuel and limestone can be injected into the lower part of the bed through a horizontal feed port located about 100 mm above the distributor plate. The feed mechanism itself is described in a later section. An identical feed port located 1.2 m above the distributor, and thus normally in the freeboard region, can be used when an overbed feed mode is desired.

To maintain a constant bed level during operation, it may be necessary to either add bed material or remove bed material, depending upon the fuel being fired. If for example, the fuel is low in ash, attrition and subsequent elutriation may progressively reduce the bed inventory. In that case additional bed material such as silica sand can be added by means of a small hopper connected to the fuel feed system. However, if a high-ash fuel is being fired, or if a sulphur sorbent such as limestone is being added with the fuel, then bed inventory is likely to increase, and removal of bed material is necessary to maintain constant bed level. The Mark II combustor has two means of removing bed material. One is a simple overflow pipe, having its inlet in the combustor wall 1 m above the distributor plate, and inclined downward at an angle of 45° from the horizontal. It automatically maintains a bed height of 1 m, provided that the material collected in the pipe is periodically removed through a valve at the discharge end. The other means for removing bed material is a horizontal pipe penetrating the combustor wall just above the distributor plate. It is equipped with a valve and a manually-operated screw, and can be used to maintain any desired bed level.

Three observation ports are located on three sides of the combustor. One consists of a horizontal pipe, 76 mm I.D., located 1.07 m above the distributor plate, opposite the overbed feed port. Its outside end is fitted with a pyrex glass window and it is serviced with a compressed air line to clear out accumulated bed material and provide cooling. A similarly constructed port, but 76 mm I.D. and inclined at 45° to the horizontal, is located at 1.2 m above the distributor plate. It provided a view of the fluidized-bed surface. The third port is an 88 x 159 mm rectangle located 813 mm above the distributor plate. It can be fitted with a saphire window flush with the inside wall of the combustor, and thus provide a view of bubble movement through the bed.

Freeboard and Freeboard Cooler

The freeboard region extends above the active bed zone for a distance of about 1.9 m and is made up in three sections, the lowest of which is the supporting point for the entire combustor. These sections are fabricated of mild steel and are lined with refractory in a manner identical to the active bed zone, thus they form a near-adiabatic zone in which residual combustion reactions can proceed and elutriated material has an opportunity to disengage from the gas stream.

Placed above the freeboard sections are two short sections, each approximately 125 mm high, each containing a water-cooled heat exchanger consisting of 8 passes of 15.8 mm I.D. steel pipe, arranged as shown in Figure 8. These coils reduce the flue gas temperature by 175° to 225°C. Thermocouples and flowmeters make it possible to measure the quantity of heat removed.

Finally, above the freeboard heat exchanger sections, is a refractory-lined tapered section which funnels the flue gases into a discharge spout, to which is attached a 200 mm I.D. flexible stainless duct. The tapered, or roof, section, is fitted with several ports through which gas sampling probes and thermocouples are inserted.

Dust collector and gas/air heat exchanger

The afore mentioned flexible stainless steel duct transports the flue gas, now at 600° to 700°C, to a small multicyclone dust collector which contains three cyclone elements arranged in parallel. Its nominal performance specifications are 90% efficiency in collecting particles equal to or greater than 10 microns in size, at a pressure drop of 50 mm W.C. To maintain cyclone pressure drop, and thus collection efficiency, at low gas flow rates, one or two of the cyclone elements can be blocked off. The dust collector hopper has a hopper bottom terminating in a rotary air lock by which the cyclone product can be removed. The entire assembly is insulated and is suitable for operation at about 600°C.

Cyclone product discharged from the rotary air lock is collected in a small drum for subsequent analytical work to determine carbon loses. Alternatively, in order to improve carbon combustion efficiency and limestone utilization the cyclone product can be directed into a pneumatic transport system which reinjects it into the fluidized bed.

Gases exiting the dust collector pass into a gas-to-air shell and tube heat exchanger designed to reduce the flue gas temperature to about 120°C. The gases travel consecutively through three vertical passes each consisting of six tubes, 76.2 mm I.D. x 2.8 m long. Fresh cooling air, supplied at the rate of 1.5 m^3/s by an induced draft fan, travels across the tubes from the bottom to the top of the heat exchanger around 9 baffles, as shown in Figure 9.

Baghouse

At the bottom of the heat exchanger the third gas pass discharges into a duct having an inside diameter of 200 mm and a straight vertical section 2 m long. This is equipped near the upper end with ports through which isokinetic dust sampling can be carried out. The duct terminates at a small baghouse, 0.83 x 1.28 x 2.44 m high, containing 40 fine-woven cotton sateen filter bags. The baghouse is designed to remove all particles greater than 0.3 micron, at flow rates between 0.14 and 0.38 m^3/s with a pressure drop in the range of 133 to 165 mm W.C. On-line bag cleaning is accomplished by means of a motorized shaker. The baghouse storage hopper has a capacity of 0.42 m^3, and it discharges into a double slide gate arrangement which permits on-line removal of the collected fly ash into a closed container.

The foregoing equipment provides for two methods of determining the amount of fly ash which escapes the cyclone dust collector. One method is to determine the dust concentration by isokinetic sampling of the flue gas in the duct joining the heat exchanger to the baghouse, and then performing the appropriate calculations. The other method is to collect and weigh the dust collected by the baghouse during a specific test period. Both methods provide samples which can subsequently be analyzed for components of interest such as carbon, calcium sulphate and lime.

The clear flue gases from the baghouse are exhausted to the atmosphere by means of an induced draft fan and a stack.

Fuel and limestone feed systems

The fuel and sorbent feed systems must monitor and control the feed rate as well as inject the feedstocks into the bed, and the commercially available systems which fulfil these functions on a small scale are few. CCRL therefore designed the arrangement shown in Figure 1.

A coal hopper fabricated from steel plate and having a capacity of about 300 kg of coal, rests upon an electronic weigh scale. To the bottom of the hopper is fitted a metering screw operated by a variable speed drive. The coal feed rate is controlled by the metering screw and monitored by means of the weigh scale. The metering screw terminates in a small transfer box from which the coal falls through a flexible, wire-reinforced fibreglass hose into a delivery screw, also operated by a variable-speed drive, which in turn injects the coal into the combustor through either the in-bed or overbed feed port. A water-cooled jacket protects the delivery screw from the high temperatures of the combustor whichever feed port is not in use is blocked off by means of a refractory plug, flush to the inside wall of the combustor, and a gasketed flange cover. The flexible hose structurally isolates the weigh scale from combustor. Changing from one feed port to the other requires relocation of the delivery screw and changing of the flexible hose, but the rest of the system is undisturbed. To prevent blow-back of furnace gases through the coal feed system, the coal hopper has a lid which can be bolted on air-tight. In the event that coal flow to the metering screw is intercepted by bridging in the hopper, a form of air cannon which provides a surge of compressed air into the base of the hopper, can be brought into service.

