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PRACTICAL ASPECTS OF MULTISOLID FLUID BED (MSFB) SYSTEMS

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RILEY STOKER MULTISOLID FLUIDIZED BED (MSFB) EXPERIENCE

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A. INTRODUCTION

The Multisolid Fluid Bed System developed in the early 1970's by Battelle Memorial Institute in Columbus, Ohio is an advanced circulating fluid bed system.

After over 7 years of testing in the 70's and preparation of a database Battelle licensed the technology by fields of use, fuels and territories in the early 1980's.

The MSFB technology has been commercialized presently to a total of 12 MSFB units at various stages ranging in sizes from 85,000 lbs/hr to 660,000 lbs/hr. Refer to Table 1. Studies and designs in the 100 to 150 MW range in a single combustor have been made with conceptualization of scaleup to units approximately 200 MW in a single unit.

The unique feature of a dense bed allows higher velocity operation (25 to 35 ft/sec) with a wider capability of fuel and limestone sizing.

The additional feature of an external heat exchanger (EHE) essentially decouples heat transfer from the combustion process and provides excellent heat transfer characteristics with flexibility to perform evaporation, superheat and/or reheat duty in separate compartments. The EHE provides the flexibilty to handle a wide range of fuels with good load following capability. Additionally the external heat exchanger, in conjunction with the dense bed, allows high turndown ratios to be achieved.

The MSFB process has been described in various other papers and presentations and the references should be used for a more detailed account of the process.

This paper is intended to describe the practical aspects of the MSFB systems.

Fourteen (14) topics will be covered as follows:

1. Control - A brief process description is presented and the control philosophy for the MSFB system.
2. Fuel FlexibilityThe MSFB system provides the flexibility to handle a wide range of fuels.
3. Emissions - Low levels of NO_X, $S0_2$, etc. have been demonstrated in commerical units.
4. Heat Transfer - Relative heat transfer rates of bubbling beds vs circulating beds vs MSFB combustor and external heat exchangers will be described.
5. Erosion Potential - Erosion potential in bubbling beds vs circulating beds vs MSFB combustor and external heat exchanger will be described.
6. Dense bed - Dense bed provides the advantage of handling a wide range of fuels and limestones, ability to operate the system at higher velocity (smaller plan area for distribution across combustor) and a control of residence time of particles important for carbon

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Table 1 MSFB Units Operating, In Design, or Construction Stage with Licensed Battelle Technology

CUSTOMER	LOCATION	INDUSTRY	APPROXIMATE INITIAL OPERATION	CONDITIONS	FUELS & SORBENT
CONOCO	UVALDE,TEXAS	ENHANCED OIL RECOVERY	12182 1 UNIT	50 MM BTU/HR 2450 PSIG 80% QUALITY	SEVERAL COALS PET. COKE LIMESTONE
KERRY COOP	LISTOWEL, IRELAND	DAIRY PRODUCTS	4184 1 UNIT	117,000 LBSIHR 350 PSIG 435'F	COALS, PEATS WOODCHIPS SAWDUST ANTHRACITE
' GENERAL MOTORS TRUCK AND BUS GROUP	FORT WAYNE, INDIANA	AUTOMOTIVE	3/87 2 UNITS	150,000 LBSIHR 700 PSIG 755'F	COALS, WASTES PAINT SLUDGES LIMESTONE
' KURARAY	JAPAN	TEXTILES	9186 1 UNIT	154,000 LBSIHR 1280 PSIG 905'F	ANTHRACITE DELAYED COKE LIMESTONE
ICI	SCOTLAND	CHEMICALS	6187 1 UNIT	85,000 LBSIHR 650 PSIG 850'F	COALS, PEATS HEAVY OIL PLASTIC WASTES
' U. OF MISSOURI	COLUMBIA, MO.	UNIVERSITY	10187 1 UNIT	200,000 LBSIHR 950 PSIG 850'F	COALS LIMESTONE
' U. OF IOWA	IOWA CITY IOWA	UNIVERSITY	9188 1 UNIT	170,000 LBSIHR 475 PSIG 760'F	COALS LIMESTONE
' IDEMITSU	JAPAN	REFINERY	6187 1 UNIT	660,000 LBSIHR 1865 PSIG 1004"F	COALS LIMESTONE
' A.E. STALEY	DECATUR, ILLINOIS	FOOD PROCESSING	10188 2 UNITS	375,000 LBSIHR 1265 PSIG 955-F	COALS LIMESTONE
' ARCHBALD POWER CORP.	ARCHBALD, PENNSYLVANIA	COGENERATION -	10188 1 UNIT	200,000 LBSIHR 1335 PSIG 955'F	ANTHRACITE CULM LIMESTONE
' CITY OF WYANDOTTE	WYANDOTTE, MICHIGAN	MUNICIPAL UTILITY	4/90 1 UNIT	250,000 LBS/HR 875 PSIG 900'F	COALS LIMESTONE

' Designed under license with or supplied by Riley Stoker

burnout and sorbent utilization. What dense bed materials are used and what are the relative usage rates and costs?

7. Scaleup - Commercial MSFB's presently range from 85,000 to 660,000 lbs/hr. How is scaleup accomplished?
8. Reheat - The external heat exchanger provides flexibility to handle reheat systems.
9. Hot recycle - Hot recycle provides the additional system flexibility to increase particle residence time as required.
10. Startup - Overview of the startup of the system from both a cold and hot condition is presented.
11. Turndown - High turndown rates of MSFB systems have been demonstrated in actual commercial units. How is this accomplished?
12. Corrosion - Potential for corrosion is reduced in using a circulating fluid bed system. A discussion related to the MSFB is provided.
13. Ash Collection - The MSFB system is designed to optimize efficiency by removing a major portion of the ash as flyash at lower temperatures.
14. Power Usage - Horsepower requirements are a function of several variables including the circulating fluid bed system itself. A typical comparison of the process horsepower requirements of a typical circulating fluid bed system vs an MSFB is provided.

