DESIGN, DEVELOPMENT AND TESTING OF A CIRCULATING FLUIDISED BED COMBUSTOR FOR INCINERATION OF AGRIWASTE

A Thesis
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CERTIFICATE

This is to certify that the thesis entitled "**DESIGN, DEVELOPMENT AND TESTING OF A CIRCULATING FLUIDISED BED COMBUSTOR FOR INCINERATION OF AGRIWASTE",** being submitted by **Mr. ISHBIR SINGH,** Registration No. 8048109, in partial fulfillment of the requirements for the award of degree of Master of Engineering (CAD/CAM & ROBOTICS) at Thapar Institute of Engineering and Technology (Deemed University), Patiala, is a bonafide work carried out by him under my supervision and guidance and no part of this thesis has been submitted to any other university or institute for the award of any degree.

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ABSTRACT

The increasing problem of the disposal of solid waste has presented many a city with a dilemma while choosing suitable disposal methods. The traditional means of disposal of solids wastes like coal washery rejects and middling, municipality waste, rice husk, saw dust etc. have been open dumping, land filling or dumping in the sea. These practices have been discouraged due to non availability of land and new environmental legislation. In India, fluidised bed combustion technology is gradually emerging as a potential technology for the incineration of solid wastes like washery rejects and middling, rice husk, saw dust and municipality wastes etc. a number of small scale fluidised bed combustion power plants have been commissioned in India in recent past.

In the present work some components of a laboratory scale circulating fluidised bed combustor have been designed and developed in the department. Agriwaste briquettes were also prepared and tested in the CFBC system. A mathematical model was also developed to study the physico-chemical parameters of a 10 MW atmospheric FBC system at Jalkheri (Fatehgarh Sahib). Effect of particle size and composition on superficial velocity, minimum fluidisation velocity and bubble diameter were investigated.

LIST OF FIGURES AND TABLES

NOMENCLATURE

A	Ash content in fuel (%)
A_c	Cross-sectional area of the particle (cm^2)
Ai	Cross-sectional area at inner surface (cm^2)
A_o	Cross-sectional area at outer surface (cm^2)
A_t	Cross-sectional area of the bed (cm^2)
C_d	Co-efficient of discharge through orifice
C_D	Drag coefficient, a function of the particle shape and Reynolds number
D_b	Bubble diameter (cm)
D_{bm}	Maximum bubble diameter (cm)
D_{bo}	Initial bubble diameter (cm)
d_{or}	Diameter of orifice (cm)
d_p	Fuel particle diameter (cm)
d_{pav}	Average diameter of fuel particles (cm)
E_{xair}	Fractional excess air
F_{ME}	Actual molar feed rate (g.mol/s)
F_{MTH}	Stoichiometric air feed rate (g.mol/s)
g	Acceleration due to gravity (cm/s^2)
g_c	Conversion factor g/(dyne.s^2)
H	Height of the bed in fluidised state (cm)
h	Heat transfer coefficient A(W/m^2K)
K	Constant (dimensionless)
k	Thermal conductivity (W/m/K)
N_D	Number of orifice openings
N_{or}	No. of orifices per unit area of distributor
Nu	Nusselt number (dimensionless)
P_{av}	Average pressure in the combustor (atm)
Pr	Prandtl number (dimensionless)
r	Radius of the particle (cm)
Re	Reynolds number (dimensionless)
R_g	Gas constant (atm.cm^3/g.mol.K)

t	Wall thickness (cm)
T_b	Bed Temperature (K)
U	Overall coefficient of heat transfer (W/m^2K)
U_{mf}	Minimum fluidisation velocity (cm/s)
U_o	Minimum fluidisation velocity (cm)
U_{or}	Velocity of fluid through orifice (cm/s)
V	Volume of the fluid (cm^3)
V_s	Velocity of the fluid (cm/s)
W_{fuel}	Fuel feed rate into the combustor (g/s)
XC	Carbon content in fuel (%)
XH	Hydrogen content in fuel (%)
XO	Oxygen content in fuel (%)
XS	Sulphur content in fuel (%)
XW	Moisture content in fuel (%)
ΔP_d	Pressure drop across the bed (atm.)
ΔP_f	Pressure drop due to static weight (hydrostatic head) of fluid in bed (atm.)
ΔP_s	Pressure drop due to static weight of the solid in bed (atm.)
ΔP_w	Pressure drop due to friction at the wall (atm.)

Greek Symbols

α	Average porosity or void fraction of bed in fluidised state
θ_1	Temperature of hot fluid (K)
θ_2	Temperature of hot fluid (K)
θ_m	Logarithmic mean temperature difference (K)
μ_g	Viscosity of fluidising gas (g/cm.s)
ρ_f	Density of the fluid (g/cm^3)
ρ_g	Density of fluidising gas (g/cm^3)
ρ_p	Density of fuel particles (g/cm^3)

CONTENTS

CHAPTER 1
INTRODUCTION

Agriwaste has traditionally been the chief source of heat energy in rural areas and a valuable fuel in the sub urban areas. Inspite of rapid increase in the supply and access to use of fossil fuels, agriwaste is likely to continue to play an important role in India, as in several other developing countries, in the foreseeable future. Thus developing and promoting techno-economically viable technologies to utilize agriwaste efficiently remains a pursuit of high priority.

India being an agriculture based country, 70% of (share in GDP) its main income comes from agriculture sector. Any enhancement of income from this sector is based upon adequate supply of basic inputs in this sector. Regular and adequate power supply is one such input. But the position of power supply in our country defies both these characteristics. A major portion of power supply produced being sent to industrial and urban consumers, there is a perennial shortage of power in the agriculture sector. Consequently, there is an emergent need to produce more power in order to fulfill the needs of this sector effectively.

One way of accomplishing this is setting up captive or rural based small power generation plants. In these power plants, instead of water-head, diesel oil or coal, we can use agriwaste to produce electricity. One such power plant can satisfy the power need of 25 to 50 nearby villages.

The agriwastes like rice straw, saw dust, sugarcane-trash, coir-pith, peanut shells, wheat stalks and straw, cottonseed stalks and husk, soybean stalks, maize stalks and cobs, sorghum, bagasse, waste wood, walnut shells, sunflower seeds, shells, hulls, kernels and coconut husk can be fruitfully utilized in power generation. This stuff is otherwise a waste and liability and consumes a lot of effort on its disposal, in addition to being a fire hazard. Apart from the above, it causes serious air pollution in the form of smoke, unburnt suspended particles and unwanted addition of heat to atmosphere. Surely, agriwaste stuff at present is available in abundance and prospects of its utilization in producing energy are enormous. These agriwaste components can be procured at low rates from farmers who will thus be benefited economically, apart from being relieved of the responsibility of its disposal.

1.1 Fluidised Bed Combustion System

The major portion of the coal available in India is of low quality, high ash content and low calorific value. The traditional grate fuel firing systems have got limitations and are techno-economically unviable to meet the challenges of future. Fluidised bed combustion has emerged as a viable alternative and has significant advantages over conventional firing system and offers multiple benefits viz. compact boiler design, fuel flexibility, higher combustion efficiency and reduced emission of obnoxious pollutants such as SO_x and NO_x. The fuels burnt in these boilers include coal washery rejects, rice husk, bagasse and other agricultural wastes. The fluidised bed boilers have a wide capacity range of 0.5 T/hr to over 100 T/hr.

1.2 Mechanism of Fluidised Bed Combustion

When an evenly distributed air or gas is passed upward through a finely divided bed of solid particles such as sand supported on a fine mesh, the particles are undisturbed at low velocity. As air velocity is gradually increased, a stage is reached when the individual particles are suspended in the air stream – the bed is called “fluidised”.

This principle of fluidisation is illustrated in Figure 1.1.

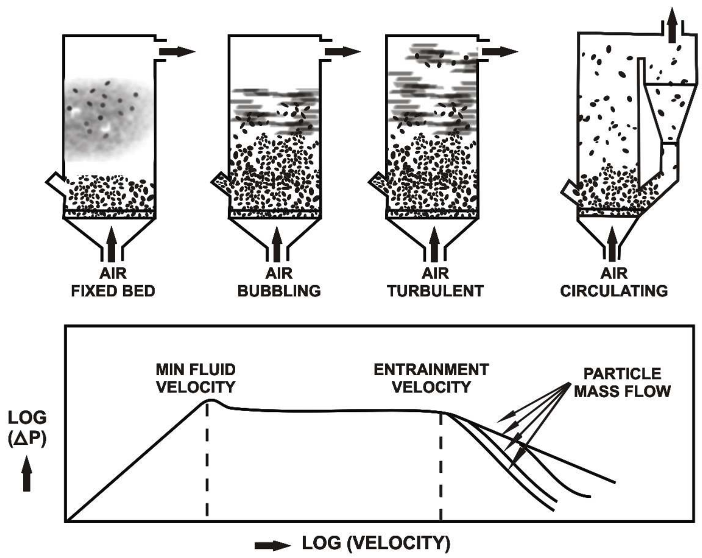
With further increase in air velocity, there is bubble formation, vigorous turbulence, rapid mixing and formation of dense defined bed surface. The bed of solid particles exhibits the properties of a boiling liquid and assumes the appearance of a fluid – “bubbling fluidised bed”.

At higher velocities, bubbles disappear, and particles are blown out of the bed. Therefore, some amounts of particles have to be recirculated to maintain a stable system – “circulating fluidised bed”.

Fluidisation depends largely on the particle size and the air velocity. This means solid velocity increases at a slower rate than does the gas velocity, as illustrated in Figure 1.2. The difference between the mean solid velocity and mean gas velocity is called as slip velocity. Maximum slip velocity between the solids and the gas is desirable for good heat transfer and intimate contact.

If sand particles in a fluidised state are heated to the ignition temperatures of coal, and coal is injected continuously into the bed, the coal will burn rapidly and bed attains a uniform temperature. The fluidised bed combustion (FBC) takes place at about 840°C to 950°C. Since this temperature is much below the ash fusion temperature, melting of ash and associated problems are avoided.

The lower combustion temperature is achieved because of high coefficient of heat transfer due to rapid mixing in the fluidised bed and effective extraction of heat from the bed through in-bed heat transfer tubes and walls of the bed. The gas velocity is maintained between minimum fluidisation velocity and particle entrainment velocity. This ensures stable operation of the bed and avoids particle entrainment in the gas stream.



Fixing, bubbling and fast fluidised beds
As the velocity of a gas flowing through a bed of particles increases, a value is reached when the bed fluidises and bubbles form as in a boiling liquid. At higher velocities the bubbles disappear and the solids are rapidly blown out of the bed and must be recycled to maintain a stable system.

Figure 1.1: Variation of Pressure Drop vs. Gas Velocity

Combustion process requires the three "T"s that is Time, Temperature and Turbulence. In FBC, turbulence is promoted by fluidisation. Improved mixing generates evenly distributed heat at lower temperature. Residence time is many times greater than conventional grate firing. Thus an FBC system releases heat more efficiently at lower temperatures.

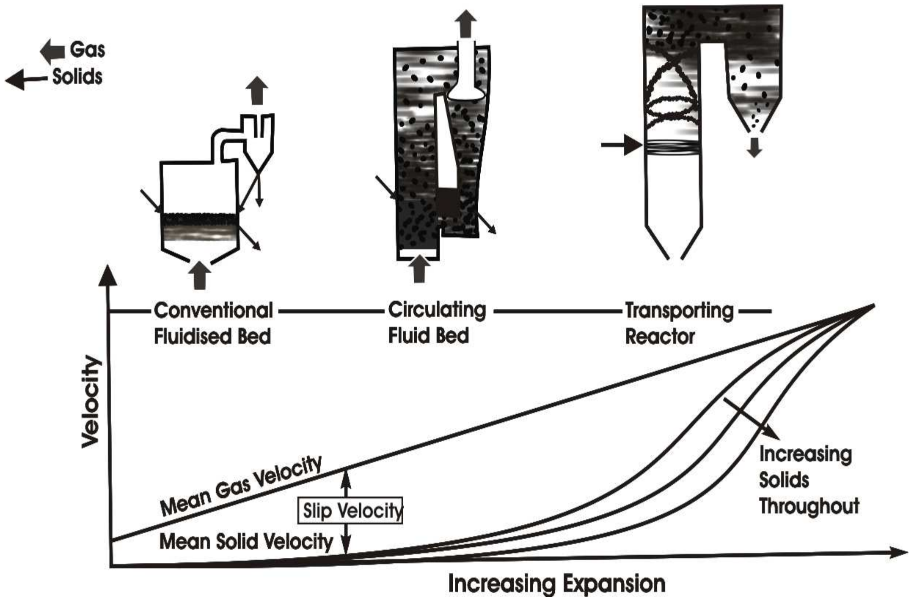


Figure 1.2: Relation between Gas Velocity and Solid Velocity

Since limestone is used as particle bed, control of sulphur dioxide and nitrogen oxide emissions in the combustion chamber is achieved without any additional control equipment. This is one of the major advantages over conventional boilers.

1.3 Advantages of Fluidised Bed Combustion Boilers

- The smooth, liquid like flow of particles allows continuous, automatically controlled operation with ease of handling.
- Rapid mixing of solids leads to nearly isothermal conditions throughout the combustor, hence the operations can be controlled easily and reliably.
- It is suitable for large scale operations.
- Heat and mass transfer rates between gas and particles are high when compared with other modes of contacting.
- The rates of heat transfer between a fluidised bed and an immersed object is high hence heat exchangers with fluidised bed requires relatively small surface areas.
- Since the bed temperature is kept normally below 1000°C, little atmospheric nitrogen is converted to NO_x.
- Low grade fuels can be used in the system.

1.4 Chronological Development of FBC

Innovation and refinement have always been generic terms of those creative activities of humanity that, in modern times we classify as technology. Each innovation is followed by a sequence of refinements, the motivation for which comes from several factors such as utility, economy, reliability, and performance etc. The area of circulating fluidised bed combustion of agriwaste for power generation has evolved as a result of these motivations.

India is perhaps one of the few countries in the world to have drawn up a comprehensive strategy and action plan and set specific medium term goals for renewable energy based capacity addition in the energy sector of the country. Growing population and the rapid pace of industrialization have resulted in high growth rates in energy demand. Today, the country consumes around 98 million tonnes of oil, around 400 million tonnes of coal and around 450 billion units of electricity. In addition, a large quantity of non-commercial forms of energy, which some estimates put at around 40% of total energy use, is also used. The non-commercial forms of energy include agriwaste, animal wastes, and draught animal power. In recent years, use of some agriwastes, typically rice husk, in industries as boiler fuel has also taken root because of the following reasons:

- Conservation of coal and other non-renewable natural resource.
- Mitigating the emission of green house gas (GHG) i.e. CO_2 as rice husk is a carbon neutral fuel.
- Contributing to a small increase in the local employment by employing skilled and un-skilled personnel for operation and maintenance of the equipment.
- Adopting an advanced and sustainable technology for long term benefits.
- Helping to abridge the gap of electricity demand and supply at local level.