Limestone feed rate is controlled by means of a proprietary feeder which combines a vibrating hopper with a variable-speed metering screw. It has accurate, reproducible metering capability when calibrated, but to avoid the need for frequent recalibration when changing limestone size consist, measurement of feed rate is provided by placing the feeder on an electronic weigh scale similar to the one used for the coal feed system. The limestone metering screw discharges into the transfer box of the end of the coal metering screw; thus the two feed streams together fall down the flexible hose into the delivery screw described previously. With this arrangement the sorbent feed rate can be varied and monitored independently from the fuel feed rate. The limestone feed hopper has a capacity of about 100 kg, and the maximum feed rate is 110 kg/h. Like the coal feed hopper, it has a gas-tight lid to prevent blow-back of furnace gases.

The transfer box has one additional connection; this is from the bottom of a small steel hopper, also equipped with a gas-tight cover. This hopper provides the means for charging bed material, and charcoal for light-off, into the combustor.

Instrumentation

The instrumentation system for the Mark II pilot-scale combustor has been designed to extract as much useful data as possible, and to record it automatically to a large degree, using a programmable datalogger.

The fuel and sorbent supply hoppers rest on electronic weigh scales as already described. The weight of each is recorded at pre-selected intervals by the datalogger, and feed rates can readily be determined from the weight loss. Fluidizing air flow is measured by means of a calibrated orifice; the pressure drop across the orifice is measured by a sensitive manometer, and is recorded manually. The flow of water through the various circuits which cool the bed heat exchange tubes, the fuel delivery screw, the freeboard cooling coils and the bed tube retainers is measured by a bank of rotameters shown in Figure 10. These flow rates are also recorded manually, as are the air and gas pressures at the various locations listed in Table 1, which are measured by a pressure transducer or by manometers. Thermocouples are used to measure temperatures of each circuit. All temperatures are recorded by the datalogger.

Concentrations of CO, CO_2, SO_2, O_2 and NO_x in the flue-gas are continuously monitored by a bank of analyzers shown in Figure 11. The CO, CO_2 and SO_2 analyzers operate on the non-dispersive, infra-red (NDIR) principle, the NO_x analyzer operates on a chemiluminescence principle, while the O_2 analyzer is of the paramagnetic type. All of them have their outputs recorded automatically by the datalogger.

At some future time it is intended to interface the datalogger with a mini-computer, which could store the data and, with suitable programming, carry out much of the data reduction. In this way, much of the manual transcription of data would be avoided.

START-UP AND OPERATING PROCEDURE

The first step in starting up the pilot-scale combustor is to charge it with bed material. Silica sand in the size range of 0.85 to 1.70 mm is normally used, and it is charged via the small hopper and the delivery screw previously described to provide a slumped bed depth of 0.5 to 0.8 m. Then, to ensure that the equipment is protected from overheating, adequate water supply to all the cooling circuits is established. Next the I.D fan is put in service, all the instruments are switched on and the analyzers calibrated.

In order to bring the bed into service it must first be preheated to the ignition temperature of the fuel. Usually 700°C is sufficient and this is accomplished in several steps. First approximately 20 kg of charcoal or reactive coal are charged into the combustor by the same means as the bed material. The fluidizing air blower is then started, the bed is fluidized briefly to mix the charcoal or reactive coal with the bed material, and the bed is slumped by closing the air damper, but leaving the fluidized air blower running. The next step is to add a small charge of charcoal soaked with light oil to the top of the bed, via the delivery screw if it is in the overbed position, or via one of the ports in the combustor. The size of the additional charge ranges from 5 to 35 kg, depending on the number of bed cooling tubes installed. Charcoal rather than coal is used for this, to avoid the danger of forming clinkers. The oil-soaked charcoal is ignited by a torch, air for combustion being provided by opening the fluidizing air damper slightly, but not enough to cause fluidization. When the top layer is burning well the bed is fluidized intermittently for short periods to initiate ignition of the fuel in the bed. The rest of the time only a percolating air flow is maintained, in order to avoid excessive heat loss. When the bed temperature rises to the ignition temperature of the fuel, the fuel feed system is brought into service at a low rate and the air flow is increased to slightly above the minimum fluidizing velocity. A rapid rise in bed temperature signifies full ignition; feed rate and air supply are then adjusted toward the designated test levels, and re-adjusted as necessary as the combustor approaches thermal equilibrium.

From ignition of the oil-soaked charcoal to initiation of continuous fuel feed normally takes 30 to 45 min. An additional 45 to 60 min. are required to bring the combustor to thermal equilibrium. While the light-up procedure just described is reliable, it is somewhat cumbersome and at some future time it may be superseded by a retractable gas-fired or oil-fired light-up burner. In that event the bed would have to be fluidized throughout the light-up period to avoid localized overheating. The ultimate objective is to develop a light-up and hold-fire system which can operate unattended to keep the bed for extended periods, overnight, for example, and thus minimize the time lost in waiting for the combustor to reach thermal equilibrium.

Once the combustor has reached equilibrium at the specified input conditions, data recording and performance of specialized test procedures such as dust sampling can commence. Adjustments are required from time to time to maintain the desired input conditions such as fuel feed rate, excess air level and bed temperature. The fuel feed rate may vary due to inconsistencies in size consist or moisture content, and 'hang-ups' in the fuel hopper may have to be overcome. Bed temperature is usually a major input parameter and its control requires close attention. It can be controlled by adjusting fuel feed rate, excess air level, cooling water flow, and the number of in-bed heat exchange tubes. The first two of these are normally input parameters themselves controlled within narrow limits, hence their usefulness in controlling bed temperature is limited. More commonly, large changes in bed temperature are achieved by changing the number of cooling tubes, while fine tuning is accomplished by adjusting the flow of cooling water.

The combustor shutdown procedure is simple. The fuel metering screw and the limestone feeder are shut off, and when the delivery screw has had time to run empty it, too, is shut off. Flow of fluidizing air and cooling water are maintained until the bed temperature drops to about 100°C, which takes about 30 min. Then air, water and all instrumentation can be safely turned off. Cooling gradients have been found to be sufficiently gentle that no damage to the combustor refractory results. Alternatively, once fuel feed has been stopped and bed temperature has begun to fall, the bed can be hot-slumped by turning off the fluidizing air blower. In this case a small flow of cooling water are maintained to prevent overheating of the delivery screw, the bed cooling tubes, and bed tube retainers. The hot-slump procedure is used if the combustor is to be operated again within a few hours, using the same charge of bed material. The bed, when hot-slumped, cools very slowly, and it is possible to re-start some hours later by simply re-fluidizing the bed and initiating fuel feed.

PERFORMANCE PREDICTIONS

In designing test programs it is necessary to predict several aspects of the combustor performance, ranging from relatively simple matters such as the fuel feed rate required to achieve a selected heat input, to more complex matters such as the bed heat exchange surface required. The following example illustrates the procedure.

The heating value of a test fuel is normally determined before combustion tests begin. Calculating feed rate (kg/h) is then a matter of dividing the desired heat input rate (MJ/h) by the heating value (MJ/kg). If the moisture content as fired differs from the moisture content as received, the appropriate correction must be made. The combustor was designed for a maximum heat input of 1400 MJ/h at 20% excess air, and this defines the upper limit on feed rate. Table 2 gives the heating value and maximum feed rate for a number of fuels which have recently been studied at CCRL. The initial deformation temperature of the ash, as determined by the ASTM ash fusion test, is also given, as this defines the upper limit of the bed temperature that can be employed for each fuel.