B. PRACTICAL ASPECTS OF MSFB SYSTEMS

1. Control Philosophy

In order to achieve an optimum operating temperature for the combustor vessel and flue gases in an MSFB unit, heat is removed from the combustion system by locating heat transfer surface within an External Heat Exchanger (EHE). The heat transfer surface is normally evaporative or a mixture of evaporative and superheater or reheater which, by removing heat from the system, generates about 60% of the total boiler heat duty. The EHE contains a non-combusting, gently fluidized (about 1 ft/s superficial velocity), conventional bubbling bed. The bed material is comprised of the fine circulating bed particles which are captured by high efficiency hot cyclones located at the flue gas exit from the combustor. The bed material passes through the EHE before being reintroduced into the combustor via a system of pipes and L-valves. A schematic of the MSFB combustion and steam generation system is shown in Figure 1. The EHE bed fluidizing air is set at a constant mass flow, and as boiler load and fuel feed rate varies, the rate of

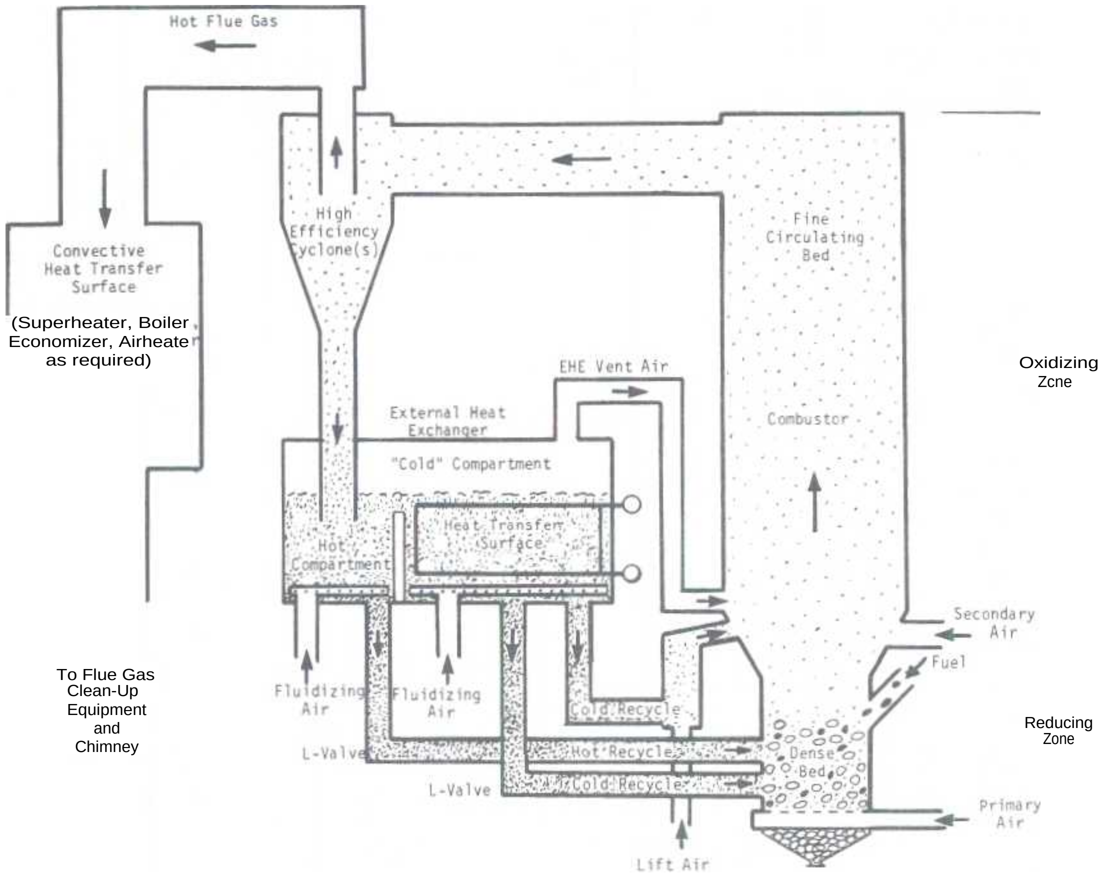


FIGURE 1

solids recycle is varied by controlling the L-valves in response to the tendency to change temperature within the combustor. This change in recycle flow rate then causes the EHE bed temperature to change, remembering that the temperature of solids leaving the combustor and entering the EHE is always controlled at an optimum constant value, and the heat transfer coefficient from the EHE bed to the immersed surface is also substantially constant. Thus, the temperature difference between bed and heating surface is changed, and the amount of heat extracted by the surface varies in proportion to this change in temperature difference. A different equlibrium recycle solid flow rate and EHE bed temperature is arrived at for any load condition, and the optimum operating temperature in the combustor can be maintained at a constant value over a wide load range completely independently from the combustion air and fuel feed controls.

The combustor temperature is controlled by the cooled recycle solids from the EHE at two quite separate locations, the exit from the lower reducing zone and the exit from the combustor itself. This contributes greatly to the system fuel flexibility (see Section 2) and load turndown (see Section 11).

Combustion air is supplied to the combustor by multiple routes, either by separate fans or an appropriate combined duty fan arrangement to provide the best capital/running cost trade off. Primary air is introduced into single or staged locations depending on emission level requirements and the desirability for operating flexibility. Secondary air enters the combustor at the level of the transition from reducing to oxidizing zones. EHE air is used to fluidize the EHE beds before it is vented to the combustor to enter at about the same level as the secondary air. Lift air is used to transport the "cold" recycle solids which control the temperature of the upper combustor and this, together with the recycle solids, again enters the combustor at about the secondary air level.

The flue gas flows from the combustor through the cyclones, from where it takes a conventional path, as required, through superheater, boiler, economizer and airheater convective heat transfer sections. Final flue gas clean-up, to reduce particulate emissions to an acceptable level, is normally effected by the use of a fabric bag filter.

The combustion air/flue gas system operates on the balanced draft principle with an induced draft fan, located downstream of the final gas clean-up equipment, discharging flue gases to the chimney. The induced draft fan is controlled to maintain a negative pressure at the point of fuel introduction into the reducing zone and simplifies the fuel feeding system.

2. Fuel Flexibility

The velocities used in the combustor result in a comparatively small plan area and hence minimize the number of fuel feed points required. The dense bed provides a very turbulent zone for fuel mixing and distribution. The size of solid fuel types can vary from lumps greater than 2" down to high fines contents, no additional fuel preparation being necessary. Fuels burned by MSFB units have included unreactive petroleum coke and anthracite, many grades of coal with low to high ash contents, peat, wood wastes and even more volatile fuels such as kerosene, thus covering a very wide spectrum of fuel types. Changeover from one fuel, or combination of fuels, is achieved simply and smoothly with negligible effect on unit performance. Large variations in fuel heating value and combustion characteristics are automatically compensated for by the separate fuel feed and combustor temperature controls, which maintain the temperatures most conducive to minimize NOx generation and high combustion and sulfur retention efficiencies.

There are outstanding benefits, both commercially and technically, in having a combustion process which is flexible enough to utilize a very wide range of fuels and it could well be justified to invest in such a capability. While pulverized coal and stoker combustion offer limited versatility on coal use, MSFB combustion offers a greater range and is not at a capital cost disadvantage for industrial boilers when all the necessary plant systems are considered for present day use. Refer to Table 2 which lists various fuels that have been burned in MSFB units.

Table 2. Fuels Burned in MSFBC

Anthracite
Industrial Waste
Sawdust
Peat
Coals
Kraft Liquor
Wood Waste
Municipal Waste

- Sewage Sludge
- Delayed Coke
- Fluid Coke
- Char
- **Rock** Containing Bitumen

Kerosene
Heavy Oil

3. Emissions

High sulfur dioxide retention efficiencies of typically 80 to 95% resulting in $S0_2$ emissions of 50-300 ppm can be achieved by the MSFB process. The required calcium to sulfur molar ratios consistent with this are 1.5 to 3.5 depending on a number of factors, the main ones being the desired sulfur dioxide emission limit and the properties of the limestone being used.