A fluidised bed combustor consists of a collection of combustible particles suspended in an upward flowing gas stream at such a velocity that the particles are not carried out of the vessel but continue to circulate vigorously within the vessel. Cavities, usually called 'bubbles' move through the suspended mass which help the vigorous circulation of the bed material. Since the bed offers resistance to flow, the drag forces, as given by pressure drop across the bed, are sufficient to support the weight of the bed.

Thus the bed has a pseudo-density and has many attributes of a liquid (Davidson et al., 1977).

During the 70's the research on fluidised bed combustion was pursued more vigorously due to the following reasons:

- Relative increase in oil prices and its uncertain supply due to political crisis in gulf countries.
- Problems faced by conventional pulverized fuel fired boilers.
- Adoption of strict pollution control regulations by environment ministries of different countries.
- Use of low grade fuels.

1.5 Types of Fluidised Bed Combustion Boilers

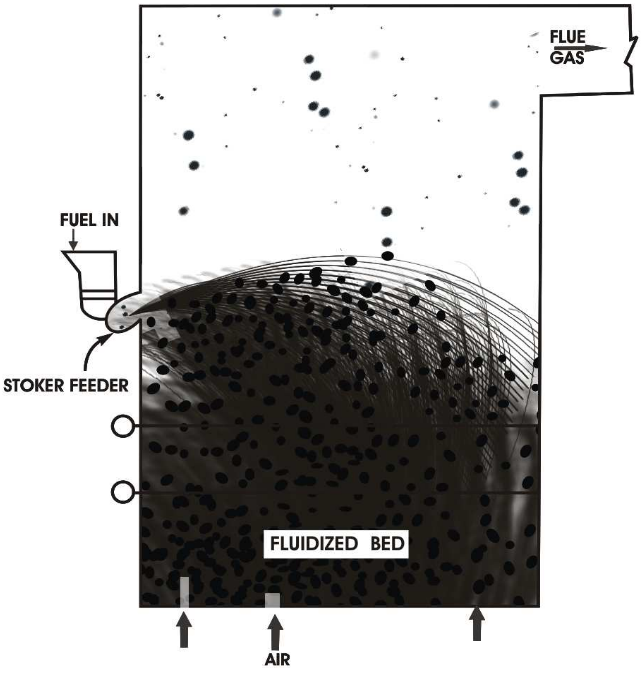
There are three basic types of fluidised bed combustion boilers:

1. Atmospheric Classic Fluidised Bed Combustion System (AFBC)
2. Atmospheric Circulating (fast) Fluidised Bed Combustion System (CFBC)
3. Pressurized Fluidised Bed Combustion System (PFBC).

1.5.1 Atmospheric Classic Fluidised Bed Combustion System (AFBC)

In AFBC, the combustible materials having wide size distribution are fed into the combustion chamber. The atmospheric air, which acts as both the fluidisation air and combustion air, is delivered at a pressure and flows through the bed after being preheated by the exhaust flue gases. The velocity of fluidising air is in the range of 1.2 to 3.7 m /sec. The rate at which air is blown through the bed determines the amount of fuel that can be combusted.

Almost all AFBC/ bubbling bed boilers use in-bed evaporator tubes in the bed of limestone, sand and fuel for extracting heat from the bed to maintain the bed temperature. The bed depth is usually 0.9 m to 1.5 m deep and the pressure drop averages about 25 mm of water per mm of bed depth. Very little material leaves the bubbling bed – only about 2 to 4 kg of solids are recycled per ton of fuel burned. Typical fluidised bed combustors of this type are shown in Figure 1.3 and Figure 1.4.



Features of bubbling bed boiler

Fluidised bed boiler can operate at near atmospheric or elevated pressure and have these essential features:

- Distribution plate through which air is blown for fluidising.
- Immersed steam-raising or water heating tubes which extract heat directly from the bed.
- Tubes above the bed which extract heat from hot combustion gas before it enters the flue duct.

Figure 1.3: Bubbling Bed Boiler-I

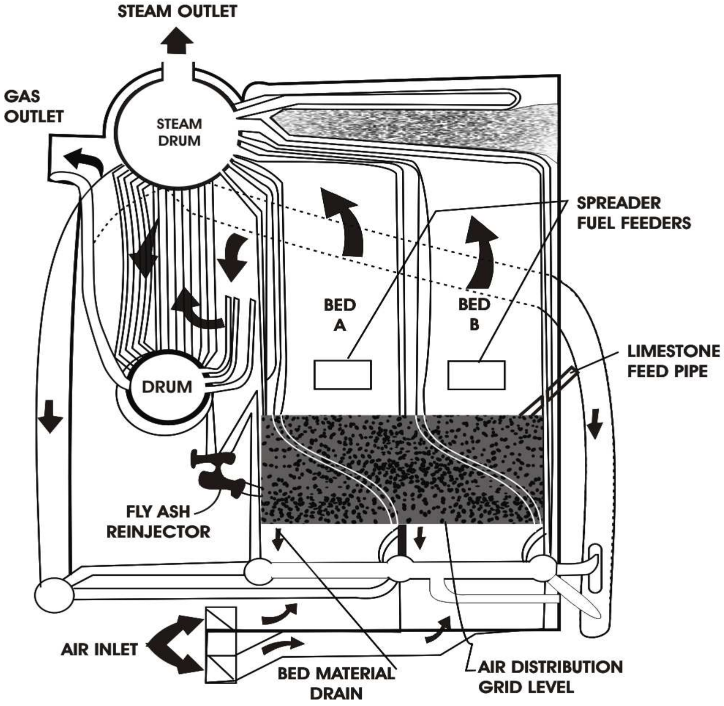


Figure 1.4: Bubbling Bed Boiler-II

The combustion gases pass over the super heater sections of the boiler, flow past the economizer, the dust collectors and the air preheaters before being exhausted to atmosphere.

The main special feature of atmospheric fluidised bed combustion is the constraint imposed by the relatively narrow temperature range within which the bed must be operated. With coal, there is risk of clinker formation in the bed if the temperature exceeds 950°C and loss of combustion efficiency if the temperature falls below 800°C. For efficient sulphur retention, the temperature should be in the range of 800°C to 850°C.

1.5.2. Circulating Fluidised Bed Combustion System (CFBC)

Circulating Fluidised Bed Combustion (CFBC) technology has evolved from conventional bubbling bed combustion as a means to overcome some of the drawbacks associated with conventional bubbling bed combustion as shown in Figure 1.5.

This CFBC technology utilizes the fluidised bed principle in which crushed (6 –12 mm size) fuel and limestone are injected into the furnace or combustor. The particles are suspended in a stream of upwardly flowing air (60-70% of the total air), which enters the bottom of the furnace through air distribution nozzles. The fluidising velocity in circulating beds ranges from 3.7 to 9 m/sec. The balance of combustion air is admitted above the bottom of the furnace as secondary air. The combustion takes place at 840°C to 900°C, and the fine particles (< 450 microns) are elutriated out of the furnace with flue gas velocity of 4-6 m/s. The particles are then collected by the solid separators and circulated back into the furnace. Solid recycle is about 50 to 100 kg per kg of fuel burnt.

There are no steam generation tubes immersed in the bed. The circulating bed is designed to move a lot more solids out of the furnace area and to achieve most of the heat transfer outside the combustion zone - convection section, water walls, and at the exit of the riser. Some circulating bed units even have external heat exchangers. The particles circulation provides efficient heat transfer to the furnace walls and longer residence time for carbon and limestone utilization. Similar to pulverized coal (PC) firing, the controlling parameters in the CFBC process are temperature, residence time and turbulence.

For large units, the taller furnace characteristics of CFBC boiler offers better space utilization, greater fuel particle and sorbent residence time for efficient combustion and SO_2 capture, and easier application of staged combustion techniques for NO_x control than AFBC generators. CFBC boilers are said to achieve better calcium to sulphur utilization 1.5 to 1 vs. 3.2 to 1 for the AFBC boilers, although the furnace temperatures are almost the same.

CFBC boilers are generally claimed to be more economical than AFBC boilers for industrial application requiring more than 75 – 100 T/hr of steam.

CFBC requires huge mechanical cyclones to capture and recycle the large amount of bed material, which requires a tall boiler.

A CFBC could be a good choice if the following conditions are met.

- Capacity of boiler is large to medium.
- Sulphur emission and NO_x control is important
- The boiler is required to fire low-grade fuel or fuel with highly fluctuating fuel quality.

Major performance features of the circulating bed system are as follows:

a) It has a high processing capacity because of the high gas velocity through the system.

b) The temperature of about 870°C is reasonably constant throughout the process because of the high turbulence and circulation of solids. The low combustion temperature also results in minimal NO_x formation.

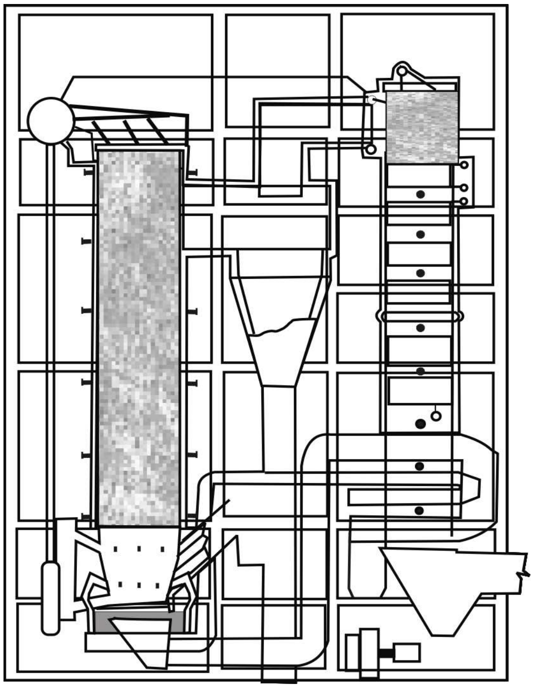
c) Sulphur present in the fuel is retained in the circulating solids in the form of calcium sulphate and removed in solid form. The use of limestone or dolomite sorbents allows a higher sulphur retention rate, and limestone requirements have been demonstrated to be substantially less than that with bubbling bed combustor.

d) The combustion air is supplied at 1.5 to 2 psi rather than 3-5 psi as required by bubbling bed combustors.

e) It has high combustion efficiency.

f) It has a better turn down ratio than bubbling bed systems.

g) Erosion of the heat transfer surface in the combustion chamber is reduced, since the surface is parallel to the flow. In a bubbling system, the surface generally is perpendicular to the flow.



Circulating Bed Boiler
At high fluidising gas velocities in which a fast recycling bed of fine material is superimposed on a bubbling bed of larger particles. The combustion temperature is controlled by rate of recycling of fine material. Hot fine material is separated from flue gas by a cyclone and is partially cooled in a separate low velocity fluidised bed heat exchanger where the heat is given up to the steam. The cooler fine material is then recycled to the dense bed.

Figure 1.5: Circulating Bed Boiler Design

1.5.3. Pressurized Fluid Bed Combustion System (PFBC)

Pressurized Fluidised Bed Combustion (PFBC) is a variation of fluidised bed technology that is meant for large-scale coal burning applications. In PFBC, the bed vessel is operated at pressure up to 16 atm. (16 kgf/cm^2).

The off-gas from the fluidised bed combustor drives the gas turbine. The steam turbine is driven by steam raised in tubes immersed in the fluidised bed. The condensate from the steam turbine is pre-heated using waste heat from gas turbine exhaust and is then taken as feed water for steam generation.

The PFBC system can be used for cogeneration or combined cycle power generation. By combining the gas and steam turbines in this way, electricity is generated more efficiently than in conventional system. The overall conversion efficiency is higher by 5% to 8%. A pressurized fluid bed combustion boiler is shown in Figure 1.6

At elevated pressure, the potential reduction in boiler size is considerable due to increased amount of combustion in pressurized mode and high heat flux through in-bed tubes. A comparison of size of a typical 250 MW PFBC boiler versus conventional pulverized fuel-fired boiler is shown in the Figure 1.7.