Calculation of the required bed heat exchange surface involves, for each case, determination of a heat balance for the entire combustor, excluding the freeboard coils. The heat losses are as follows:

- sensible heat in dry flue gas
- latent and sensible heat in fuel moisture
- radiation from the combustor surface
- convection from the combustor surface
- losses to cooling water in bed tubes, bed tube retainers, and delivery-screw water jacket

This ignores minor losses such as sensible heat in the fly ash, sensible heat in drained bed material, and superheat of moisture in the combustion air. The cooling water losses can be determined by calculating the first four losses listed, and subtracting from the heat input, assuming, at this stage, no loss due to unburned carbon.

To calculate the losses, the ultimate analysis of the fuel must be known, and a number of assumptions must be made. For this example Highvale sub-bituminous coal has been chosen; its ultimate analysis and heating value are given in Table 3. The assumptions made are listed in Table 4, and it can be seen that some of these, such as bed temperature, coal feed rate, and excess oxygen level, are in fact test input parameters. Additional assumptions are that the entire bed and freeboard, up to the freeboard cooling coils, are at a uniform temperature, that the combustor exterior has a uniform emissivity, and that the exterior surface area of the combustor is defined by the overall outside dimensions; that is, no correction has been made for protruding ports and flanges.

Calculations on the foregoing basis, using established engineering procedures, lead to the heat loss distribution given in Table 5, which shows that for this specific case the cooling water losses amount to 52% of the heat input. Subsequent measurements have shown the calculations to be accurate within 10%.

The cooling water losses, as previously noted, are divided among the bed tubes, the bed tube retainers, and the delivery screw water jacket. The last two of these are fixed in area, whereas the first is variable, and the purpose of the calculations is to determine what area should be installed for a specific set of test conditions. Further calculation lead to the results summarized in Table 6, which shows that for the specified conditions, a bed tube area of 0.177 m^2 is required, which can be provided by 10 tubes.

In the course of a test program with a single coal, the number of bed tubes required may change several times as heat input, bed temperature and excess air level are varied according to the test matrix. The correct number of tubes can of course be determined experimentally, but this is time-consuming, and it has been found more expedient to develop a computer program to perform the calculations outlined in the foregoing. As further operating experience identifies refinements to the assumptions on which the calculations are based, the dependability and accuracy of the prediction method will be improved.

SUMMARY OF TEST CAPABILITIES

The capabilities of the Mark II fluidized-bed combustor are summarized in Table 7, in terms of what input conditions can be handled, and what measurements can be taken.

The two-screw feed system has been found to perform satisfactorily with coal or coal-like materials, and causes only minor size degradation of the fuel. However, it is not suitable for materials such as wood waste, which tend to pack and jam in small screw feeders. To date CCRL has not attempted to burn liquid fuels in the fluidized-bed, but the experience of others indicates that this is not a difficult problem.

The present system for recycling fly ash from the cyclone dust collector has also performed satisfactorily, but it has not yet been tested in a situation where the recycle rate is several times the fuel feed rate. Since recycle capability is viewed as an important feature, improvements will be made if necessary. There is no capability, and at present no plans for, recycle of fly ash from the baghouse.

The fate of sulphur in the fuel is in many cases adequately traced simply by monitoring the SO_2 content of the flue gases. However, a complete sulphur balance can be carried out by determining the weight and sulphur content of the bed residue and the fly ash streams. CCRL has acquired analytical equipment to rapidly determine the sulphur content of fuel and ash samples for this purpose.

The carbon balance is almost always important, since it defines the combustion efficiency. It requires measurement of the weight and carbon content of each ash stream. The bed residue and cyclone product can be collected an weighed directly; the fly ash escaping the cyclone can be collected in the bag filter and weighed, or it can be calculated from batch-type in-situ dust loading measurements, using the sampling train shown in Figure 12.

An example has already been given of how the thermal balance can be established. The ability to vary the number of bed cooling tubes is one of the most significant features of the combustor design, and instrumentation is such that bed-to-tube heat transfer rates can readily be determined.

The ability to conveniently change bed tubes makes the combustor an excellent facility for studying high-temperature corrosion phenomena in fluidized-beds. CCRL is not planning any work of this nature in the immediate future, but a probe to measure the partial pressure of oxygen in the bed is under development, and will be used, during the course of combustion performance evaluations, to generate information on the atmospheric environment in the bed.

CONCLUSION

It is a common misconception that the role of research and development is completed when a new technology reaches the stage of commercial utilization. In fact, the need for R & D usually continues as long as the technology is in use. A good example of this is provided by CCRL's activities in pulverized-coal-firing technology. Even though this technology has been the standard means for burning coal in large steam generators for over fifty years, R & D effort has had to be increased steadily to meet the new challenges presented by the need to utilize new and often lower-grade coals, the need to broaden the fuel specifications for existing equipment, and the need to meet increasingly stringent environmental regulations.

A similar situation is expected to develop with respect to fluidized-bed combustion technology. Its potential role in the Canadian energy picture is large. It includes the environmentally-acceptable utilization of high-sulphur coal, high-ash coal wastes, relatively unreactive coke or char byproducts of oil sands extraction, and biomass fuels such as wood waste. It may well expand into the development of more efficient cycles for thermal generation of electricity. The role of R & D will by no means be ended when the first commercial FBC boiler is successfully commissioned. Each new fuel, each new sorbent, virtually every application will present new problems.

The pilot-scale research facility described in this report, having excellent flexibility in terms of input conditions and extensive instrumentation and measurement capabilities, provides a new and important tool for fostering the rapid development of FBC to its optimum role in Canada.

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Table 1 - Thermocouple and pressure transducer locations

Thermocouple No.	Location*	Pressure Port No.	Location*
1	-6	1	Windbox
2	55	2	127
3	130	3	318
4	200	4	dust collector inlet
5	320	5	pressure drop across dust collector
6	550	6	pressure drop across air supply orifice plate
7	610		
8	760		
9	880		
10	1190		
11	1470		
12	2130		
13	2440		
14	3260		
15	water inlet		
16	RS tube retainer inlet		
17	LS tube retainer inlet		
18	freeboard cooling coil outlet		
19	delivery screw outlet		
20	air supply entering W/B		
21	air supply upstream of orifice plate		
22	cyclone outlet		

*Numbers refer to distance from top of nozzles (mm)

Table 2 - Maximum feed rate and heating value for several fuels

Name	Rank	Heating Value (as received) MJ/kg	Feed Rate kg/h	Initial Ash Deformation Temperature °C
Onakawana	Lignite A	12.94	108	1149
Klimax	Lignite A	15.17	92	1110
Coalspur	Sub-bituminous B	24.58	57	1327
Judy Creek	Sub-bituminous B	15.81	89	1316
Highvale	Sub-bituminous B	20.84	67	1271
Hat Creek	Sub-bituminous C	19.46	72	1380
Luscar	Sub-bituminous C	26.17	53	1188
Line Creek	M.V. Bituminous	28.24	50	1482+
Sage Creek	M.V. Bituminous	26.38	53	1366
Minto	M.V. Bituminous	25.79	54	1093
Syncrude	Coke	26.17	53	1277
Suncor	Char	33.56	42	1304
Wood[5]	-	14.35	98	-
Peat [5]	-	14.50	97	-