NO_x and carbon monoxide levels of less than 100 ppmv each at MCR have been measured and these pollutants can be readily controlled below present day emission limits. Hydrocarbon emission levels of 50-100 ppmv are quite normal for the MSFB process.

A major factor in the generation of all the above mentioned pollutants is combustion temperature. The relative ease and degree of controllability of temperatures within the MSFB combustor make the system particularly suited to the optimization of emission control over a wide load range.

The emission of particulates to atmosphere is regulated by the use of a bag filter, and a level of 0.03 lb per million BTU is typical.

4. Heat Transfer

Heat transfer in a fluidized bed is a very complex mechanism with a large number of variables. Without going into excessive detail on this topic, it is perhaps sufficient to say that although many predictive correlations have been produced, each one will invariably have a narrow range of application. This is perhaps not so surprising when we consider the variables which affect the heat transfer coefficient. Refer to Table 3.

Table 3. Variables that Affect Heat Transfer Coefficient

- Bed Temperature
- Heating Surface Temperature
- Heating Surface Emissivity
- Bed Particle Emissivity
- Fluidizing Velocity
- Bed Material Physical Properties
- Fluidizing Medium Physical Properties
- Mean Particle Size
- Particle Size Distribution
- Particle Sphericity
- Heating Surface Arrangement

The closest that one can get to a universal correlation for fluidized bed boilers with typical bed materials, operating temperatures, and particle sizes and distributions is probably the relationship between the heat transfer coefficient and the particle concentration in the bed. This is illustrated in Figure 2. The possible variation in heat transfer coefficients is small below particle concentrations of 0.001 lb/ft^3 (i.e. approaching clean gas) but increases to a possible variation of about 2:1 at concentrations in excess of 50 lb/ft^3. For comparison purposes typical values for MSFB and circulating fluidized bed combustors are shown. An EHE bed exhibits coefficients at the highest part of the bubbling bed range.

Precise methods of correlation have been developed for both the MSFB combustor and EHE in order to account for the particular operating conditions found in this system.

5. Erosion

Erosion in a fluidized bed is also a complex and often unpredictable subject and it can be influenced by a number of factors:

a. Gas Distribution
b. Particle Distribution
c. Angle of Impingement
d. Surface Temperature
e. Particle Abrasiveness
f. Collision Probability
g. Average Particle Concentration
h. Average Velocity

For application in most fluidized bed boilers, items (d) and (e) will have very similar effects in different units while items (a), (b), (c), and (f) will depend on the actual physical arrangement of components in a particular unit. Items (g) and (h) depend on the basic process design of a unit and research has revealed that these two factors are very much predominant in providing the potential for erosion to occur. The many published references and studies on erosion show that the rate of erosion varies in direct proportion to the average particle concentration (which can be expressed as lb/ft^3). The effect of average velocity is reported as varying to a power of between 2 and 3.5 but in general an index of 3 is felt to be reasonably conservative.

In terms of predicting the potential for erosion, a generalized relationship $E = C \times V^3$ may be used where:

E = Erosion Potential Factor lb/s^3
C = Average Particle Concentration lb/ft^3
V = Average Velocity ft/s

This relationship should be used with care as it gives only a broad comparison, but nevertheless it does provide an indication of the potential for erosion to occur. To study individual cases of erosion, which very often are localized, then all the previously mentioned factors should be considered. Examples of the application of the erosion potential are shown in Table 4.

FIGURE 2 HEAT TRANSFER VS. PARTICLE CONCENTRATION

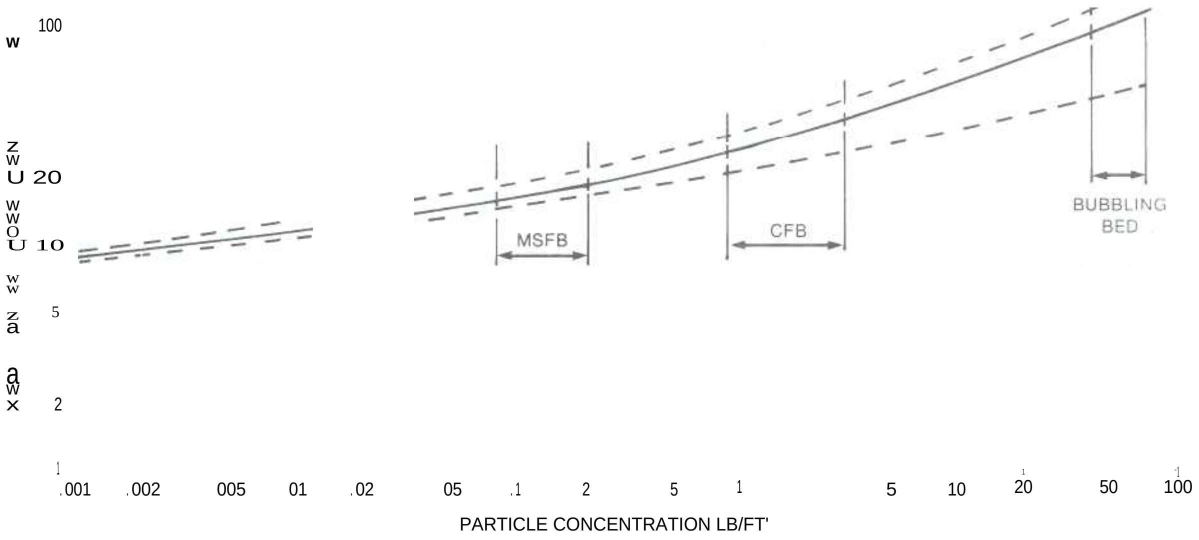


Table 4. Comparison of Erosion Potential.

Erosion Potential = $V^3 \times C$

MSFB	$30^3 \times .08 = 2{,}160$
MSFB	$30^3 \times .2 = 5{,}400$
CFB	$20^3 \times .9 = 7{,}200$
CFB	$15^3 \times 3 = 10{,}120$
EHE Bed	$1^3 \times 65 = 65$
Bubbling Bed Boiler	$8^3 \times 45 = 23{,}040$

Since the relationship is only broadly comparative in nature, the conclusions that can be drawn from the above are that the erosion potentials for MSFB is lower but of similar magnitude to other circulating bed combustors. The potential for the EHE bed is very much lower, and that for a conventional bubbling bed is significantly higher. By and large, these trends have been borne out in practice.

The potential for erosion of combustor waterwall tubes due to localized effects is addressed in the MSFB by applying a protective refractory layer in suspect areas such as the lower part of the combustor, the combustor roof and the combustor sidewalls at gas exit to the cyclones. Should unpredicted problems arise then the amount of protection can be extended with negligible effect on unit performance since the bulk of the heat removed from the combustion system is in the EHE.