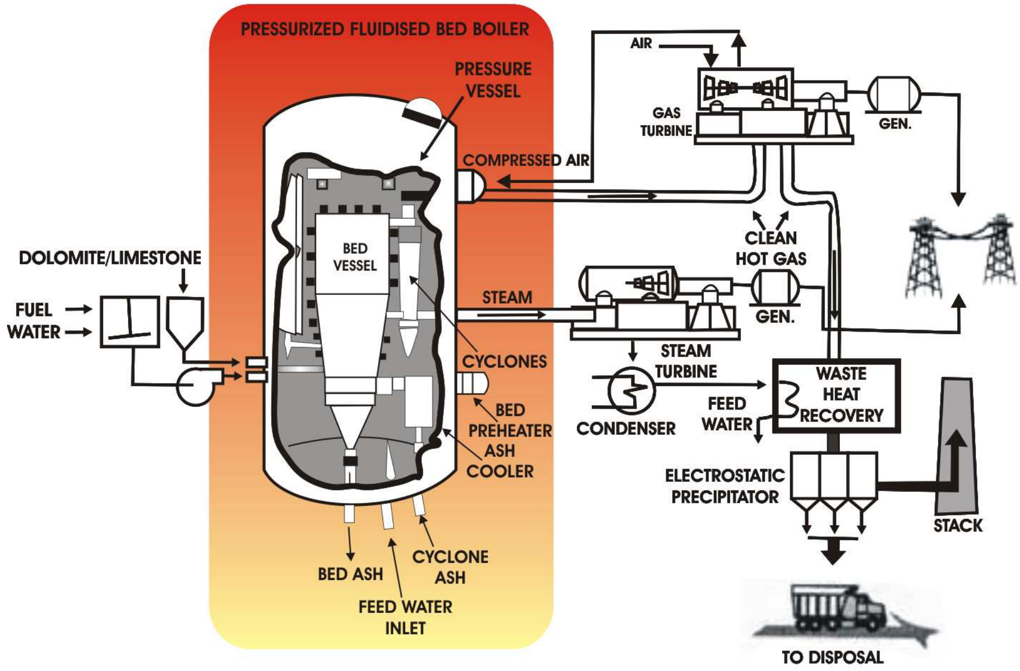


Figure 1.6: PFBC Boiler for Cogeneration

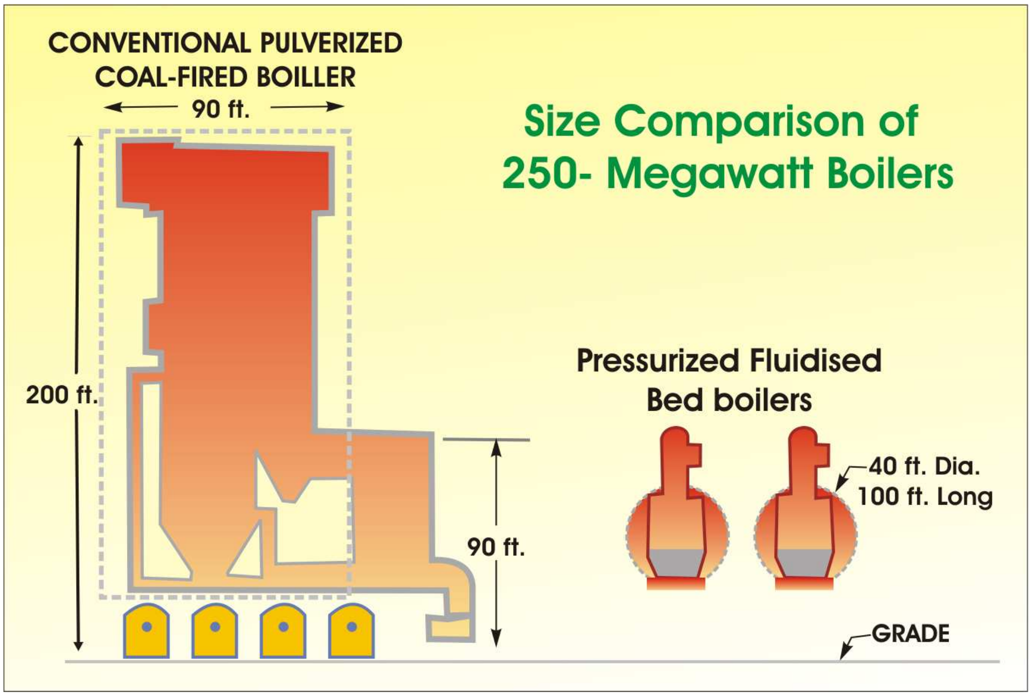


Figure 1.7: Comparison of PFBC Boiler and Pulverized Fuel Boiler

CHAPTER 2

LITERATURE REVIEW

Power is a critical infrastructure for economic development and for improving the quality of life. The achievement of increasing installed power capacity from 1362 MW to over 100,000 MW since independence and electrification of more than 500,000 villages is impressive in absolute terms. However, it is a matter of concern that the annual per capita consumption of India, at about 350 kWh is among the lowest in the world. Further, people in a large number of villages have no access to electricity.

Table 2.1 gives status of agriwaste power/co-generation in India.

Table 2.1: Status of Agriwaste Power/Co-Generation in India

SOURCE OF AGRIWASTE	AGRIWASTE GENERATED	SURPLUS AGRIWASTE
Crop & Agri Industrial Residue (excl. Bagasse)	465	115-135
Forest Sources	35	25-35
Total (Million Mt/Yr)	**500**	**140-170**

POWER POTENTIAL

From Surplus Agriwaste	16,000 MW
From Bagasse	3,500 MW
Total	**19,500 MW**

BAGASSE CO-GENERATION POTENTIAL

STATE	POTENTIAL (IN MW)
Maharashtra	1000
Uttar Pradesh	1000
Tamil Nadu	350
Karnataka	300
Andhra Pradesh	200
Bihar	200
Gujarat	150
Punjab	150
Haryana & Others	100
Total	**3500**

2.1 Agriwaste Based Power Generation/Cogeneration in India

Status: Agriwaste, consisting of wood fuels, crop residues and animal dung continues to dominate energy supply in rural and traditional sectors, having about one-third share in the total primary energy consumption in the country. Co-generation technology, based on multiple and sequential use of a fuel for generation of steam and power, aims at surplus power generation in process industries such as sugar mills, paper mills, rice mills, etc. The aggregate biomass combustion based power and sugar-cogeneration capacity by the end of December 2000 was 273 MW, with 210 MW of cogeneration and the rest biomass power. In the area of small-scale biomass gasification, a total capacity of 35 MW has so far been installed, mainly for stand alone applications. The combined potential of biomass and sugar-cogeneration based power generation is estimated to be 19.5 GW. The cogeneration potential from bagasse in existing 21430 sugar mills is alone about 3.5 MW, with Maharashtra and Uttar Pradesh accounting for about 2 GW potential.

Development Stages: The prime power generation technologies using biomass are direct combustion, cogeneration and gasification. Bioenergy systems are ideal for decentralized power applications as well as grid connections. Power generation systems can range from small scale (5-100 kW), medium scale (1-10 MW) to large-scale (about 50 MW) (Ravindranath and Hall, 1995) applications. Unlike other energy forms like wind, small hydro and solar, biomass power is not site specific, i.e. it can be set up at any location where plants can be grown and domestic animals reared. Cogeneration and biomass based power generation offer attractive alternatives for captive power generation when grid electricity supply is unreliable. Agriwaste based power generation offers *environmental benefits* such as reclamation of degraded land and improvements in land productivity, lower level of emissions of carbon dioxide and local pollutants like particulates and SO_x. Organized production of wood fuels and modernized conversion has potential to make wood fuels a competitive commercial fuel vis-à-vis the fossil fuels. Power projects based on biomass plantations have the potential to offer new avenues of employment through collection, storage, handling and utilization of biomass materials especially in rural areas, promote rural industries and generate rural employment. Besides all this, energy plantations can become means to restore deforested and degraded lands in tropical and subtropical regions. Table 2.2 provides detailed data of agriwaste in India.

2.2 Agriwaste-Based Power Generation/Cogeneration in Punjab

2.2.1 Agriwaste projects to generate more power

Government of Punjab has drawn out a proposal for setting up 10 biomass-based projects of total 100 MW capacity in areas where biomass is available in abundance. The proposal has been sent to the Ministry of Non-Conventional Energy Sources (MNES) to seek international funding from Japanese Bank for International Cooperation (JBIC) under Overseas Development Assistance programme of the Japanese government.

The sites identified by Punjab Energy Development Association (PEDA), which is the nodal agency for setting up these biomass-based projects are Mansa, Dera Bassi, Nawanshahr, Barnala, Raikot, Garhshankar, Jaito, Sultanpur Lodhi, Tarn Taran and Bathinda. According to a survey conducted by PEDA along with the Ministry officials to ascertain the availability of biomass in 37 tehsils of the state, it was found that an estimated of 342 MW of power can be generated from this sector and setting up of these projects would help harness at least 100 MW of the available potential.

Of the total project cost of Rs. 450 crore, 90 per cent (Rs. 405 cr) has been sought from the JBIC as a soft loan package at a rate of interest of 1.5 per cent and 10 per cent (Rs. 45 cr) will be provided by PEDA. The Union Ministry of Environment and Forest, Department of Economic Affairs and Ministry of Finance, will facilitate international funding for these projects.

At present, the state has the capacity to generate about 200 MW of power through these projects. PEDA has already identified 135 small micro/hydel sites having a potential of generating 135 MW of power.

2.2.2 PEDA to produce power from agriwaste

In a significant development which could enable the Punjab Government to overcome the acute shortage of electricity, the Punjab Energy Development Agency (PEDA) has allocated six projects to private companies to produce 66 MW of power from agriwaste.

Six projects, which would be set up in Sangrur and Patiala districts, would get a subsidy of 20 per cent from the Central Government and would start producing electricity within two years. The power produced by these projects would be purchased by the Punjab State Electricity Board (PSEB) under its power purchase agreement (PPA).

Not only this, the PEDA has also decided to set up 10 projects on its own to produce 120 MW of electricity to enable the PSEB to overcome the shortage of power.

For this, the PEDA has taken up its case with the World Bank demanding Rs. 700 crore for funding the projects.

Six projects have already been allocated to private companies while work on other 16 projects is going on. PEDA had decided to set up these projects after it came to know that the PSEB was running its agriwaste project at **Jalkheri**, in Fatehgarh Sahib district for the past many years.

Agriwaste electricity projects were being set up in those pockets of the state where the availability of agriculture wastes like rice husk was significant. Energy produced by such projects would be sold to the PSEB at the rate of Rs. 3.48 per unit despite the fact that during peak demand season, the board had been buying power at the rate of Rs. 9 per unit.

Quantum of energy produced by biomass projects would not be enough to overcome the power shortage but these would be helpful in bringing down the demand-supply gap to a considerable extent.

Table 2.3 gives the locations where PEDA is planning to set up biomass/agriwaste power projects to be set up in Punjab.

Table 2.3 Agriwaste Power Projects to be set up in Punjab (The Tribune, Nov. 18)

Taluka	**District**	**Estimated power generating potential (MW)**
Sunam	Sangrur	31
Ludhiana	Ludhiana	15
Nakodar	Jalandhar	12
Fatehgarh Sahib	Fatehgarh Sahib	11
Shahkot	Jalandhar	10
Phillour	Jalandhar	10
Patiala	Patiala	10
Ajnala	Amritsar	10
Jagraon	Ludhiana	10
Faridkot	Faridkot	9
Amloh	Fatehgarh Sahib	6
Anandpur Sahib	Roopnagar	5
Nihalsingh wala & Baghapurana	Moga	5
Samrala	Ludhiana	5
Abohar	Ferozepur	5
Phagwara	Kapurthala	5
Hoshiarpur-I	Hoshiarpur	4.5
Kharar	Ropar	2
Gurdaspur	Gurdaspur	2
Total		**167.5**

2.3 Review of Mathematical Models Available in Literature Regarding Combustion of Rice-husk / Agriwaste in FBC System

Mansaray et al. (2000) developed two models (a single compartment and a two-compartment) capable of predicting the steady state performance of a dual-distributor-type fluidised bed rice husk gasifier under a wide range of operating conditions. The models were based on material balance, energy balance and chemical equilibrium relations. The single compartment model neglected the complex hydrodynamic conditions prevalent in the gasifier and has only a single parameter (overall carbon conversion) that can be used to improve the fit between predicted and experimental gas compositions. The two-compartment model takes into consideration these complex hydrodynamic conditions and has two parameters (carbon conversion in the core and annular regions) that can be independently adjusted to account for the effect of various operating and design on the composition of the gasification products. The models could be used to predict the performance of the gasifier when operation on the other biomass materials.

The efficient operation of a fluidised bed rice husk gasifier is dependent on a number of complex chemical reactions, including fast pyrolysis of the rice husks, partial oxidation of pyrolysis products, gasification of the resulting char, conversion of tar and lower hydrocarbons, and the water gas shift reaction (van den Aarsen et al., 1982). These complicated processes, coupled with the sensitivity of the product distribution to the rate of heating and residence time in the reactor, called for the development of mathematical model capable of predicting the effect of process variables on the performance and dimensions of the gasifier. As a result, various models with widely differing complexity have been proposed to describe fluidised bed biomass gasification. These models range from complex kinetic models incorporating bed hydrodynamics and particle distributions (Gururajan et al., 1992; Wang & Kinoshita, 1993) to simple thermodynamic models based on reaction stoichiometry, chemical equilibrium, and mass and energy balances (Bacon et al., 1985; Double & Bridgewater, 1985; Maniatis, 1986; Double et al., 1989).

Mansaray et al. (2000) further checked the performance of two thermodynamic (one compartment and a two-compartment models), developed for fluidised bed gasification of rice husk, analyzed and compared in terms of their predictive capabilities of the product gas composition. The two-compartment model was the most adequate to simulate the fluidised bed gasification of rice husk, since the complex hydrodynamics present in the fluidised bed gasifier were taken into account.

Therefore, the two compartment model was tested under a wide range of parameters, including bed height, fluidisation velocity, equivalence ratio, oxygen concentration in the fluidising gas, and rice husk moisture content. The model sensitivity analysis showed that changes in the bed height had a significant effect on the reactor temperatures, but only a small effect on the gas composition, higher heating value, and overall carbon conversion. The fluidisation velocity, equivalence ratio, oxygen concentration in the fluidising gas, moisture content in the rice husk had dynamic effects on the gasifier performance. However, the model was more sensitive to variations in the equivalence ratio and oxygen concentration in the fluidising gas.

Mansaray et al. (2000) verified the two-compartment model developed for fluidised bed gasification of biomass and tested its validity using experimental data obtained from a dual-distributor-type fluidised bed gasifier. The fluidised bed was operated on rice husks at various bed heights (19.5, 25.5 and 31.5 cm), fluidisation velocities (0.22, .28, and 0.33 m/s), and equivalence ratios (0.25, 0.30 and 0.35). The model gave reasonable predictions of the core, annulus, and exit temperatures as well as the mole fractions of the combustible gas components and product gas higher heating value, except for the overall carbon conversion, which was overestimated. This could be attributed to uncertainties in the sampling procedure.

According to M. Shyam (2002) energy consumption in the rural India, particularly in the form of petroleum-based fuels, has increased manifold during the last 40 years. Fast depleting stocks of fossil fuels and steep increases in their prices may lead to an energy crisis in the not-too-distant future. Such a crisis will have a serious effect on all economic and domestic activity, particularly in the vast rural areas. Large quantities of crop residues resulting from crop cultivation activity are a promising source of energy supply for production, processing and domestic activities in rural India. The available crop residues are either being used inefficiently or burnt in the open to clear the fields for subsequent crop cultivation. A crop residue-based energy/electricity supply system will also help establish agriwaste based productive activities in rural areas and hence create large-scale employment for rural youth. Important biomass-based energy technologies developed under the All-India Co-ordinate Research Project on Renewable Sources of Energy for Agriculture and Agri based Industries and having potential for wider adaptation are described in this paper.

According to Bahillo et al. (2003) circulating fluidised bed technology is developed for the combustion of mixtures of different coals and wood- based waste to operate in an environmentally friendly way. Agriwaste has combustion characteristics which improve the combustion behaviour of low quality coal due to high volatile content and low sulphur, nitrogen and ash contents. In this work, the objective is to improve co-combustion of coal and wood- based biomass waste in CFB by pilot plant experiments, modeling and validation. The new CFB model can be effectively used to optimize co-combustion of coal and biomass from the point of view of the carbon combustion efficiency and the sulphur retention.

According to Nguyen Le Truong et al (2004) Vietnam is a developing country with an ever increasing power demand. The development of power sources is limited mainly to large central power plants using hydropower and traditional fossil fuels. Agriculture still plays a vital role in production activities generating high quantity of residues (biogas, straw, rice husk, etc.). These biomass residues could be a potential source for energy supply as well as for power production.