Table 3 - Coal characteristics used for the example heat loss calculations

Ultimate Analysis	
Name	Highvale
Rank	Sub-bituminous
Composition	wt % (dry basis)
Ash	16.02
C	63.54
H	2.54
N	0.78
S	0.24
O (by diff.)	16.88
Heating Value (dry)	24.31 MJ/kg
Moisture	15%

Table 4 - Assumptions for the example heat loss calculations

Location	Temperature °C	Heat Transfer Coefficient kJ/h m^2 °C
Ambient	25	-
Bed and freeboard	900	-
Outside combustor wall	50	-
Bed tube retainer wall (inside)	150	-
Bed to combustor wall	-	5.4
Bed to water	-	1500.6*
Cooling water inlet	4	-
Cooling water outlet (max)	80	-
Exposed area of combustor = 13.4 m^2		
Emissivity of combustor wall = 0.65		
Coal feed rate (dry) = 30 kg/h		
Excess O_2 in flue gas = 5%		

*based on inside surface area of tube

Table 5 - Heat loss distribution resulting from the example heat loss calculations

Source	% of Input
Loss to flue gases	37.0
Moisture loss	1.7
Convective loss	8.6
Radiation loss	0.7
Cooling water losses (by diff.)	52.0
	100.0

Table 6 - Distribution of cooling water losses and bed tube requirements resulting from the example calculations

Total cooling water flow req'd	5.26 USGPM
Distribution of cooling water losses	% of total
Bed tube retainers	40.0
Delivery screw water jacket	1.0
Bed tubes	59.0
	100.0
Bed tube cooling water flow req'd	3.10 USGPM
Bed tube area req'd	0.177 m^2
No. of bed tubes req'd (½ in. nom. pipe x 380 mm)	10

Table 7 - Summary of capabilities of the Mark II combustor

Input Capabilities

- Burns coal or coke with a particle size range up to 50 mm
- In-bed or over-bed feed
- Separate limestone feed to provide a wide range of Ca/S ratio
- Bed depth up to 1 m
- Bed temperature range 700 to 1200°C
- Heat input range 500 to 1400 MJ/h
- Excess O_2 in flue gas range 0 to 10%
- Superficial fluidizing velocity range 1 to 4 m/s
- Optional recycle of fly ash from cyclone dust collector
- Bed heat exchange area range 0 to 0.90 m^2 (inside surface area) (0 to 48 tubes)

Measurement Capabilities

- Complete sulphur balance
- Complete carbon balance
- Complete solids balance
- Complete thermal balance, including measurement of heat extracted by the bed cooling tubes and determination of heat transfer coefficients between the bed and cooling tubes
- Continuous flue gas analysis for CO_2, CO, O_2, SO_2 and NO_x
- Temperature throughout the system
- Pressure throughout the system

Table 8 - Range of operating conditions*

Parameter	Range
Input	
Bed temperature	700 - 1100°C
Heat input rate	500 - 1400 MJ/h
Excess O_2 (in flue gas)	2 - 10%
Fluidizing velocity	1 - 4 m/s
Ca/S ratio	0 - 5
Output	
CO conc.	100 - 1000 ppm
CO_2 conc.	10 - 18%
NO_x conc.	50 - 200 ppm
SO_x conc.	50 - 6000 ppm
Carbon carryover	1 - 5%
Elutriated Material	
Ash	75 - 100%
Limestone	0 - 30%
Bed material	0 - 10%