6. Dense Bed Material

In addition to the circulating bed material, the reducing zone of the combustor contains a dense fluidized bed of large particles, with a size range between 1/4" and 3/4". This dense bed assists in providing a stable combustion zone, but also has the effect of greatly increasing the residence time of the fine bed particles, together with any small entrained unburnt carbon particles which may otherwise be carried over to the cyclones in the flue gas stream. Thus, in combination with an appropriate gas residence time in the oxidizing zone, the combustion and sulfur dioxide reduction efficiencies of the system are maximized.

A number of suitable dense bed materials may be used, but the one which has gained most popularity so far is ordinary river gravel with a silica content in the order of 9810. This suffers from a degree of degradation and attrition in use, but it is usually obtained locally at low cost so making it the best economic choice. Typical usage rates are 25 to 150 pounds per hour, depending on material characteristics and MSFB unit size. There is no need for continuous feeding, topping up once or twice a day is quite adequate. Detailed testing and research has been carried out to establish alternative dense bed materials with lower usage rates but in general rounded silica gravel remains the first choice due to its low cost.

Dense bed draining is not required for normal operation when firing the design fuels and utilizing an appropriate dense bed material.

Draining may have to be done however, under the following unusual and infrequent circumstances:

(a) Planned shutdown for inspection and/or maintenance when the draining would be done off-line.

(b) A unit trip, due to maloperation or an upset condition, after which circulating bed material may on occasion accumulate in the combustor until the fans can no longer cope with the loading. Some bed material then has to be drained to an acceptable level to allow restart of the fans.

(c) Increase in dense bed level. If the fuel contains a significant amount of stone, or if the ash exists as large particles, as may happen for high ash coals, then an increase in dense bed level will be observed. To correct this, material can be drained off at intervals while the unit is on-line. It is impossible to be precise as to the required frequency of draining, but between upper and lower limits, the exact dense bed level is not critical. In this event replenishment with fresh dense bed material may well not be required.

(d) If the dense bed material has a high attrition rate and if the particles break down to a predominate size range of 1/8" to 1/4", then they may accumulate in the lower combustor as fresh dense bed material is added to maintain the observed level. This situation may be corrected by on-line draining at an anticipated frequency of perhaps three times a day and then reestablishing dense bed level with new material. This situation will normally be avoided by selection of an appropriate dense bed material.

On all present MSFB units, the nature of the dense bed draining process is such that it is simply achieved by dropping the material into an open top carbon steel plate "skip" with a capacity of about 30 ft^3. This skip is then removed by a forklift truck, and the material is dumped at a safe location to allow it to cool down. For situations (a) and (b), and possibly (c), the bed material may be reused if it is so desired.

7. Scale Up

The first MSFB boiler had a steaming capacity of 50,000 lb/hr and was built under license from Battelle for Conoco at their Uvalde, Texas, site for enhanced oil recovery. This was followed by a 117,000 lb/hr unit, which was built for the Kerry Co-op dairy plant in Listowel, Ireland, and which has been in operation since 1984.

Riley Stoker Corporation's first MSFB contract was for two 150,000 lb/hr units for the General Motors Truck and Bus plant at Fort Wayne, Indiana. These units started up in 1987. A second contract was received from the University of Missouri for a 200,000 lb/hr unit, and this is due to start-up in late 1987. In 1986, Riley Stoker was awarded a contract for two 375,000 lb/hr units by A.E. Staley at Decatur, Illinois, and these units are scheduled to start-up in late 1988.

Meanwhile, Riley Stoker's licensee for the MSFB technology in Japan, Mitsui Engineering and Shipbuilding, has succeeded in obtaining two very significant contracts in Japan. The second of these represents a major advance towards utility sized boilers in that it is a 660,000 lb/hr unit for Idemitsu oil refinery at Chiba, Japan, (Figure 3).

Other MSFB units have been sold as illustrated by Table 1, but the projects mentioned above trace the history of the development of the MSFB technology from the small industrial boiler to units bordering on utility boiler steam outputs, pressures, and temperatures. It is worthy of note that all licensees of the MSFB technology freely share experience and product development through the offices of the Battelle Institute, and in the case of Riley Stoker and Mitsui there is, of course, a direct interchange.

At present, detailed proposal designs are being furnished to the industry for boilers which will produce steam at the quantities, pressures, and temperatures needed to generate 80 MW of electricity. Such MSFB boilers are only slightly larger than the Idemitsu unit and will incorporate reheat as required by the steam cycle. An 80 MW MSFB with reheat is illustrated in Figure 4. Consequently, boilers with power generation capabilities in excess of 100 MW now fall within Riley Stoker's standard size range of MSFB units and can be offered with full commercial assurances.

Good control of combustor temperature (see Section 1) is of the utmost importance for all circulating fluidized bed boilers, and this must be borne in mind when considering the scale-up of combustor size.

A proportion of the total heat removed from the MSFB combustion system is achieved by the combustor waterwalls, but this typically amounts to 3-9% of total boiler heat duty depending on unit size. The amount of heat absorbed by the combustor waterwalls is then far from being critical to the operation and performance of the unit. This is very different to a circulating fluidized bed without an EHE, where the full 60% of total boiler heat duty must be absorbed in the combustor, and with regard to unit scale-up the advantages of the EHE can probably be best illustrated by now considering the means of combustor temperature control in a circulating fluidized bed boiler without an EHE.

The desired combustor operating temperature in a *non-EHE* unit is determined from:

(a) The heat released by the fuel in the combustor.

(b) The sensible heat contained in the combustion air supplied to the combustor.