This paper summarizes and quantifies the potential of distributed power generation and cogeneration from biomass residues in Vietnam. Besides, present situation, obstacles and future trends of producing power from renewable energy in general and biomass energy in particular, are also discussed.

Chungsangunsit et al. (2004) described that the energy demand of Thailand has been steadily increasing at about 4% per year. A large portion of the fossil fuels is imported thus causing concern for energy security. In addition, utilization of fossil fuels is associated with emissions of CO_2, SO_2 and NO_x leading to environmental impacts. To approach the reduction of these problems, alternative (renewable) energy sources are proposed. Rice husk is a potential source of energy for an agricultural country like Thailand with high rice production. Rice mills can use rice husk generated by them as a fuel to produce energy. However, the environmental profile of the energy production must be assessed to ensure reduced environmental damage. This study has been carried out at the Roi ET Green Project which is a pilot project of capacity 9.8 MW using rice husk as the feedstock. The power plant uses 290 tons of rice husk and 1,400 tons of water in one day, and has a power requirement of 1 MW. Net power output is 8.8 MW, which will be sold to Electricity Generation Authority of Thailand (EGAT) for 21 years under the small power producer (SSP) scheme.

The raw materials consumed and environmental emissions of energy production from rice husk are determined. The study shows that the emissions of SO_2 and NO_x are lesser in case of coal and oil- fired power generation, but higher than for natural gas. The emission of CO_2 from combustion of rice husk are considered zero since they do not contribute to global warming. CO and dust emission are slightly higher than conventional power plant. Overall, the study indicates that rice husk is a viable feedstock for electricity production and performs better than fossil fuels (especially coal and oil) from the point of view of environmental emissions.

Kwong et al. (2004) pointed out biomass as a major form of renewable energy due to its neutral position in the emission of green house gases such as carbon dioxide. An experimental study was conducted to investigate the effect of co- combustion of coal and rice husk on the combustion performance and pollutant emissions in a bench scale pulverized fuel combustion reactor. Parameters including the blending ratio of rice husk in coal and the excess air ratio were investigated. Apart from gaseous pollutants, information on the emission of particulate matters was also collected. Due to the decrease in the heating value of rice husk, combustion temperature and energy output from the co-firing process were lower compared to coal combustion alone. However, it was seen that pollutant emission was reduced in the co-combustion process. Gaseous pollutant emissions including CO, CO_2, NO_x and SO_2 were reduced substantially with the increase of the blending ratio of rice husk in coal. An optimum range between 10% and 30% rice husk to coal ratio was found to be the optimum point in terms of gaseous pollutant emission per energy output for SO_2 and NO_x. Emission of particulate matters was found to decrease with co- combustion of rice husk and coal. The finding from this study confirmed that rice husk can be a good renewable fuel for co-firing with coal combustion in terms of energy efficiency and environmental impact.

James R. Arcate (2005) described biomass power as a proven electricity generating option in the United States. By separating biomass processing from the energy application, the proposed concept eliminates some of the efficiency and cost disadvantages of today's biopower industry. The concept entails production of charcoal from biomass at separate, independent, dedicated charcoal plants. A variety of biomass is used as feedstock for charcoal e.g., wood and wood wastes, agricultural crop waste byproducts, and crops grown specifically for energy production.

The preferred method for producing charcoal from biomass is a high-yield pressurized process developed by Dr. Michael J. Antal at the University of Hawaii, Hawaii Natural Energy Institute. Conversion times are less than 2 hours with yields from 35% to 50%.

Charcoal is delivered to Pressurized Fluid Bed Combustion (PFBC) power plants where it is used as a fuel to generate steam and electricity. Charcoal is co-fired with coal, or if sufficient quantities of biomass for charcoal are available, dedicated charcoal PFBC power plants can be developed. Commercially available first generation PFBC power plants have efficiencies up to 42 percent. Advanced PFBC power plants in the development stage are expected to have efficiencies of 45 to 50 percent.

CHAPTER 3

DESIGN ASPECTS OF CFBC SYSTEM

A Circulating fluidised bed combustor has been designed and developed in the department of mechanical engineering at TIET Patiala. Some of its design aspects that have been discussed in this chapter are:

i) Design of distributor plate
ii) Design of heat transfer coil
iii) Design of components of an experimental CFBC system at TIET, Patiala (viz. Furnace, Plenum, Nozzles)

3.1 Design of Distributor Plate

The purpose of the distributor plate is to introduce the fluidising air evenly through the bed cross section thereby keeping the solid particles in constant motion, and preventing the formation of defluidisation zones within the bed. The distributor, which forms the furnace floor, is normally constructed from metal plate with a number of perforations in a definite geometric pattern. The perforations may be located in simple nozzles or nozzles with bubble caps, which serve to prevent solid particles from flowing back into the space below the distributor.

The distributor plate is protected from high temperature of the furnace by:

i) Refractory Lining
ii) A Static Layer of the Bed Material or
iii) Water Cooled Tubes.

Experiments have shown that the quality of bubbling fluidisation is strongly influenced by the type of gas distributor used. The findings are summarized below:

- For few air inlet openings the bed density fluctuates appreciably at all flow rates (20 to 30%) though more severely at high flow rates. The bed density varies with height and gas channeling may be severe.
- For many air inlet openings the fluctuation in bed density is negligible at low flow rates and again becomes appreciable at high flow rates. Bed density is more uniform throughout, bubbles are smaller, and gas-solid contacting is more intimate with less channeling of gas.

- Although contacting is superior when densely consolidated porous media or plates with small orifices are used, still, from the standpoint of industrial or large-scale operations, such distributors have the serious drawback of high pressure drop. This may significantly increase the power consumption of the blowers, often a major cost factor.
- In the design of a good distributor, first the available pressure drop is determined and with this in mind, the type of distributor prior to detail design is selected.
- In the choice of materials both metallic and ceramics have certain advantages. Ceramics are more resistant to corrosive gases and to high temperature, but they have a very low strength against thermal shock or expansion stresses. Ceramics are also relatively easily eroded, resulting in a gradual widening in the orifice opening. In general metallic distributors are preferred because of strength and overall economics.

Figure 3.1 illustrates several examples of grids and distributors. Type (a) a flat perforated plate or wire mesh, is commonly used for laboratory-scale operation. It has the advantage that fines are apt to fall through the orifices when the gas flow is stopped. This can be countered by using two staggered perforated plates (b). This is convenient for industrial operations because it retains the advantages of the single plate, i.e. ease of design and construction coupled with good gas distribution.

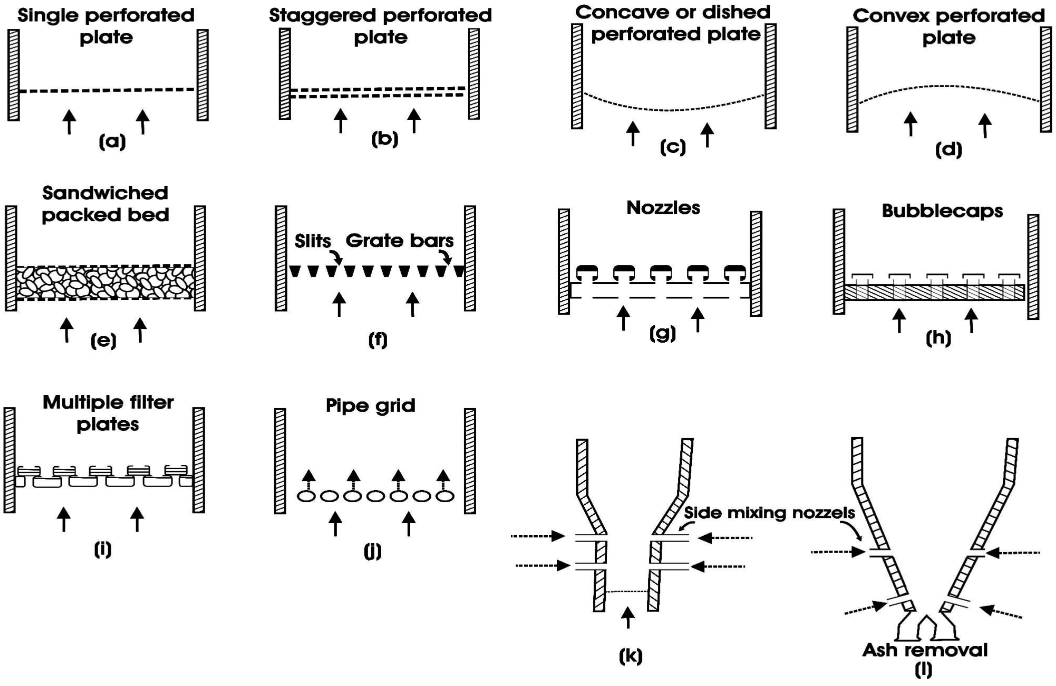


Figure 3.1: Various Distributors for Fluidised Bed

With heavy load in large diameter beds, flat plates deflect unpredictability, hence curved plates, types (c) and (d) are used. These withstand heavy loads and thermal stresses well. Because bubbling and channeling tend to occur preferentially near the center axis of a fluidised bed, the design helps to counter this tendency. Distributor type (d) can achieve good contacting only with more orifices near the perimeter and fewer in the central region, a disadvantage from the point of view of fabrication. Actually for any perforated plate the dual requirement of good gas distribution and low pressure drop may require careful design with non-uniform orifice spacing.

When the inlet gas is free of solids, type (e) a packed bed of granular material sandwiched by two perforated plates, is a good distributor and an excellent thermal insulator protecting low temperature inlet gases from a hot bed. Type (f) that consists of slits between grate bars has roughly the same characteristics as flat perforated plate, but somewhat less uniform gas distribution.

Nozzle type (g) and bubble caps type (h) have been used to prevent solids from falling through the distributor. In spite of their complicated construction, gas distribution is not superior to (b) and (e). In addition, solids are apt to settle and sinter and stick on the bottom surface.

The multiple filter plates of type (i) give better gas distribution than (g) and (h), however special precaution may be needed to ensure that the inlet gas is free from filter clogging material. Sometimes to improve the flow characteristics, in a fluidised bed, gas is injected through nozzles arranged on the sidewalls as in type (k). This has been used in the roasting of palletized zinc blank.

In the new design for winkler generator, gas is introduced through six side mixing nozzles in to bed as in type (l). This is claimed to be a great improvement over the original mechanical grates with their high maintenance cost.

As there are many possibilities in the design of distributors, and only good judgment and experience will tell what modification and combination of types in any given application. Distributors should be selected and designed with care, for this is the first step to the successful application of a fluidised bed process.

The design of distributor plates comprises of following steps:

- Determination of pressure drop across the distributor plates.

  Minimum fluid velocity necessary for fluidisation can be calculated by equating the drag force on a particle due to motion of the fluid to the weight of the particle. Thus,

$$C_D A_c \rho_f \frac{V_s^2}{2g_c} = V\rho_p \frac{g}{g_c} \qquad (01)$$

Where,

C_D : Drag coefficient, a function of the particle shape and Reynolds number, dimensionless
A_c : Cross-sectional area of the particle = πr^2 (cm^2)
r : Radius of the particle (cm)
ρ_f : Density of the fluid (g/cm^3)
V_s : Velocity of the fluid (cm/s)
V : Volume of the fluid = $\frac{4}{3}\pi r^3$ (cm^3)
ρ_p : Density of the solid particle (g/cm^3)
g : Acceleration due to gravity (cm/s^2)
g_c : Conversion factor, 10^{-2} g/(dyne.s^2)

For a spherical particle the above equation becomes,

$$V_s = (\frac{8}{3C_D}\frac{\rho_s}{\rho_f} rg)^{1/2} \qquad (02)$$

The total pressure drop ΔP in a fluidised bed is composed of three components:

$$\Delta P = \Delta P_w + \Delta P_s + \Delta P_f \qquad (03)$$

Where,

ΔP_w : Pressure drop due to friction at the wall (atm.)

ΔP_s : Pressure drop due to static weight of the solid in bed (atm.)

ΔP_f : Pressure drop due to static weight (or hydrostatic head) of fluid in bed (atm.)

Fluidised beds usually have large wall diameters, so ΔP_w is relatively small. The fluid in a fluidised-bed combustor varies in a complex manner from air to hot gaseous combustion products. Their average density is much smaller than that of the solids, and ΔP_f, therefore, is also relatively small. So, the above equation reduces to

$$\Delta P = \Delta P_s = H(1-\alpha)\rho_s \frac{g}{g_c} \qquad (04)$$

Where,

H : Height of the bed in fluidised state (cm)

α : Average porosity or void fraction of bed in fluidised state

= Fraction not occupied by solids (dimensionless) = 0.4

- Calculation of Reynolds number for the total flow approaching the plate and select the corresponding value of C_d.
- Determination of velocity of fluid through orifice using :

$$U_{or} = C_d\left(\frac{2g\Delta P_d}{\rho_g}\right)^{1/2} \qquad (05)$$

- No. of orifices per unit area of distributor, Nor is decided and the corresponding orifice diameter is calculated as :

$$U_o = \frac{\pi}{4} d_{or} U_{or} N_{or} \qquad (06)$$

Where,

U_{or} : Velocity of fluid through orifice (cm/s)

C_d : Co-efficient of discharge through orifice (Generally taken as 0.62)

g : Acceleration due to gravity (cm/s^2)

ΔP_d : Pressure drop across the bed (atm.)

ρ_g : Density of fluidising gas (g/cm^3)

d_{or} : Diameter of orifice (cm)

U_o : Minimum fluidisation velocity (cm)

N_{or} : No. of orifices per unit area of distributor

Distributor plate is fabricated from mild steel (18 gage) sheet. Diameter of the distributor plate is 406 mm. With 14 nozzles, 1 nozzle at the centre, 5 nozzles at the radial distance of 102 mm and remaining 8 nozzles at a radial distance of 203 mm. This distributor plate is fitted at the distance of 51 mm from the bottom of the furnace and welded to the furnace to make a leak proof joint.

3.2 Design of Heat Transfer Coil

Heat transfer coil is a device in which energy is transferred from one fluid to another across a good conducting solid wall. The purpose of designing heat transfer coil is the effective transfer of heat energy between the two fluids. For the effective heat transfer it is made of copper metal because of the reason that thermal conductivity of copper is high and the bed material selected is sand, ash, crushed refractory or limestone, with an average size of about 1 mm. Depending on the bed height these are of two types: shallow bed and deep bed.