*Output parameters will be dependent on coal composition

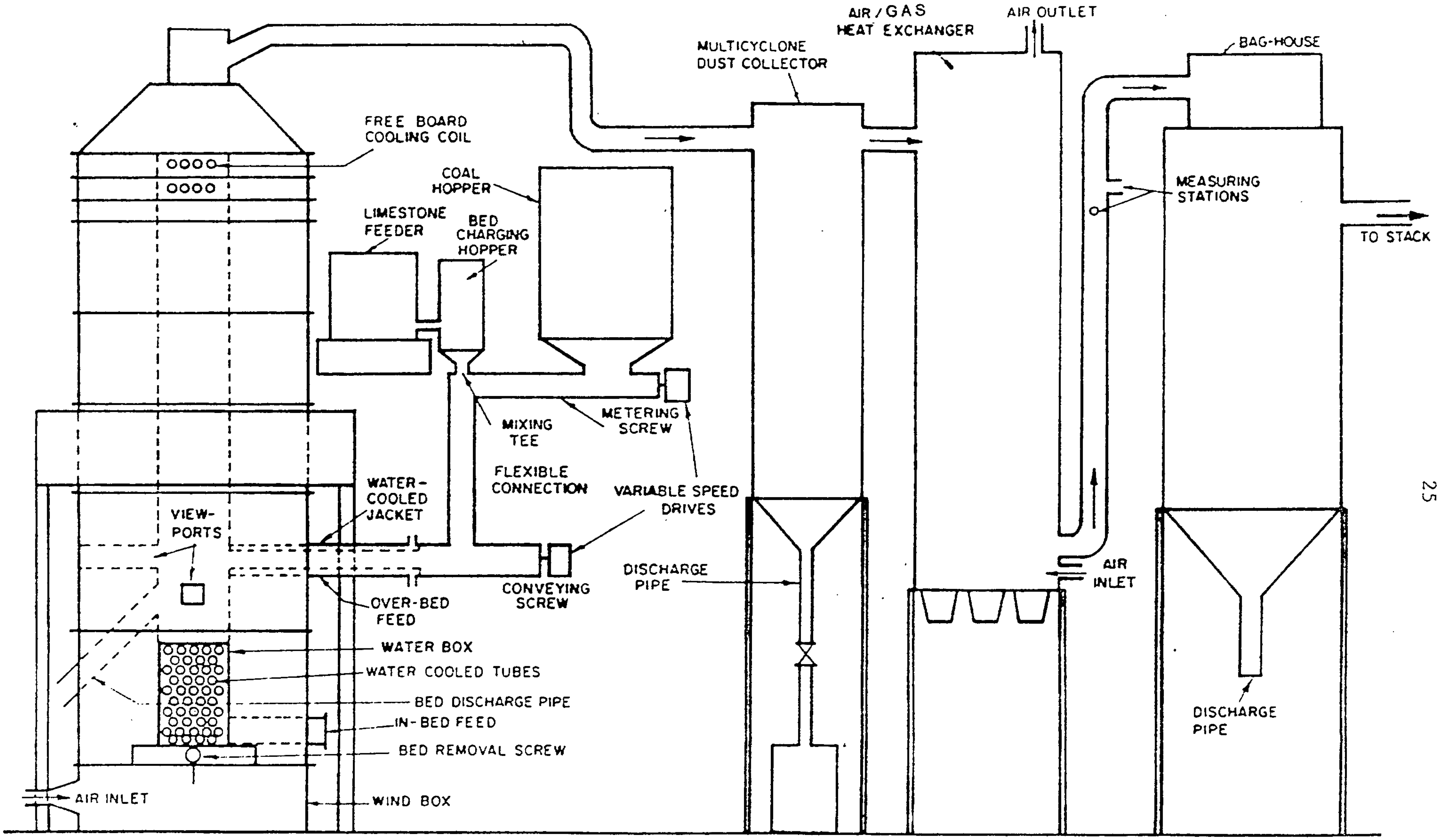

Fig. 1 - Schematic of Mark II combustor

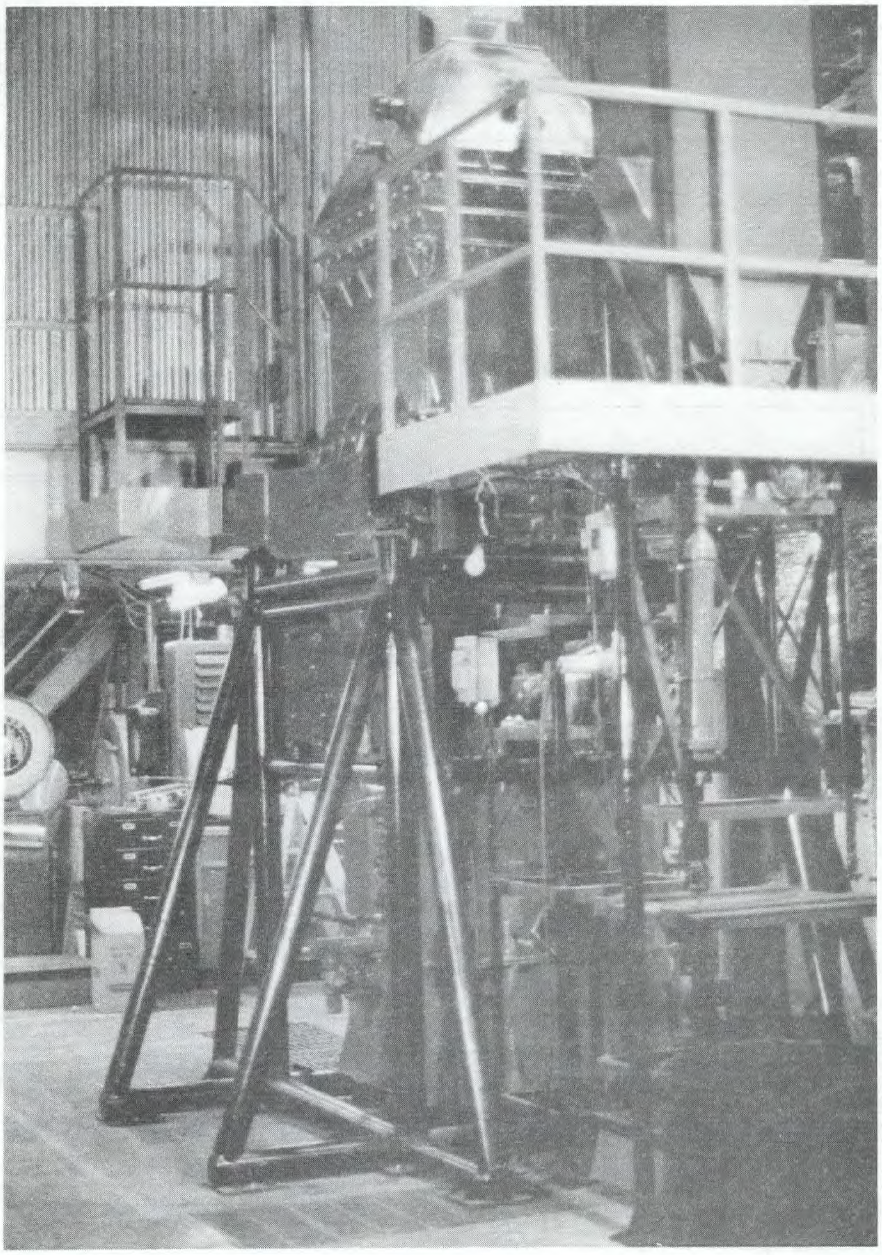

Fig. 2 - View of Mark II combustor

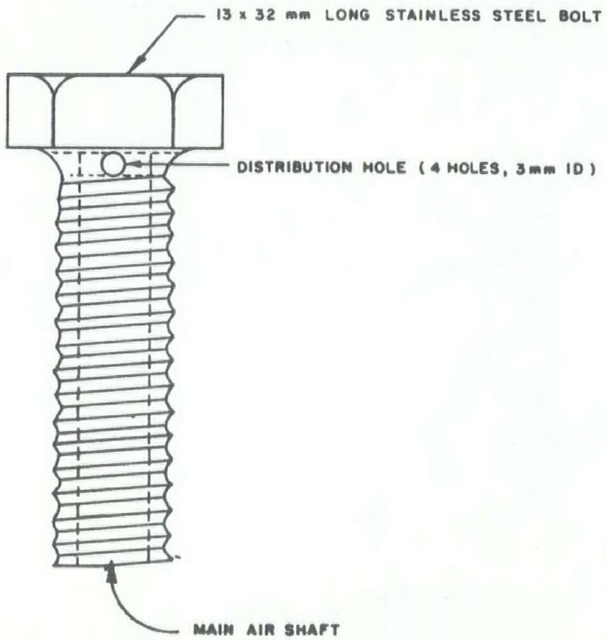