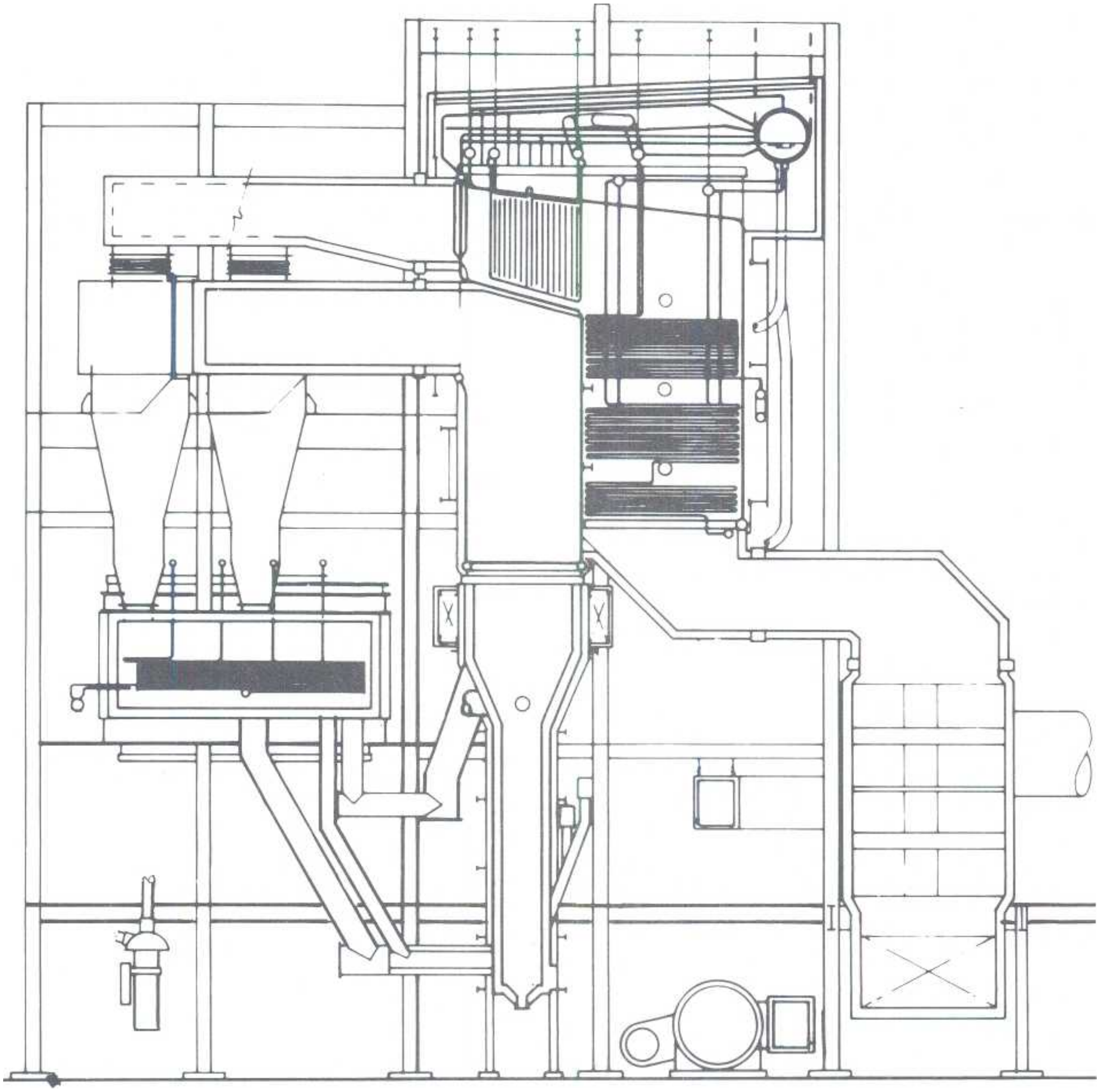
(c) The amount of heating surface, the majority or total of which will comprise the combustor enclosure waterwalls.

(d) The heat transfer coefficient from the solids and flue gas to the heating surface in the combustor.

(e) The temperature difference between the solids and flue gas and the heating surface in the combustor.

The amount of heat supplied, (a) and (b), will increase in direct proportion to the unit capacity, but the heating surface to absorb heat (c) does not. The "heat supplied" to "heating surface" ratio decreases with increased unit capacity so producing a tendency towards higher combustor temperatures than desired in larger units, which is only partly alleviated by the increased temperature difference (e). Within limits, there are a number of steps that can be taken to counteract this tendency:

1. Increase the relative combustor height to increase the amount of heating surface. This has practical and economic limits.
2. Change the combustor plan aspect ratio to a more rectangular instead of square arrangement to improve the "heat supplied" to "heating surface" ratio. This also has practical and economic limits.
3. Use combustor division waterwalls to increase the amount of heating surface. This appears to be reasonable for units of perhaps 100-150 MW capacity, but there will again be practical and economic limits.



IDEMITSU KOSAN CO.
CHIBA REFINERY LTD.
660,000 lbslhr-1849 psig operating-1004F
Riley Multisolid Fluidized Bed Combustion
Steam Generator
Fired by Coal
Riley-Mitsui Consortium