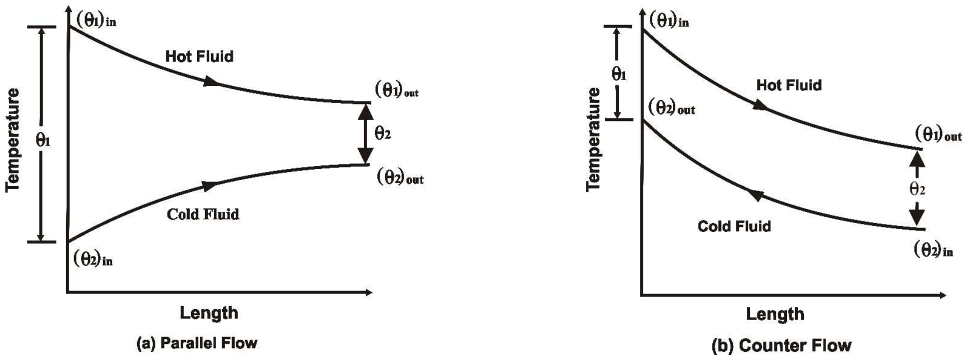
At the same fluidising velocity, the two ends fluidize differently, thus affecting the heat transfer to an immersed heat transfer surfaces. A shallow bed offers a lower bed resistance and hence a lower pressure drop and lower fan power consumption. In the case of deep bed, the pressure drop is more and this increases the effective gas velocity and also the fan power.

In a fluidised in-bed heat transfer, it is necessary to transfer heat between the bed material and an immersed surface, which could be that of a tube bundle, or a coil. The heat exchanger orientation can be horizontal, vertical or inclined. From a pressure drop point of view, a horizontal bundle in a shallow bed is more attractive than a vertical bundle in a deep bed. Also, the heat transfer in the bed depends on number of parameters like:

(i) Bed pressure
(ii) Bed temperature
(iii) Superficial gas velocity
(iv) Particle size
(v) Heat exchanger design
(vi) Gas distributor plate design

Depending on the type of fluid flow, heat transfer coils have two types of arrangement: parallel flow arrangement and counter flow arrangement. In the co-current of parallel flow arrangement, the fluid (hot and cold) enter the unit from the same side, flow in the same direction and subsequently leave from the same side Figure 3.2(a). So the flow of fluids is unidirectional and parallel to each other.

In the counter-current or counter flow arrangement, the fluids (hot and cold) enter the unit from opposite ends, travel in opposite direction and subsequently leave from opposite ends Figure 3.2(b). So the flow of liquids is opposite to each other.



(a) Parallel Flow

(b) Counter Flow

Figure 3.2: Temperature changes of fluids during parallel and counter flow

For a given surface area, the counter-flow arrangement gives the maximum heat transfer rate and is naturally preferred for the heating and cooling of fluids. Counter flow heat exchanger design is most efficient in terms of heat transfer rate per unit surface area. This is due to the fact that the average T (difference in temperature) of the two fluids is maximized as shown in Figure 3.2(b). Therefore the log mean temperature difference (LMTD) for a counter flow heat exchanger is more than that of a similar parallel or cross flow heat exchanger.

Table 3.1 gives the details of the parameters assumed for calculation of pipe length of heat transfer coil.

Minimum fluidising velocity at 200°C, U_{mf}	0.25 m/s

Parameter	**Value**
Mass flow of gasses, m	0.5 kg/s
Air inlet temperature, $(\theta_1)_{in}$	50°C
Air outlet temperature, $(\theta_1)_{out}$	200°C
Water inlet temperature, $(\theta_2)_{in}$	20°C
Water outlet temperature, $(\theta_2)_{out}$	80°C
Tube material	copper
Tube bore, d_i	12 mm
Tube outside diameter, d_o	15 mm
Chosen particle	Silica sand
Particle size, d_p	427 µm

Table 3.1: Parameters Assumed for Calculation of Pipe Length

Table 3.2: Physical Properties Assumed for Calculation of Pipe Length

Physical Properties	
Particle density, ρ_p	2640 kg/m^3
Air mean specific heat, S_{air}	1.04 KJ/kgK
Air thermal conductivity at 200°C, K_a	3.87×10^{-2} W/mK
Air density at 1atm, 200°C, ρ_g	0.746kg/m^3
Air viscosity at 200°C, μ_g	2.58×10^{-5}kg/ms
Water viscosity at 50°C, μ_w	544×10^{-6}kg/ms
Water Prandtl number at 50°C, Pr	3.54
Water specific heat, S_w	4.18kJ/kgK
Water thermal conductivity, K_w	643×10^{-6}kW/mK
Copper thermal conductivity, K_{Cu}	380W/mK

Table 3.2 gives the list of various physical properties assumed in the calculation of pipe length of heat transfer coil.

The duties required from the heat exchanger and water flow rate are:

Duty, $D = m \times S_{air} \times \Delta t$ (07)

$= 0.5 \times 1.04 \times (200\text{-}50)$

$= 78$ KW

Water flow rate, $Q_w = D/(S_w \times \Delta t)$ (08)

$= 78 / 4.18 \times (80\text{-}20)$

$=0.311$kg/s

If this water flow is passed through a single tube, the water velocity will be:

Water velocity, $u_w = Q_w / A_t$ (09)

$= 0.311 / (\pi/4 \times 0.012^2\times10^3)$

$= 2.74$m/s

We now proceed to estimate the heat transfer coefficient at the inner and the outer surface of the tube using the following empirical correlations:

At the inner surface,

$$Nu = 0.023\,(Re)^{0.8}(Pr)^{0.4} \quad (10)$$

Where,

Nu : Nusselt number (dimensionless)

Re : Reynolds number (dimensionless)

Pr : Prandtl number (dimensionless)

A_t : Area of tube = $\pi d_i^2/4$ (m^2)

We know,

$$Re = (\rho_w \times u_w \times d_i / \mu_w) \tag{11}$$

$= (10^3 \times 2.74 \times 0.012) / (544 \times 10^{-6})$

$= 60441.176$

Using equation 10, we get,

$Nu = 0.023\ (60441.176)^{0.8} (3.54)^{0.4}$

$= 254.92$

At the inner surface,

Heat transfer coefficient,

$$h = Nu \times K_w / d_i \tag{12}$$

$= 254.92 \times 643 \times 10^{-6} / 0.012$

$= 13.61\ KW/m^2K$

At the outer surface, first checking that it is not outside its range of applicability [$Ar < 26000$ and $Re_{mf} < 12.5$]

Archimidies number,

$$Ar = (d_p)^3 \times \rho_g \times \rho_p \times g / (\mu_g)^2 \tag{13}$$

$= (427 \times 10^{-6})^3 \times 0.745 \times 2640 \times 9.81 / (2.58 \times 10^{-5})^2$

$= 2260$

Reynolds number at minimum fluidisation velocity,

$$Re_{mf} = \rho_g \times U_{mf} \times d_p \tag{14}$$

$= 0.745 \times 0.25 \times 427 \times 10^{-6} / (2.58 \times 10^{-5})$

$= 3.08$

Using equation

$$h_{max} = 35.8 \times \rho_p^{0.2} \times K_a^{0.6} \times d_p^{-0.36} \tag{15}$$

$= 35.8 \times (2640^{0.2}) \times (3.87 \times 10^{-2})^{0.6} \times (427 \times 10^{-6})^{-0.36}$

$= 402 W/m^2K$

70 % of this value gives the heat transfer coefficient at the outer surface of the tube.

i.e h_o = 70 % of ($402 W/m^2K$)

$= 281 W/m^2K$

Overall heat transfer coefficient in terms of bed to liquid thermal resistance, (1/ UA) is given by:

$1/h_oA_o$: Convection resistance due to fluid film at outside surface (W/m^2K)
$1/h_iA_i$: Convection resistance due to fluid film at inside surface (W/m^2K)
t/kA_m : Wall conduction resistance(W/m^2K)

$$\frac{1}{UA} = \frac{1}{h_oA_o} + \frac{1}{h_iA_i} + \frac{t}{kA_m} \tag{16}$$

Where,

$A_o = \pi d_o L$
$A_i = \pi d_i L$
$A_m = 0.5\,\pi\,(d_o+d_i)\,L$

$$\text{Hence } (1/UA) = \frac{1}{\pi L}\left[\frac{1}{0.281\times 0.015} + \frac{1}{13.61\times 0.012} + \frac{0.003}{0.380\times 0.027}\right]$$

$$= 243.6/\pi L \; W/m^2K$$

Logarithmic mean temperature difference (LMTD) is based on water inlet and outlet temperature and the assumption that the temperature of the bed of the fluidised particle is that of the outlet temperature of the gas namely 200°C.

$$\text{Thus, (LMTD), } \theta_m = \frac{\theta_1 - \theta_2}{\log_e(\theta_1/\theta_2)} \tag{17}$$

$$= \frac{(200-80)-(200-20)}{\ln\frac{200-80}{200-20}}$$

$$= 148 \text{ K}$$

The overall thermal resistance = (LMTD) /duty

Equating (1/ UA) and overall thermal resistance, we get,

Tube length, L required = (243.6 × 78) / (148×π)

= 40.87 m

3.3 Design of Components of an experimental CFBC System at TIET Patiala

After designing distributor plate and heat transfer coil, components of CFBC system need to be designed. These designed components after assembly will help us in setting up an experimental set-up of CFBC system. Some of the components designed in this work are:

- Furnace
- Plenum
- Nozzles
- Cyclone
- Tubing
- Chimney
- Steam Outlet
- Economizer
- Ash Sump
- Piping

Table 3.3 gives the basic details i.e. names and specifications of some of the components of the experimental CFBC system set-up at TIET Patiala.

Table 3.3 Specifications of Components of CFBC System at TIET

Components/parts	Material/specification
Furnace, cyclone, economizer	Mild steel – 18 gage
Nozzles	Mild steel – tapered drilled
Tubing	Copper
Base plate	Mild steel
Piping	G.I
Insulation	Fireclay
Bed	Silica sand, dolomite
Rotameter	
Manometer	
Thermocouples	
Blower	3hp, air velocity = 30.5m/s, 2.2kW

3.3.1 Furnace

Furnace is made up of mild steel (18 gage) sheet rolled to form a cylinder. The internal diameter of the cylinder is 406 mm and height is 914 mm. With the plenum at the base, the furnace contains four input windows for feeding fuel at a height of 127 mm, 279 mm, 432 mm, and 559 mm from the bottom of the furnace. These windows can be closed or opened as desired.

Figure 3.3 shows the model of furnace designed with the help of Pro-E software.

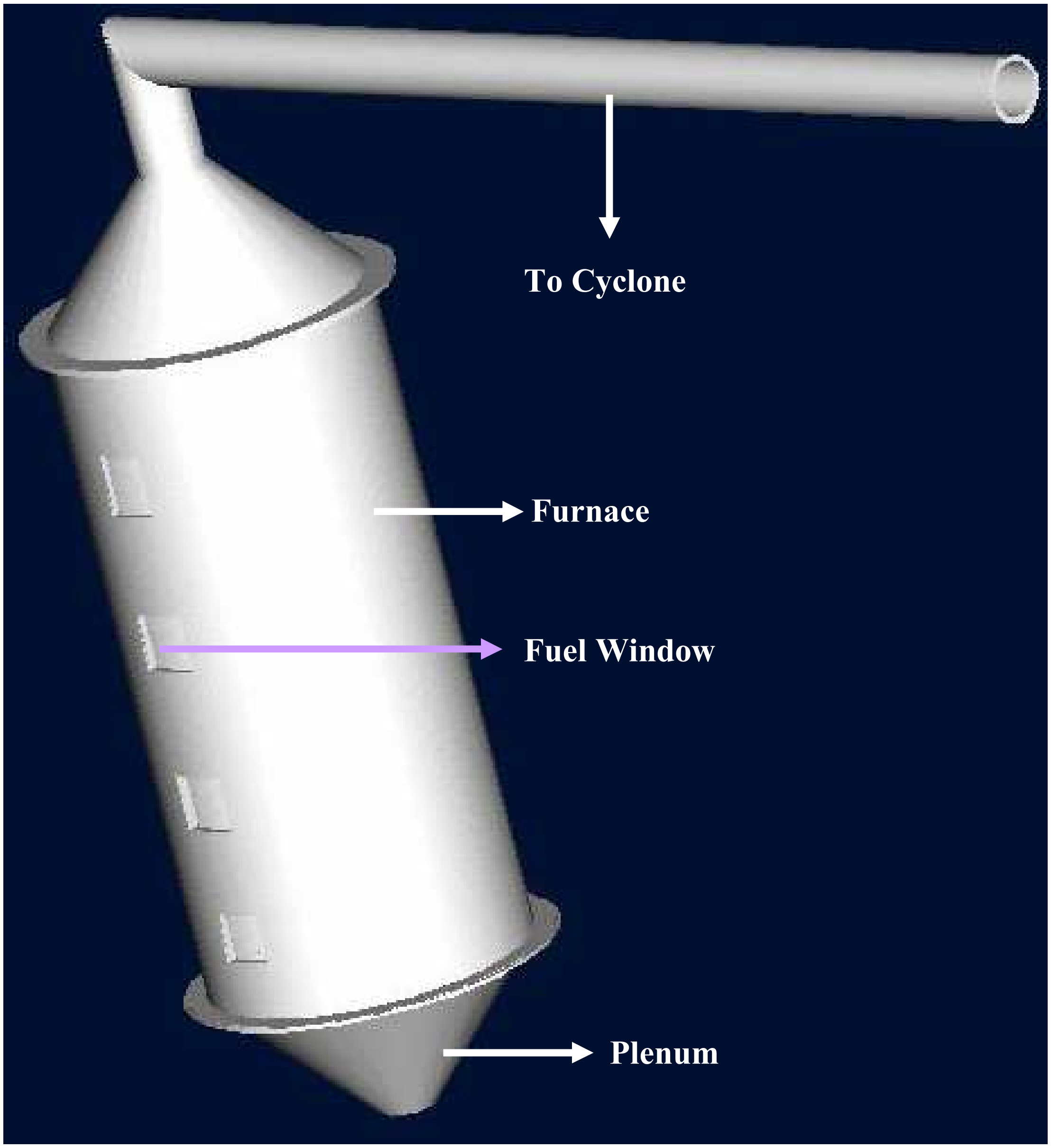


Figure 3.3: Furnace

3.3.2 Plenum

Plenum is used to collect the air from blower and to pass the air equally into the furnace through the nozzles in the distributor plate.

The plenum is made of a frustum of a cone of mild steel (18 gage) sheet. The height of the frustum is 203 mm, with 406 mm bigger diameter and 76 mm smaller diameter. Air is fed from the blower into the plenum with the 76 mm diameter GI pipe fitted at 76 mm diameter of the frustum.