Fig. 4 - Detail of air distribution nozzle

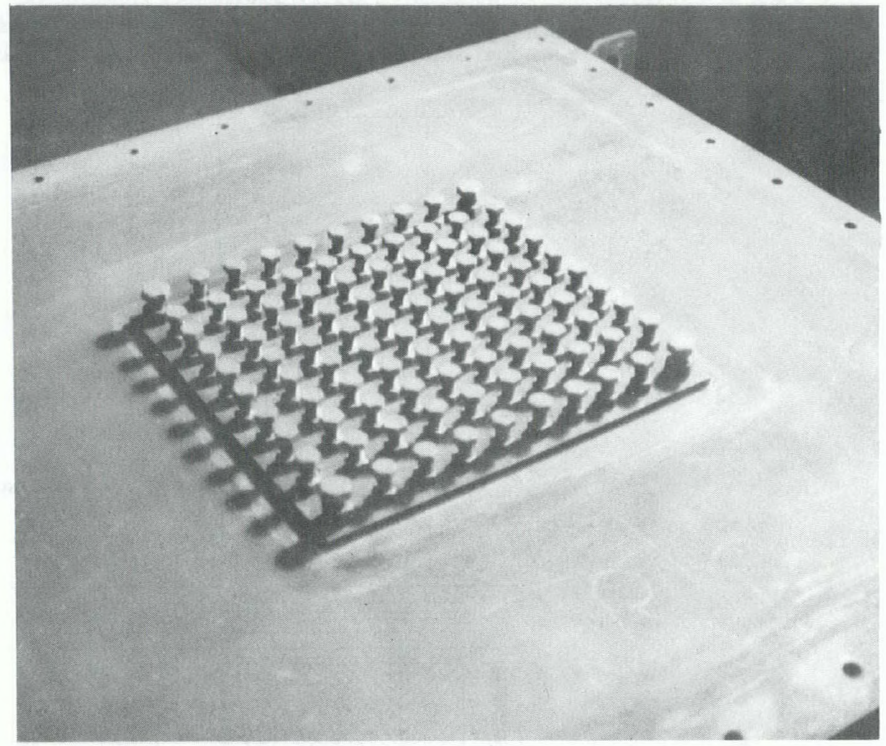

Fig. 3 - Arrangement of distributor plate

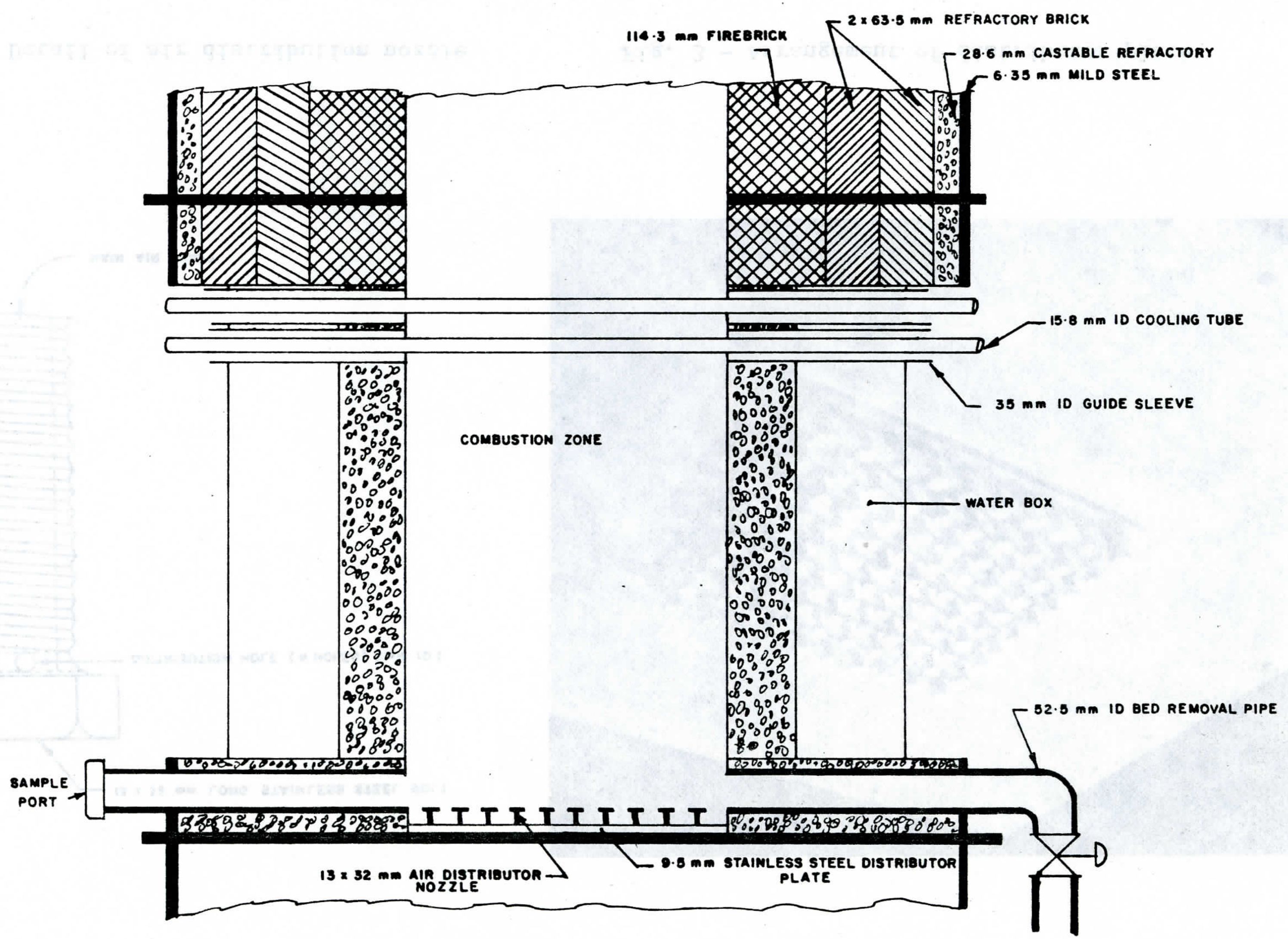

Fig. 5 - Cross-sectional view of active bed zone

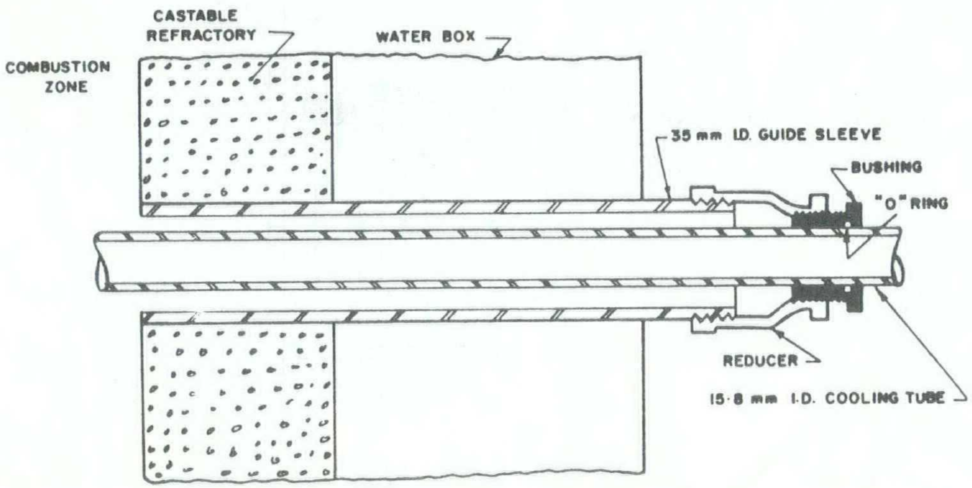