FIGURE 3

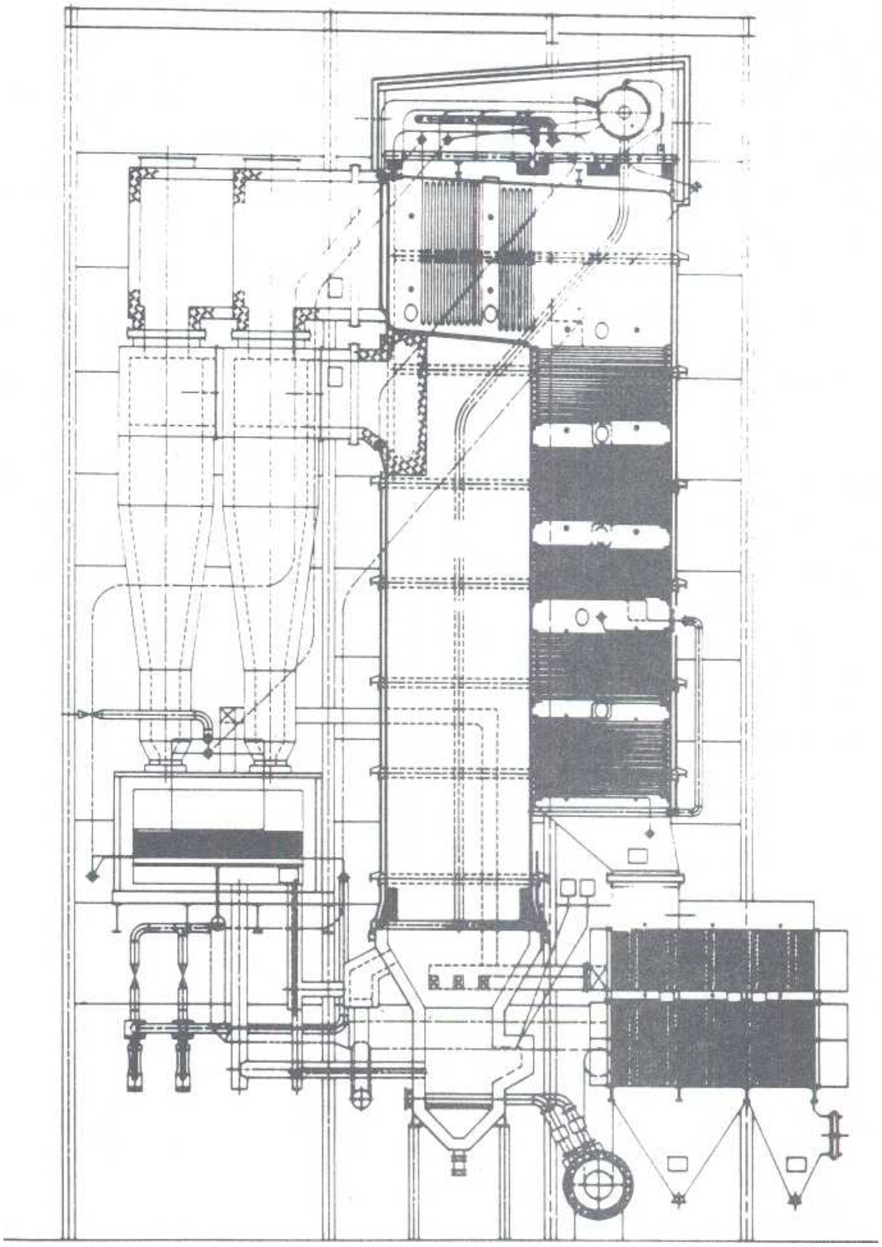


FIGURE 4

4. Place pendant superheater surface in the upper combustor to increase heating surface. This raises a very real concern about tube erosion in an extremely heavily particle laden environment.
5. Use extended surface (fins) to increase waterwall heating surface. There are erosion and localized tube heat flux concerns, but with care this may be used within practical limits.
6. Vary superficial velocities and/or the amount of solids circulated in order to change the solids concentration and hence the heat transfer coefficient (d) in the combustor. This has combustion pressure drop limits and may lead to control problems as the saturated solids carrying capacity of the flue gas is approached. There is also an erosion concern as the solids concentration is increased in the non-EHE units.

By utilizing various combinations of the above methods, unit steam capacities with a single undivided combustor of 450,000-550,000 lb/hr can be achieved without excessive difficulty, but it is at outputs greater than this that the use of an EHE really comes into its own. Without the reliance on combustor heat transfer surface to control combustion temperatures, there is no scale-up limitation in this respect for MSFB unit sizes presently being conceptualized, i.e., up to 300 MW capacity.

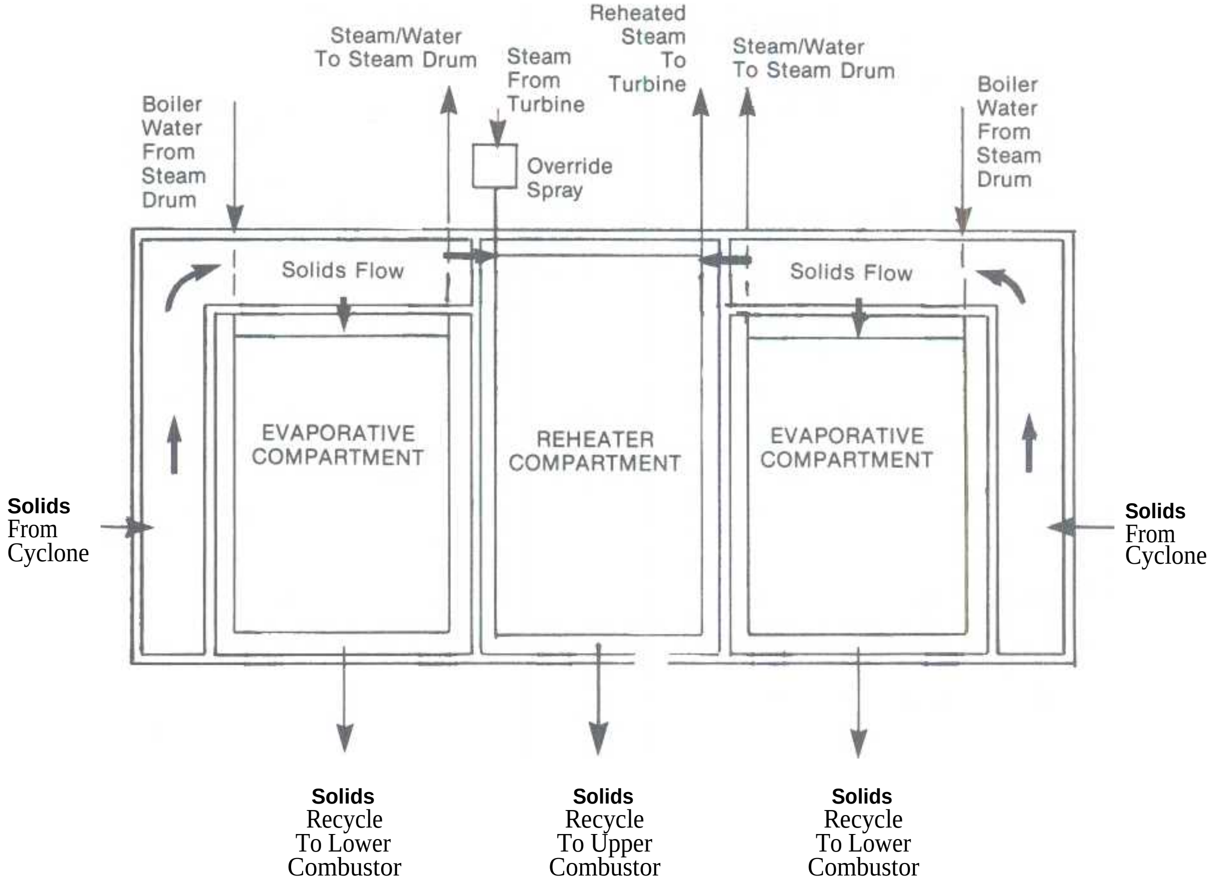
In both EHE and non-EHE units extraction of heat from the flue gas after it leaves the cyclones is achieved by long established conventional means, and there are no new scale-up problems in this area by virtue of the combustion technology being fluidized bed.

Another major scale-up concern is with the plan areas and dimensions of the EHE and combustor as related to solids distribution, heat distribution, air and flue gas distribution, and fuel and sorbent distribution. There need only be a few carefully chosen nominal unit depth dimensions for the EHE and combustor, which span the range of all MSFB units sold to date. Thus, having determined the optimum depth dimensions, scale-up can be accomplished in one direction by increasing the width of the unit to maintain constant fluidizing velocities and the correct proportion of EHE surface. The number of fuel and sorbent feed points and the number of solids recycle Lrvalves will be designed in general proportion to the unit width, so there is no need for major scale-up requirements of line sizes and distribution areas and distances from those presently designed.

8. Reheat

Reheat surface will normally be placed in the EHE, and a typical schematic of this arrangement is shown in Figure 5. Control of reheat temperature will be accomplished by varying the recycle solids flowrate through the reheater compartment. This particular recycle solids stream is used to assist in controlling the temperature in the upper combustor. The balance of solids flow to fully achieve combustor temperature control is provided by the evaporative surface compartments. This method of reheat steam temperature control will have a relatively slow response, during temperature reduction so an override spray will also be installed to provide protection during transient conditions.

FIGURE 5



The reheater compartment bed will be designed to operate at about 1200°F at full boiler load, which will result in normal maximum metal temperatures of 1040-1070°E As a safeguard, however, the reheater tube material will be chosen to withstand the full bed temperature in order to handle the possibility of an operational trip or power failure. Thus, the tube material will be austenitic stainless steel. This apparently high material cost plus the low bed to steam temperature difference, is adequately compensated for by the high bed to tube heat transfer coefficients, which can be in the order of 100 BTU/ft^2.hr.R.