This plenum is welded at the extreme bottom of the furnace to form a leak proof space between the distributor plate and the cone.

Figure 3.4 shows the model of plenum designed with the help of Pro-E software.

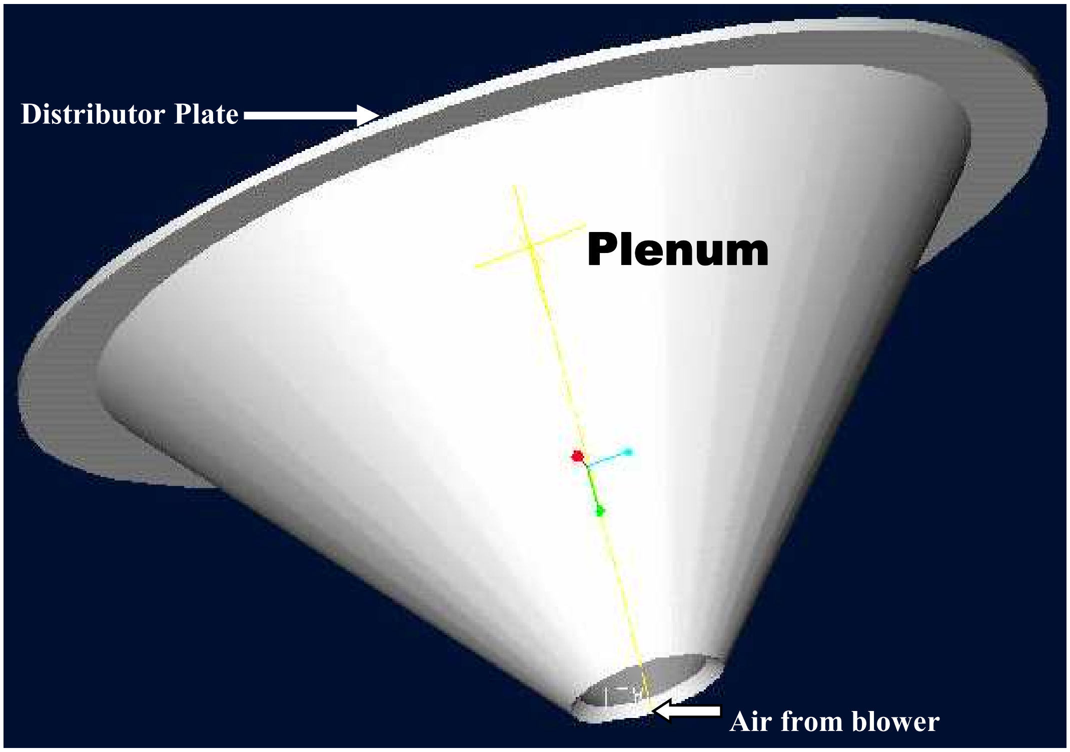


Figure 3.4: Plenum

3.3.3 Nozzles

The nozzles are used to inject air at high pressure into the furnace and distribute air equally into the furnace, these are also used to form hydrodynamics in the furnace. The nozzles are made from mild steel rod of diameter 19 mm. This rod is tapered drilled with inlet port diameter 15 mm and exit port diameter 3 mm. the height of the nozzle is 63.5 mm. Each nozzle contains one exit port only.

3.3.4 Cyclone

The design of cyclone is shown in the figure below along with its working. A cyclone has been made with an internal diameter of 178 mm and height 635 mm.

Figure 3.5 shows the cyclone which is a part of a CFBC system set-up at TIET, Patiala.

Figure 3.5: Cyclone

The shape of cyclone is cylindrical at the top and conical at the bottom. The flue gases are allowed to enter tangentially into the cyclone.

3.3.5 Tubing

The tubing made of copper is used for producing steam. The internal diameter is 12 mm and outer diameter is 15 mm. The length of the pipe taken is 13 m. With 1.17 m forming the uppermost and the lowermost horizontal tube and 10.7 m forming the middle vertical tube. The inlet of water is from the lower most horizontal tubing to the vertical middle tubing and then to the uppermost horizontal tubing which exits steam out of the furnace.

3.3.6 Chimney

The design of chimney is shown in the figure. The height of chimney is 2.4 m and having base diameter 571 mm.

Figure 3.6 shows the chimney which is a part of a CFBC system set-up at TIET, Patiala.

Figure 3.6: Chimney

3.3.7 Steam Outlet

The design of steam outlet is shown in the figure. The size of the steam outlet is 76 ×356 mm.

Figure 3.7 shows the steam outlet which is a part of a CFBC system set-up at TIET, Patiala.

Figure 3.7: Steam outlet

3.3.8 Economizer

The water before feeding into the copper tubing is first preheated in economizer to elevate its temperature and hence increasing the overall efficiency of the system.

3.3.9 Ash Sump

The ash and the dust remains in the flue gases settle in the ash sump. The flue gases are then exhausted into the atmosphere through ash sump.

3.3.10 Piping

These above explained components are then assembled together with the help of GI pipes of variable diameters.

Table 3.4 gives the specifications of various pipe fittings used for the assembly of designed components.

Table 3.4: Specifications of Various Pipe Fittings

S.No	Parts	Quantity	Length	Specifications(diameter)
1	Elbows	2		76 mm
		3		51 mm
2	Sockets	2		76 mm
		3		51 mm
3	Pipe length	2	5 ft	76 mm, 51 mm
		1	3 ft	51 mm
4	Reducers	4		

After assembling all the components designed for furnace we get a final shape of the furnace. Figure 3.8 shows final setup of an assembled furnace.

Figure 3.8: Assembled Furnace

Assembly of furnace and all other necessary components gives the final CFBC system. Figure 3.9 shows the final assembly of experimental CFBC system set-up at TIET Patiala.

Figure 3.9: Experimental Set-up of CFBC System at TIET Patiala

CHAPTER 4

PREPARATION OF AGRIWASTE BRIQUETTES

4.1 Experiment

Shredding leaves of ashoka and teakwood tree.

4.1.1 Apparatus

Shredding machine, three phase power supply.

4.1.2 Procedure

1. Ashoka and teakwood tree leaves were collected.
2. Collected leaves were dried in sunlight for one day.
3. Dried leaves were put in the shredding machine.
4. Shredded leaves were collected from the box at the bottom of the machine.
5. Shredded leaves were again dried for one day in sunlight.
6. Fuel was made out of these shredded leaves.

4.1.3 Precautions

1. Leaves should be properly dried.
2. While putting leaves in the machine do not insert hand in the machine.
3. Wires of shredding machine should be properly insulated.

Figure 4.1 shows shredding machine in use for the case of ashoka tree leaves.

Figure 4.1: Shredding Machine

4.2 Procedure for Making Briquettes of Ashoka Tree Leaves and Cow Dung

4.2.1 Apparatus Required

1. 203 mm dye.
2. Shredded leaves of ashoka tree.
3. Universal testing machine.
4. One tray for making slurry.

4.2.2 Procedure

1. Cow dung and shredded leaves of ashoka tree were taken in same amount.
2. Cow dung was mixed with water in the tray and slurry was made.
3. Mixed it with shredded leaves of ashoka tree.
4. Then this mixture was put into the dye.
5. Then this dye was placed in the universal testing machine.
6. 2-5 KN pressure was put on the mixture placed in the dye.
7. Briquettes were removed from the dye and were placed in sunlight till they dried.

4.2.3 Precautions

1. Bolts of dye should be properly tightened.
2. Leaves should be properly shredded.

Figure 4.2 shows the briquettes made from ashoka tree leaves and cow dung.

Figure 4.2: Briquette of Ashoka Tree Leaves and Cow Dung

4.3 Procedure for Making Briquettes of Teakwood Tree Leaves and Cow Dung

Procedure adopted for making briquettes of teakwood tree leaves and cow dung is same as described before in the case of ashoka tree and cow dung.

Figure 4.3 shows the briquettes made from teakwood tree leaves and cow dung.

Figure 4.3: Briquette of Teakwood Tree Leaves and Cow Dung

4.4 Testing of Briquettes in CFBC System

For testing of briquettes in CFBC system a well set procedure is followed. According to which to clean the combustion bed, blower is switched on and the fan is made to run for 10 minutes. Then burnt particles and other residues are removed from the combustion chamber using some tool. Fan is used to remove burnt particles from the nozzles. Then dry sand is added into the bed combustion chamber taking precaution that it doesn't enters into the nozzles.

The layer of sand is made to the height of 38 mm. After this dolomite is added to the combustion chamber through the inlet opening. It is added in amount just to cover the sand spread in the chamber. Now charcoal is added just to make the chamber hot. Then kerosene oil is added to burn the charcoal. Afterwards the fuel amount of 250gm in the shape of small cubes of 51×51 mm made up cow dung, leaves and grass is added into the combustion chamber. Then water supply is opened so that water flows through the pipes inside the chamber. After proper burning of fuel pressure reading is noted through pressure gauge for every 5 minutes which is 70 psi. Then temperature readings at different points of the boiler are taken through the thermocouples which are printed out through data logger.

The apparatus for testing consist of a F.D fan, combustion chamber, steam outlet, I.D fan, chimney, blower, thermocouples, electric power and small turbine.

The fuel made up of mixture of cow dung, ashoka tree leaves is used. About 5 kg charcoal was also used for initial burning. The particle of size of charcoal used was 5-10 mm. 2 kg dolomite was also used in the base of the combustion boiler because dolomite coal burns properly. Figure 4.4 shows dolomite coal used in the CFBC system.

Figure 4.4: Dolomite

Dry sand (2 kg) is also used at the bottom of the combustion bed because it is bad conductor of heat and restricts heat transfer. About 1 litre kerosene oil is used for initial burning of charcoal. The kerosene oil is used for charging the furnace. Waste cotton is also used for initial burning.

Figure 4.5 shows thermocouples used for measuring bed temperature and the combustion chamber while combusting briquettes in CFBC system.

Figure 4.5: Combustion Chamber

4.4.1 Drawbacks

The drawback noticed during operation was the problem comes in exhaustion. The pipe fitted on top of the combustion chamber had small diameter and needed to be of 76 mm instead of 63.5 mm.

4.4.2 Precautions

1. The sand used in combustion chamber should be dry.
2. The sand and dolomite should be added properly so that it doesn't enter into the nozzles.
3. The exhaust should be good so that fuel should burn properly and proper pressure should be maintained in the combustion chamber.
4. The readings should be taken accurately.
5. The induction of apparatus should be proper so that heat is not lost.
6. The electric connections should be proper.

CHAPTER 5

FUEL ANALYSIS

Fuel samples (feed, carryover and overflow) collected from the 10 MW FBC plant at Jalkheri and the briquettes made of teakwood leaves, ashoka tree leaves and cow dung were subjected to proximate analysis in the laboratory.

5.1 Proximate Analysis of Fuel

The term proximate analysis is defined as the determination of moisture, ash, volatile matter and fixed carbon.

5.1.1 Determination of Moisture

The moisture is defined as the difference in weight of sample when the same is heated at 110 °C for one hour under specified conditions.

5.1.1.1 Apparatus Required

1. Air Oven

Ventilated drying oven in which constant and uniform temperature of 110°C can be maintained.

2. Silica Crucible

One silica crucible is required.

3. Weighing Machine

Weighing machine is required for weighing sample.

5.1.1.2 Procedure

Silica crucible was taken, cleaned and dried in an oven at 110°C for one hour. It was cooled for 15 minutes and then weighed accurately. Approximately one gram of sample was weighed and put into the silica crucible. Then crucible was kept in an air-dried oven, which was maintained at 110°C for one hour. After one hour crucible was removed from the oven, cooled in a desicator and then weighed accurately.

5.1.1.3 Calculations

Weight of dried and empty crucible with lid = a gm
Weight of sample and crucible = b gm
Weight of sample and crucible after heating = c gm
Therefore, weight of sample after heating = (b-a) gm.
Moisture = (b-c) gm.
Percentage of Moisture = {(b-c)/(b-a)}×100

5.1.2 Determination of Volatile Matter

Volatile matter is defined as the loss of weight of sample when the same is heated under specified conditions in the absence of air at 900◦C for 9 minutes.

5.1.2.1 Apparatus Required

1. Muffle Furnace

A muffle furnace capable of giving uniform temperature of 900°C with the necessary thermocouples and pyrometers.

2. Silica Crucible

A translucent silica crucible with lid having external diameter of 25 mm should be used. The total height of crucible should not exceed 38 mm and internal diameter should not be less than 22 mm

5.1.2.2 Procedure

For the determination of volatile matter, a crucible with lid was taken and then weighed accurately. Now one gram of sample was weighed accurately into the crucible and spread evenly in the crucible by gentle tapping the crucible with the lid was transferred in the furnace at 900°C for nine minutes.

After nine minutes, the crucible was removed from the furnace and placed on a cooled iron plate to ensure rapid cooling. Then the crucible was placed in a desicator for 15 minutes for further cooling and then weighed accurately.

5.1.2.3 Calculations

Weight of dried and empty crucible with lid = a gm
Weight of sample and crucible = b gm
Weight of sample and crucible after heating = c gm
Therefore, weight of sample after heating = (b-a) gm.
Loss of weight = (b-c) gm.
Percentage of Volatile Matter = {(b-c)/(b-a)}×100

5.1.3 Determination of Ash

Ash is defined as the weight of residue left when a known weight of sample is burned at 800°C for one hour under specified conditions.

5.1.3.1 Apparatus Required

1. Muffle Furnace

A muffle furnace is capable of giving uniform temperature of 900°C with the necessary thermocouples and pyrometers.

2. Silica Crucible

A translucent silica crucible with lid having external diameter of 25 mm should be used. The total height of crucible should not exceed 38 mm and internal diameter should not be less than 22 mm.

5.1.3.2 Procedure

For the determination of ash silica dish was taken, and heated at 800°C for one hour. Then the dish was cooled for 20 minutes and then weight of empty dish was taken. Then one gram of sample was weighed accurately in a balance and the sample was spread evenly in the crucible.

Then silica dish containing sample as placed in the furnace at 450°C for half an hour. Then the temperature of the furnace was raised to 800°C. The dish was kept at this temperature for another one hour. Then the dish was taken out, cooled and weighed accurately.

5.1.3.3 Calculations

Weight of dried and empty crucible with lid = a gm
Weight of sample and crucible = b gm
Weight of sample and crucible after heating = c gm
Therefore, weight of sample after heating = (b-a) gm.
Weight of Ash = (c-a) gm.
Percentage of Ash = $\{(c-a)/(b-a)\}\times100$

Table 5.1 gives the results obtained after proximate analysis of different briquettes made of agriwaste.