Fig. 7 - Isolated view of cooling tube arrangement

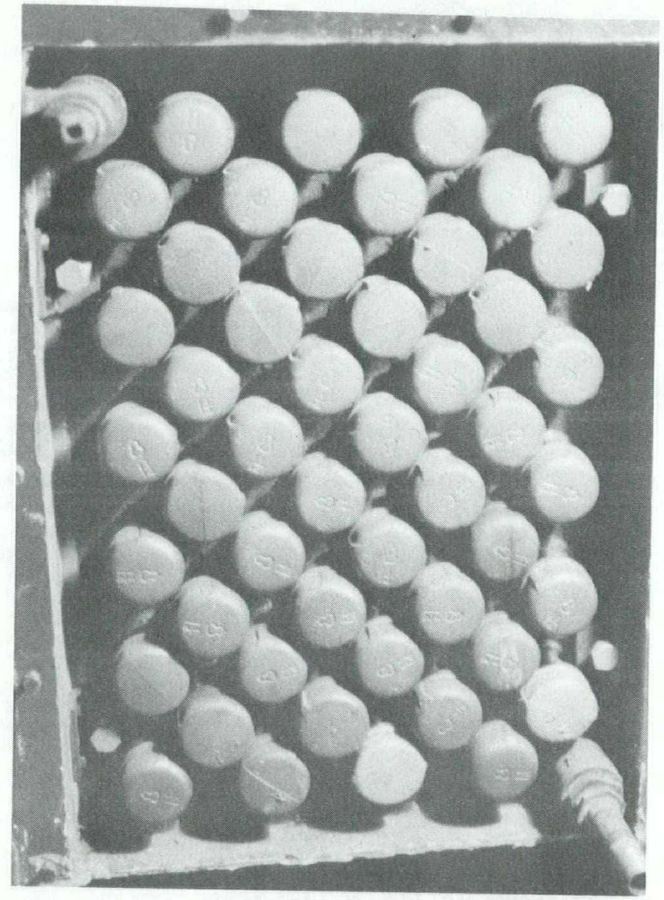

Fig. 6 - View of waterbox arrangement

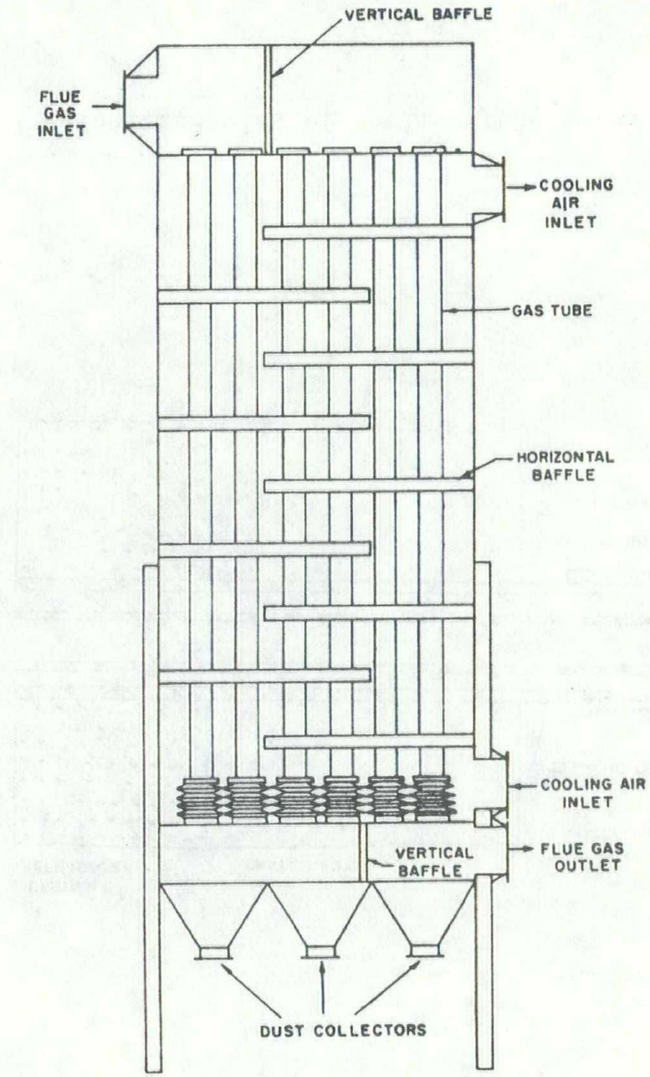

Fig. 9 - Cross-sectional view of gas/air heat exchanger

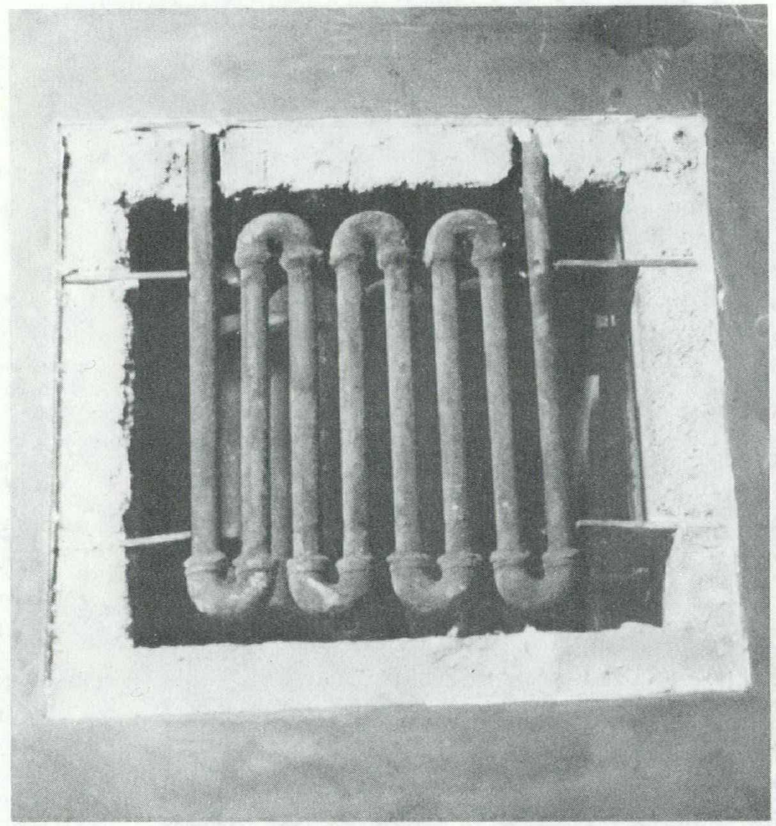