The advantages of the reheater system as described are:

(a) The reheater is fully protected during unit start-up when the reheat steam flow is low by virtue of the tube material selection criteria. Also, the reheater compartment simply need not be fluidized during the start-up phase, so that there will be no heat transfer.

(b) Location of the reheater in the EHE and the tube material design philosophy provides flexibility to minimize the steam side pressure drop to improve cycle efficiency.

(c) The absence of spray for steam temperature control under normal operating load conditions gives an improvement in cycle efficiency and reduces the possibility of other recognized problems associated with the use of spray attemperators.

(d) A reheat steam temperature control range from about 50% to 100% load can be obtained. This range is easily matched by superheat temperature due to the operating characteristics of the MSFB system.

(e) The reheater steam temperature control is completely independent from the superheater steam temperature control. There is no interaction between the two systems, which may otherwise require the use of flue gas flow balancing dampers and/or a flue gas recirculation system, which can, of course, cause appreciable mechanical problems in themselves.

Since the environment in the EHE is relatively benign, fluidizing velocities being very low with little combustion occurring, corrosion and erosion of pressure parts and supports is undetectable.

(g) A circulating fluidized bed system without an EHE would require reheater and/or superheater surface to be located in the combustor in order to obtain the correct proportioning of heat duties at utility boiler steam and feedwater conditions. This is avoided completely along with all the attendant problems of erosion, start-up protection, and steam temperature control as previously discussed.

9. Hot Recycle

The rate of fine solids passing through the EHE fluidized bed (which contains heat transfer surface) and hence the circulation rate of the cooled solids in the MSFB system, is dictated by the boiler operating load rather than by optimization for carbon particle burn-up or sulfur dioxide retention. To overcome this, the EHE is divided into separate compartments; small hot compartments (1500-1600°F) which have no heat transfer surface and into which the cyclones first discharge the hot circulating material and "cold" compartments which contain the heat transfer tubes. The "cold" compartments are termed such as a means of distinction although they normally operate at about 1100-1200F at MCR load. Each compartment discharges into its own "L" valve/solids return pipe system. The hot solids recycle rate may then be set to give an optimum total solids recycle rate to maximize combustion and sulfur dioxide reduction efficiency over the load range. It has negligible effect on the MSFB system heat balance, while the "cold" solids recycle flow rates to the reducing and oxidizing zones are independently varied according to boiler operating load and resulting combustion zone temperatures.

10. Start-Up

When first starting up the unit, sand is used as a circulating bed material and over a period of time this becomes wholly or partially replaced by limestone particles and particles of coal ash depending on the nature of the ash. The MSFB system is designed such that during normal operation, bed material make-up, other than the required limestone feed, is not required, and nor is any significant drain of hot materials from the combustor or EHE.

Start-up of the unit from cold is effected by an oil or gas fired burner in series with, and between the primary air fan and combustor. The primary air, and consequently, the dense bed and combustor is gradually heated until temperatures high enough to sustain stable combustion of main fuel are attained. This is normally in the 1100-1400°F range. Main fuel feed is then initiated, and start-up fuel reduced, to achieve a smooth transition to full solid fuel firing at a unit load of 6-10% MCR.

Since the temperatures in both the reducing and oxidizing zones of the combustor are separately controlled, at very low operating loads good stable combustion of the main fuel can be maintained without the need for using an intermediate auxiliary fuel firing stage. Thus, the use of more expensive start-up fuels is minimized.

The total start-up time is dictated by the recommended heat-up rate for the refractory used in the combustor and cyclone system. Heat-up rates of up to 200F per hour have been recommended by refractory manufactureres which will result in a start-up time from cold of about 8 hours. Whenever possible, however it is usually preferred to use a heat-up rate of 100F per hour as this will enhance the longevity of the refractory throughout the system.

Start-up from a hot condition depends on the residual temperature of the refractory and may or may not require the use of the start-up burner. The limiting factors are the recommended refractory heat-up rate and the attainment of the main fuel permissive interlock temperature of the dense bed.

11. Turndown

The load turndown ratio of an MSFB is high for a solid fuel fired boiler, with stable loads on main fuel firing as low as 10% MCR being attainable. The normal minimum operating load while maintaining very low levels of NO_x formation is 10-30% MCR depending on the stringency of the allowable NO_x emission level.

The concepts described in sections 1 and 7 regarding combustor temperature control should also be considered when thinking about turndown. Non EHE circulating fluidized beds have a fixed amount of combustor heating surface of course, and as load decreases the "heat supplied" to "heating surface" ratio decreases so producing a tendency for lower combustor temperatures. This is counteracted somewhat by the fact that the heat transfer coefficient and temperature difference between the solids and the heating surface also tends to reduce with load. Heat transfer coefficients can also be further affected by changes to excess air and/or solids circulation rates. Thus a limited control can be achieved but the lowest unit load that can be obtained in a non EHE unit with a combustor temperature high enough to sustain stable combustion is about 30% MCR.

The MSFB also has fixed combustor surface and the EHE heat transfer coefficient does not change appreciably with load but the EHE bed temperature reduces from a maximum at MCR down to a minimum (about boiler saturation temperature) at about 10% MCR. Thus the temperature difference between bed and heating surface (and consequently the heat removed "indirectly" from the combustion system) also reduces from a maximum at MCR down to zero at about 10% MCR. The combustor temperatures, and consequently the EHE bed temperature, are accurately controlled by the rate of circulating solids through the L-valves. Moreover, since the temperatures in the upper and lower combustor are separately controlled, the temperature of the dense bed (in the lower combustor) can be controlled at 1600°F from 100% down to 10% load to sustain stable combustion even though the temperature at the combustor exit may well be significantly lower than 1600°F at loads from 10% to 30% MCR. This then allows the MSFB's high turndown ratios to be achieved. The dense bed ensures good combustion and mixing within the combustor even with minimal circulating solids flow rates.

12. Corrosion

There are certain advantages regarding a reduced potential for corrosion, and maintenance of maximum performance, in a circulating fluidized bed boiler when compared to a conventional boiler. These advantages are:

(a) Slagging of combustor waterwall surfaces is practically eliminated along with the associated tube corrosion problems.

(b) Fouling of superheater surfaces is reduced, and any deposits are easily removed, again reducing the risk of tube corrosion.

(c) The flue gas temperature and hence convective superheater tube metal temperatures are relatively low. This gives more leeway in metal selection, but more importantly, gives greater margin with regard to the temperatures at which corrosion occurs.

(d) The sulfur trioxide content in the flue gas is very low, and this again reduces the propensity for tube corrosion, both on high temperature superheater surfaces and low temperature airheater surfaces, as well as other back-end equipment.