Table 5.1 Proximate Analysis of Briquettes

Fuel	Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)
Briquettes made of teakwood leaves and cow dung	12.5	30	10	47.5
Residue left after burning of briquettes made of teakwood leaves and cow dung	-	-	52.5	47.5
Briquettes made of ashoka leaves and cow dung	20	25	10	45

CHAPTER 6

OPERATION OF 10 MW FBC SYSTEM AT JALKHERI USING AGRIWASTE

6.1 Introduction of the Plant

Bharat Heavy Electrical Ltd (BHEL), Tiruchirapalli has been engaged in the development of Fluidised Bed Combustion boilers since 1975 and has several versatile test facilities. After establishing the fluidised bed combustion of rice straw in their test facilities, BHEL engineered a 10 MW rice straw fired power plant. The plant is installed at Jalkheri in Fatehgarh Sahib District by the joint efforts between BHEL and Punjab State Electricity Board. Some of the physico-chemical parameters of the plant are given in Table 6.1.

The furnace arrangement of the boiler is shown in Figure 6.1.

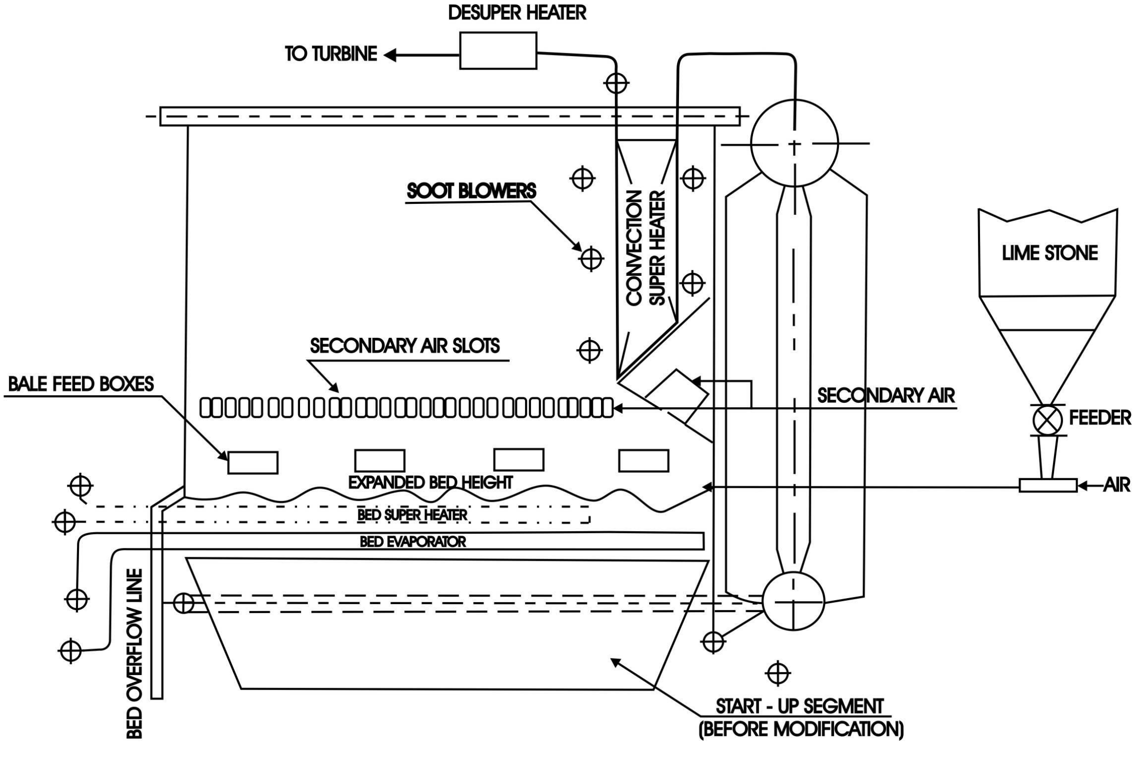


Figure 6.1: Furnace Arrangement of 10 MW Straw Fired FBC Boiler

Table 6.1: Design Parameters of Boiler

Type of boiler	:	Fluidised bed
Fuel	:	Rice straw from Punjab fields to be fired in the form of bales
Unit size	:	10 MW
MCR steam flow	:	13.89 kg/s
Pressures at outlet of Main Steam stop valve	:	64.70 bar
Main steam temperature	:	723 K
Temp of feed water at ECO inlets	:	393 K
Fuel fired at MCR	:	3.87 kg/s

6.2 Observations Regarding Operation of the Plant

The quantity of secondary air provided in the free board was insufficient causing slow combustion of volatile with a dull upward flame.

The enhancement of secondary air quantity will therefore assist in release and completion of combustion of volatile and char in the immediate vicinity of the bed and assist in reducing the flue gas temperature entering the convection superheater.

The light-off segment is very close to the convection superheater and the residence time is very less for volatile combustion to be completed. Due to the burning of straw near the convection superheater the gas temperature at the inlet is high (more than 1173K) which causes the softening and deposition of ash on the tubes.

The light-off of the unit with the bed segment farthest from the convection superheater tubes will ensure combustion of straw well before the gas enters the super heater section.

According to Albertson (1989) limestone reacts with the alkalis in the straw ash and increases the softening temperature of its ash. It was therefore planned to provide a system for continuously adding limestone into the fluidised bed.

The following modifications based on the analysis of observations were carried out to improve the performance:

6.2.1 Modified secondary air arrangement

The secondary air system was modified to increase the quantity of secondary air to about 30% of the total air. This could be achieved by providing additional openings on both the side walls and also new ones on the rear wall below the arch portion.

The secondary air tapping was shifted to the outlet of forced draft fan instead of the air heater outlet to enhance the air pressure available to this system.

A small proportion of the air was also admitted above the bale feed-box so that the loose straw pieces are forced down into the bed to increase the in-bed combustion/residence time.

6.2.2 Removal of in-bed superheater

The in-bed superheater was removed totally to enable light off of the unit with the bed segment that is the farthest from the convection superheater tubes. As the heat absorption in the bed superheater was very low due to lower operating bed temperatures, the reduction in super heat temperature was within limits.

6.2.3 Bed material size

In order to ensure proper fluidisation even after reducing the fluidising air, (as secondary air is increased) the average bed particle diameter was reduced (top size of 1.5 mm against 3 mm adopted earlier).

6.2.4 Additional soot blowers

As the soot blower provided was found to be insufficient, four additional long retractable soot blowers were added (three in front of the convection superheater and two at the rear) so that ash deposits can be dislodged and they are kept clean for flow of flue gas through it.

6.2.5 Feeding system for additives

A pneumatic feeding system was designed and incorporated so that limestone (top size of 1.5 mm) flows to each segment. The light-off compartment contains only in-bed evaporator surface.

The light-off of the boiler is with the help of charcoal and kerosene. This method is adopted in many installations. However it was successfully employed for deep beds in this boiler.

During the initial trails, difficulties were encountered in ensuring uninterrupted feeding of rice straw bales into the furnace. The bales could not pass through the wear plates provided at the exit of the bale feeding box since they were restricted at the cross section.

6.3 Observations During Initial Trials

The rice straw burns with a dull flame in the freeboard rising upto the roof/convection of superheater probably due to insufficient mixing of air and combustibles. Due to the burning in the freeboard, higher than expected proportion of the heat is released in the freeboard zone. The resultant high gas temperature softens the ash due to its high alkali content and the ash deposits on the convection superheater tubes on the flue gas path. The ash deposition rate is such that in less than 12 hours of operation, the space between the convection superheater tubes are bridged with ash and flue gas could not pass through it.

However, the ash deposition is observed to be related to the surface temperature as there were no deposits on the furnaces walls, roof and hanger tubes which carry water/steam mixture. The rate of ash deposition on the convection superheater tubes increases on increasing the firing rate. As the soot blower was located after the convection superheater, the cleaning of the ash deposits at superheater inlets was insufficient. The ash deposit (larger mass) falls back on the furnace and disturbs the fluidisation. The fly ash when allowed to accumulate in the hoppers is observed to sinter and affect the flowability of ash from the hoppers.

6.4 Brief Description of the Boiler

The boiler is of natural circulation, bottom supported, bi-drum configuration. The bed has a cross sectional area of 37m^2. As the biled straw is fed from the sides by a feeding mechanism through eight ports on the side walls, the in bed tubes are made horizontal.

An expanded bed height of 1100 mm is provided so that the coils are fully submerged with sufficient height for straw bales to remain fluidised. The in-bed evaporator tubes are of forced circulation.

The superheated steam system is in two sections. The first stage superheater is located at the furnace outlet section and the second stage within the bed to ensure the rated superheated steam temperature. A superheater is provided in between the two stages of superheater to control the final steam temperature.

After the superheater, the gas passes through the boiler bank tubes. An economizer is arranged after the boiler bank section and is followed by a tubular air heater as the last stage of heat recovery.

An electrostatic precipitator is located after the air heater to reduce the particulate emissions to 150 mg/Nm^3. The boiler is equipped with two radial induced draft fans after the dust collecting system. The de-ashing of fly ash hoppers is by a hydrovac system which is designed for intermittent operation.

As the fuel contains about 60% volatile matter (Table 6.2), a system is provided to supply about 15% of total air as secondary air in the free board. The boiler is provided with adequately sized forced draft fans for supplying the fluidising and secondary air. Because of the alkalis in the rice straw ash and the softening temperature, soot blowers are installed at the convection superheater outlet and in boiler bank and economizer areas.

Analysis of rice straw is presented in Table 6.2.

Table 6.2: Rice Straw Analysis

Proximate		**Raw Straw Sample**
Moisture	%	6.1
Volatile	%	62.1
Ash	%	15.7
Fixed carbon	%	16.1
HHV	MJ/Kg	14.53
Ultimate :		
Carbon	%	37.39
Hydrogen	%	5.34
Sulphur	%	2.57
Nitrogen	%	1.27
O_2 by diff	%	31.53
Ash Composition:		
SiO_2	%	78.4
Al_2O_3	%	78.4
TiO_2	%	78.4
Fe_2O_3	%	78.4
CaO	%	2.6
MgO	%	1.8
Na_2O	%	2.2
K_2O	%	5.1
P_2O_5	%	2.1
Sulphur	%	-
IDT	K	1033
HST	K	1193
FT	K	1473

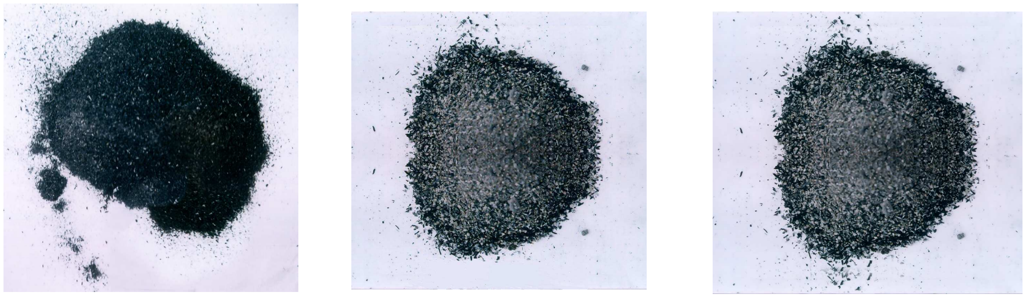
6.5 Straw Feeding Arrangement

The rice straw is compacted in standard baling machines to a height and width of 360 mm and 460 mm respectively, the length being 920 ± 100 mm. The weight of each bale is between 15 to 18 kg. The bales are transported on trailers on which the bales are hand stacked in a module system with 8 bales in each layer, so that the stacks are square. These bales can be fed continuously into the freeboard just above the bed level at the rate of 0.028 to 0.056 kg/s (100 to 200 kg/h).

6.6 Samples Collected from FBC System at Jalkheri

The samples shown below were subjected to proximate analysis. The results were used as input parameters in the development of a mathematical model to describe the mathematical parameters.

Samples (feed, carryover and overflow) collected from the Jalkheri plant are shown in Figure 6.2 and the physico-chemical parameters of the plant are given in Table 6.3.



APH Hopper Bank Hopper Eco Hopper

ESP HOPPER 1 ESP Hopper 4 Wood Chips

Figure 6.2: Samples Collected from Jalkheri Plant

Table 6.3: Physico-Chemical Parameters of the Jalkheri Plant

Parameter	Symbol	Value	Units
Fuel feed rate	W_{fuel}	3472.22	g/s
Moisture content	XW	11.94	%
Carbon content	XC	38.23	%
Hydrogen content	XH	5.8	%
Sulphur content	XS	0.041	%
Oxygen content	XO	40	%
Fractional excess air	E_{xair}	0.10	-
Bed temperature	T_b	973.15	K
Pressure in the combustor	P_{av}	1.01	atm.
Cross-sectional area of the bed	A_t	369000	cm^2
Fuel particle diameter	d_p	0.6	cm
Ash content	A	14.22	%
Number of orifice openings	N_d	24192	-
Bed height	Z	110	cm

CHAPTER 7

DEVELOPMENT OF THE MODEL

7.1 Physico-Chemical Parameters of the Jalkheri Plant

A mathematical model has been developed to study the physico-chemical parameters viz. superficial velocity, minimum fluidisation velocity and bubble diameter of an atmospheric FBC system using agriwaste at Jalkheri.