Fig. 8 - Freeboard cooling coil arrangement

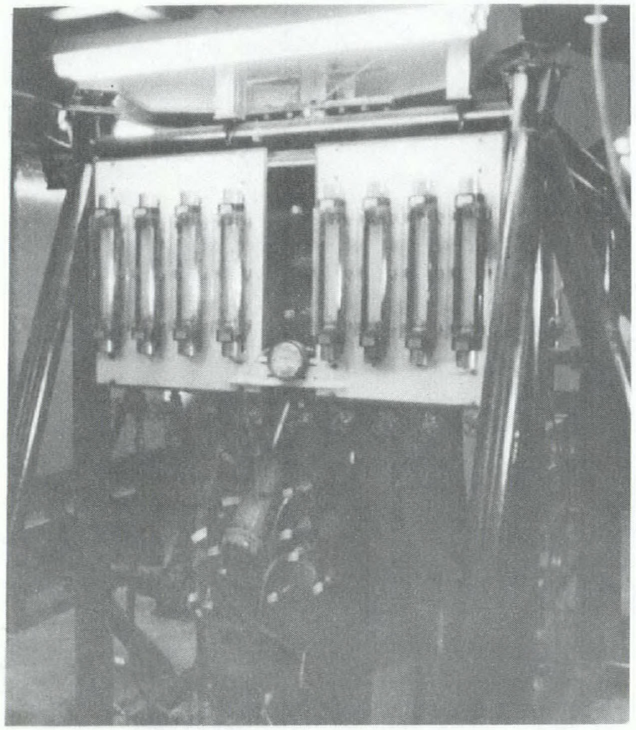

Fig. 10 - Water flowmeter panel

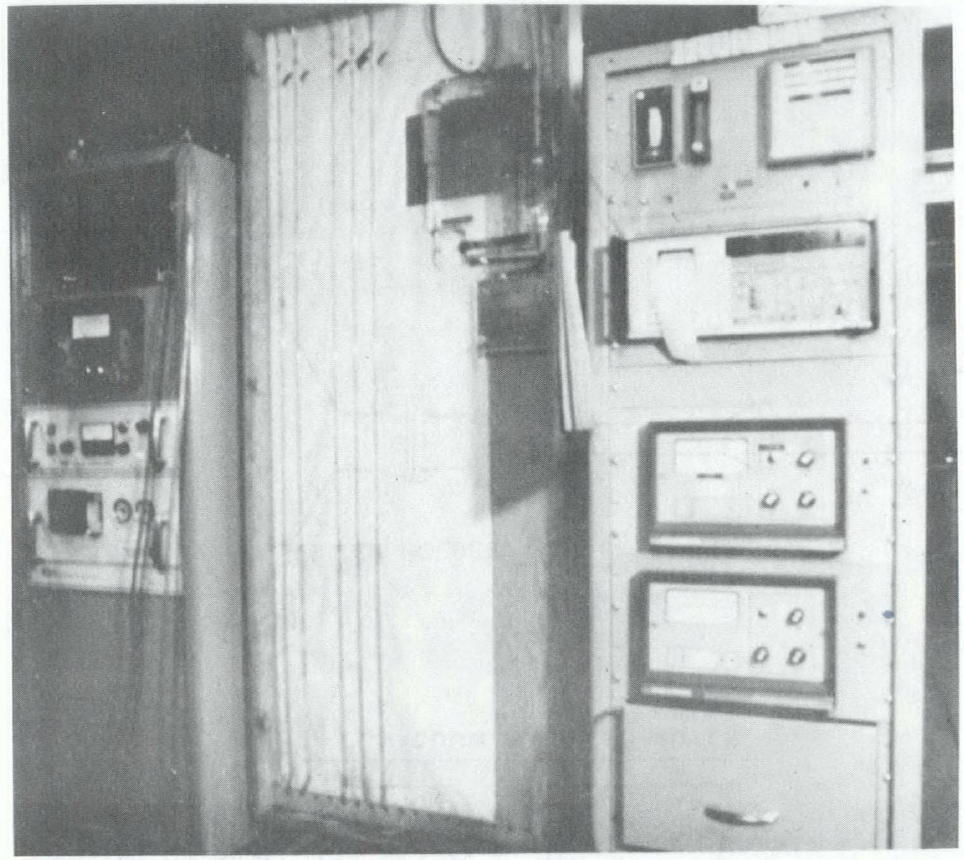

Fig. 11 - Datalogger and flue gas analysers

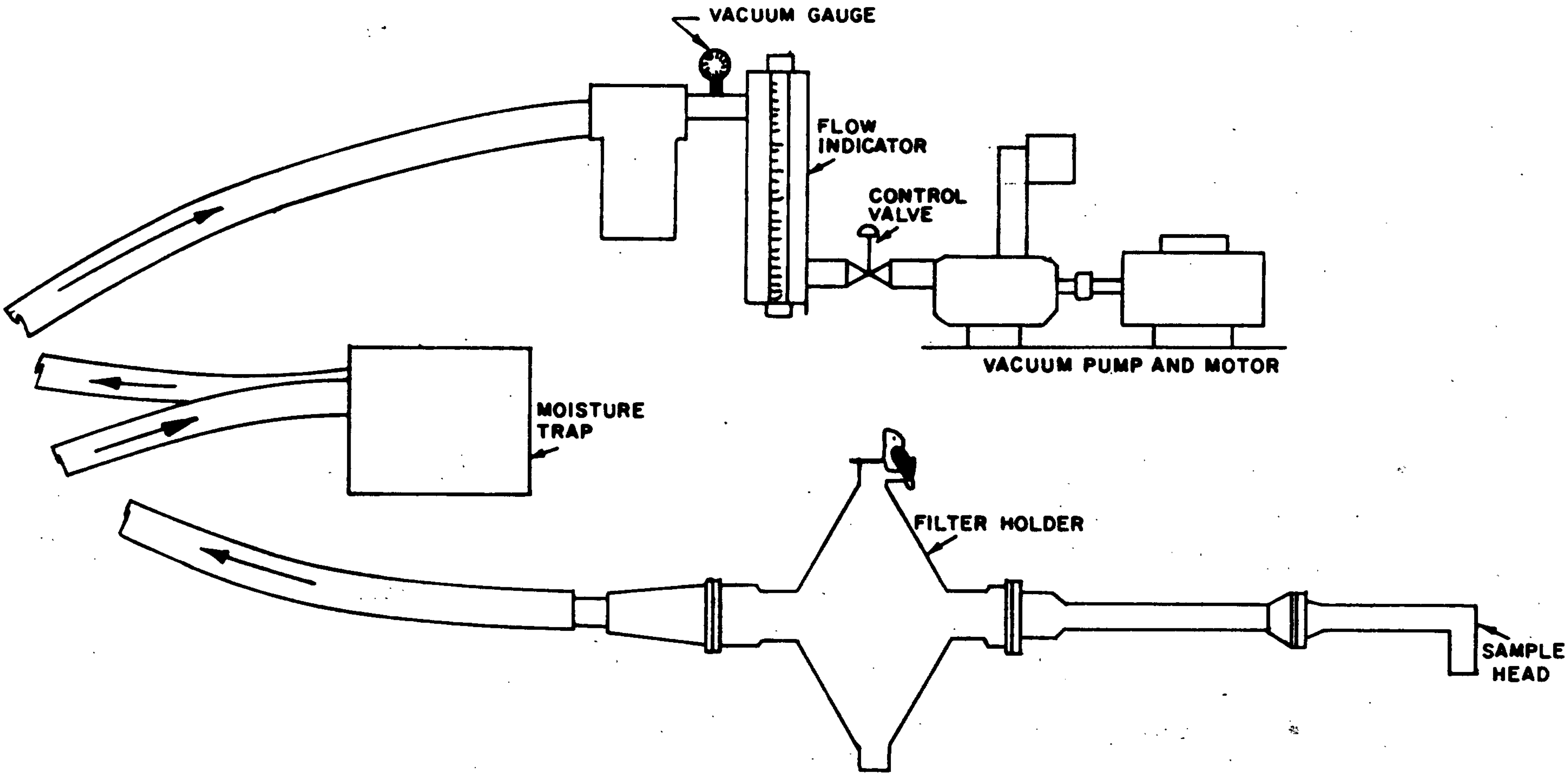

Fig. 12- Schematic of dust sampling technique