13. Ash Collection

The solids material balance on the MSFB system is very straightforward. The flyash leaving the cyclones in the flue gas stream is designed to be equal to the solids input to the combustor from the limestone, fuel ash and very small amounts of dense bed make-up. The flyash in the flue gas is fine and is collected by the fabric bag filter. The flyash is cooled down by the convective heating surfaces so minimizing the loss to boiler efficiency due to the

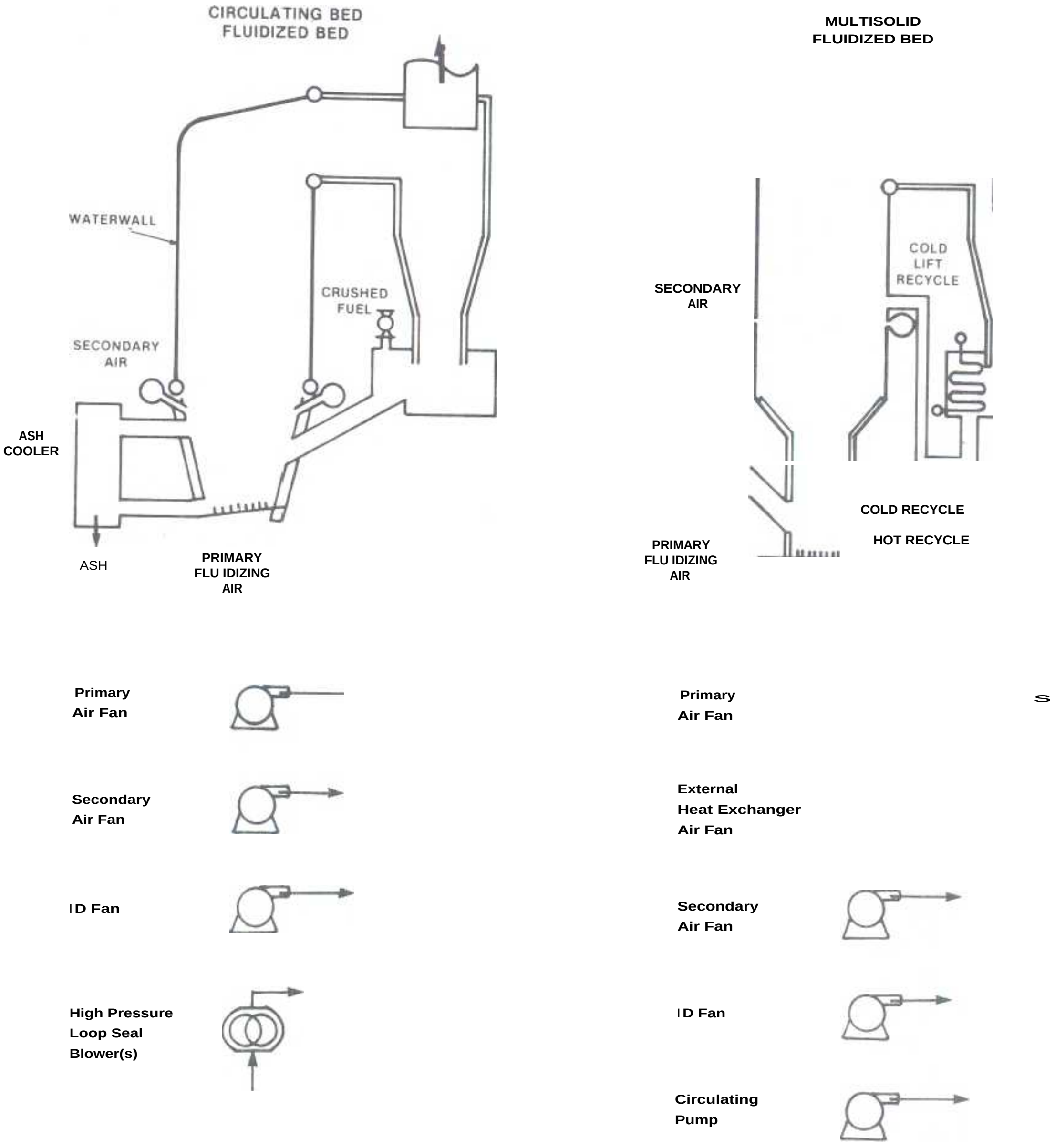


FIGURE 6

sensible heat of the solids exiting the system. Ash hoppers are normally provided at strategic points below the boiler, economizer and airheater, but experience has shown that these are little used. A material drain is also provided from the "cold" compartment of the EHE so that the circulating material inventory in the system can be maintained during abnormal operating conditions or when using significantly off-design fuel ash content or limestone.

A drain is also provided at the bottom of the combustor (see Section 6), but it would not normally be connected to the automatic ash removal system as its use is infrequent.

14. Power Usage

The MSFB system with the unique features of a dense bed and an external heat exchanger are, on the surface, thought to be a high power user compared to other CFB technologies. Due to lower solids density in the combustor and the EHE only using approximately 10% of the total air requirements, the usage is comparable to other systems.

The figure shown attached (Figure 6) shows a typical CFB system without an EHE and without a dense bed in the lower combustor (left side of figure). Also in Figure 6 note the main power users in such a system.

Table 5. Power Consumption Comparison

Typical Example:
300,000 lbs/hr steam
300°F stack temperature
Process air horsepower - $3.56 \times 10^{-5} \times$ lbs/hr x in. w.c.
(all except ID fan)
Process air horsepower $5.02 \times 10^{-5} \times$ lbs/hr x in. w.c.
(I D fan)

	CFB w/o EHE			MSFB with EHE		
	lbs/hr	M.W.C	AHP	lbs/hr	M.W.C.	AHP
Primary Air	239,460	55.5	473.1	186,100	47.0	311.4
EHE Air				70,700	23.5	59.1
Sec. Air	128,940	30.0	137.7	182,300	9.0	58.4
Induced draft	397,870	17.0	339.5	397,870	30.0	599.2
Circulation Pump				0.15 H P per 1000 lbs.		45.0
High Pressure Loop Seal Air	0.25 HP per 1000 lbs.		75.0			
			1025.3			1073.1

The right of Figure 6 shows the MSFB system with an EHE and dense bed. Again note the power users.

Proper fan and motor selection must be made to optimize the kilowatt usage. To make a comparison of a typical CFB process vs the MSFB, the air horsepowers required for the process are utilized here.

In the example we have picked 300,000 lbs/hr as a typical average size industrial system.

Note in Table 5 an example of the typical system CFB without a dense bed and external heat exchanger vs the MSFB system. Note the comparable major power requirements of the two systems.

In closing, the intent of this paper was to present several of the "Practical Aspects" of the MSFB systems and show some of the distinct differences between typical CFB's and the Multisolid Fluid Bed System (MSFB).

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The Company reserves the right to make technical and mechanical changes or revisions resulting from improvements developed by its research and development work, or availability of new materials in connection with the design of its equipment, or improvements in manufacturing and construction procedures and engineering standards.