7.1.1 Superficial Velocity

The stoichiometric air feed rate is determined from fuel composition and fuel feed rate from simple stoichiometric relationship as follows:

$$F_{\mathrm{MTH}} = W_{\mathrm{fuel}}\left(1.0 - XW\right)\frac{\left[\frac{XC}{12.0}+\frac{XH}{4.0}+\frac{XS}{32.0}-\frac{XO}{32.0}\right]}{0.21}\ \text{g.mol/s} \tag{18}$$

Where W_{fuel} is the fuel feed rate into the combustor (g/s), and *XC, XH, XS, XO,* and *XW* are the ultimate carbon, hydrogen, sulphur, oxygen and moisture content of the fuel respectively. The actual molar feed rate of fluidising air is calculated as:

$$F_{\mathrm{ME}} = F_{\mathrm{MTH}}(1.0 + E_{\mathrm{xair}})\ \text{g.mol/s} \tag{19}$$

Where,

E_{xair} : fractional excess air

Now the superficial velocity is calculated as:

$$U_0 = \frac{F_{\mathrm{ME}} R_{\mathrm{g}} T_{\mathrm{b}}}{P_{\mathrm{av}} A_{\mathrm{t}}}\ \text{cm/s} \tag{20}$$

Where,

R_g : Gas constant = 82.06 atm.cm^3/(g.mol.K)
P_{av} : Average pressure in the combustor (atm)
T_b : Absolute bed temperature (K)
A_t : Cross-sectional area of the bed (cm^2)

7.1.2 Minimum Fluidisation Velocity

Many a correlation is available in the literature to define minimum fluidisation velocity, the application of which varies to a great extent depending upon the particle size in the bed. Geldart (1981) has pointed out that for particle size$\rangle 100\,\mu m$, the Wen and Yu (1966) correlation gives the best result. However, none of the correlation is valid if agglomeration and sintering is taking place in the fluid bed. The Wen and Yu (1966) correlation was used to calculate the minimum fluidisation velocity in the present model because the particles are greater than 100 μm.

$$U_{mf}=\left(\frac{\mu_g}{d_p.\rho_g}\right)\left[\left\{(33.7)^2+\frac{0.0408(d_{pav})^3\rho_g(\rho_p-\rho_g)g}{\mu_g{}^2}\right\}^{0.5}-33.7\right]\ \text{cm/s} \tag{21}$$

Where, $\rho_g = 353.2\times10^{-5}/T_b$ (22)

and $\rho_p = K + \frac{A}{100}$ (23)

Where,

U_{mf} : Minimum fluidisation velocity (cm/s)

μ_g : Viscosity of fluidising gas (g/cm.s)

d_p : Fuel particle diameter (cm)

d_{pav} : Average diameter of fuel particles (cm)

ρ_g : Density of fluidising gas (g/cm^3)

ρ_p : Density of fuel particles (g/cm^3)

T_b : Bed Temperature (K)

K : Constant =1.25

A : Ash content in fuel (%)

7.1.3 Viscosity of Fluidising Gas

The viscosity of fluidising air is estimated from Chapman-Enskog equation using the values of collision integral and Lennard-Jones parameters at the prevailing bed temperature. These important parameters can be found in the work of Bird *et al.* (1960).

The final viscosity expression, which is a function of bed temperature, is presented below

$$\mu_g = 1.4(10^{-5})(T_b)^{1/2}\ \text{g/cm.s} \tag{24}$$

7.1.4 AVERAGE EQUIVALENT BUBBLE DIAMETER

A number of correlations are found in the literature for the estimation of bubble diameter in a fluidised bed. One of the widely used correlation was proposed by Mori and Wen (1975) taking into account the effect of bed diameter and distributor type on bubble diameter as follows:

$$D_b = D_{bm} - (D_{bm} - D_{bo})\exp(-0.15/D_R) \qquad (25)$$

Where, $D_{bm} = 1.6377[A_t(U_o - U_{mf})]^{0.4}$ (26)

and $D_{bo} = 0.8716[A_t(U_o - U_{mf})/N_D]^{0.4}$ (27)

(for the perforated distributor plates with number of orifice openings = N_D)

and $D_{bo} = 0.376(U_o - U_{mf})^2$ for porous distributor plate (28)

Where,

D_b : Bubble diameter (cm)
D_{bm} : Maximum bubble diameter (cm)
D_{bo} : Initial bubble diameter (cm)
N_D : Number of orifice openings

However, Mori and Wen (1975) correlation so far has been used for laboratory type fluidised bed combustors having porous or perforated distributor plates, where the bubble growth is restricted by the walls of the combustor, but Rowe (1976) has presented an expression to estimate bubble diameter for industrial scale combustors where such restrictions are not expected due to large cross-section of such combustors which is given below:

$$D_b = (U_o - U_{mf}).Z^{0.75}.g^{-0.25} \qquad (29)$$

Where,

Z : Bed height (cm)

We have used Mori and Wen (1975) correlation for estimation of bubble diameter as the Jalkheri plant is an industrial scale combustor.

The computer program for these physico-chemical parameters was also written in C/C++ language.

CHAPTER 8

RESULTS AND DISCUSSION

The mathematical model developed predicts the variation of physico-chemical parameters viz. superficial velocity, minimum fluidisation velocity and bubble diameter.

Effect of different parameters like bed temperature, particle size, moisture and ash content in the fuel on superficial velocity, minimum fluidisation velocity and bubble diameter have been studied.

Figure 8.1 describes the variation of superficial velocity with bed temperature. It has been observed that as the bed temperature increases superficial velocity also increases because superficial velocity is directly proportional to bed temperature. This is due to the fact that as the bed temperature increases resistance offered to the fluid flow is reduced. As a result less velocity is required to drag the fluid particles.

Figure 8.2 describes the variation of superficial velocity with moisture content in fuel. It has been observed that as the percentage of moisture content in the fuel fed to the combustion chamber increases superficial velocity decreases.

This is due to the fact that as moisture content in fuel increases stoichiometric air feed rate decreases due to which actual molar feed rate of fluidising air decreases because superficial velocity is directly proportional to actual molar feed rate of fluidising air. So, as a result superficial velocity also decreases with increase in moisture content.

Figure 8.3 describes the variation of minimum fluidisation velocity with bed temperature. It has been observed that as the bed temperature increases minimum fluidisation velocity also increases. This is due to the fact that as bed temperature increases viscosity of fluidising gas increases. Due to increase in viscosity of fluidising gas, resistance offered to fluid flow increases as a result minimum fluidisation velocity increases.

Figure 8.4 and 8.5 describe the variation of minimum fluidisation velocity with particle size and ash content in the fuel respectively. It has been observed that as particle size and ash content increase minimum fluidisation velocity also increases. As the size and density increase, it gives more resistance to the fluidising gas and causes more pressure drop.

Figure 8.6 and 8.7 describe the variation of bubble diameter with particle size and ash content in the fuel respectively. It has been observed that as particles size and ash content in fuel increase bubble diameter decreases.

It is due to the fact that with increase in particle size and ash content in fuel there is increase in minimum fluidisation velocity which in turn reduces the bubble diameter. This has also been established in the work of Stubington et al. (1984). They have measured bubble sizes in a fluidised bed of elutriated carbon at temperatures ranging from ambient to 1000°C, using a three dimensional resistivity probe and a stainless steel tuyere cap distributor plate which is similar to the one used in Jalkheri plant. They have reported that with excess fluidising gas velocity, the bubble diameter reduces by 5 to 15 % with increase in particle size.

Importance of Bubble-Stirred Bed of Particles

- Bubbles may cause oxygen by-passing.
- Bubbles stir in the bed and thus enhance heat transfer to immersed tubes; control of bubble size may thus be very important.
- Bubbles promote particle mixing. The relative magnitude of particle mixing times and carbon burnout times may decide the spacing of fuel feed points.
- The mechanism of bubble formation is important in distributor design.
- Knowledge of bubble mechanics gives a fair idea whether combustion is controlled by chemical rate or by diffusion.

According to Davidson (1977) the latter is usually dominant for combustors with bed temperatures above 800°C. If chemical reaction rate at the carbon particle surface controls the combustion, bubble size may be relatively unimportant. But if combustion is controlled by diffusion resistance, then bubble size may be of greater significance.

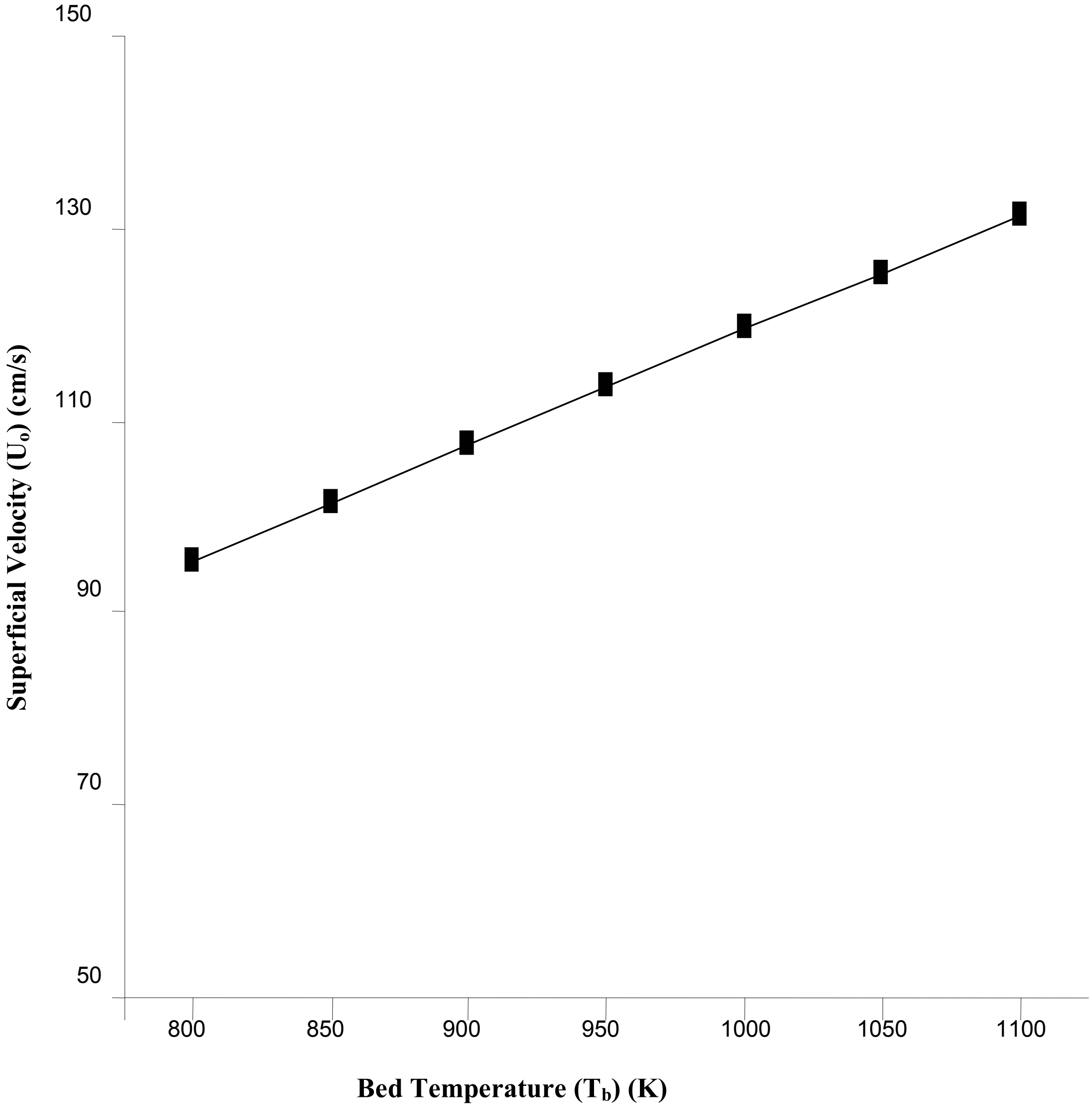


Figure 8.1: Effect of Bed Temperature on Superficial Velocity

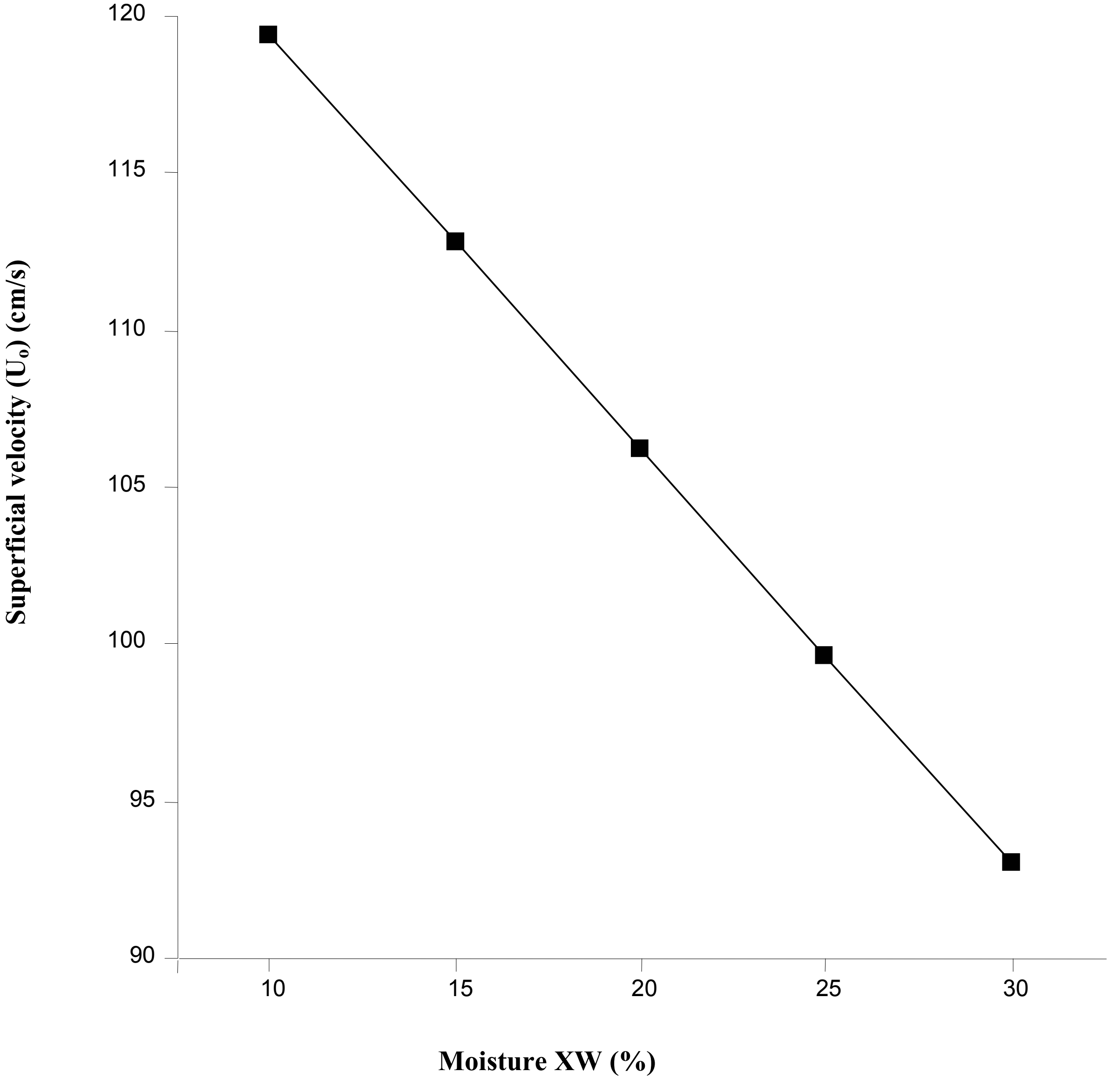


Figure 8.2: Effect of Moisture on Superficial Velocity

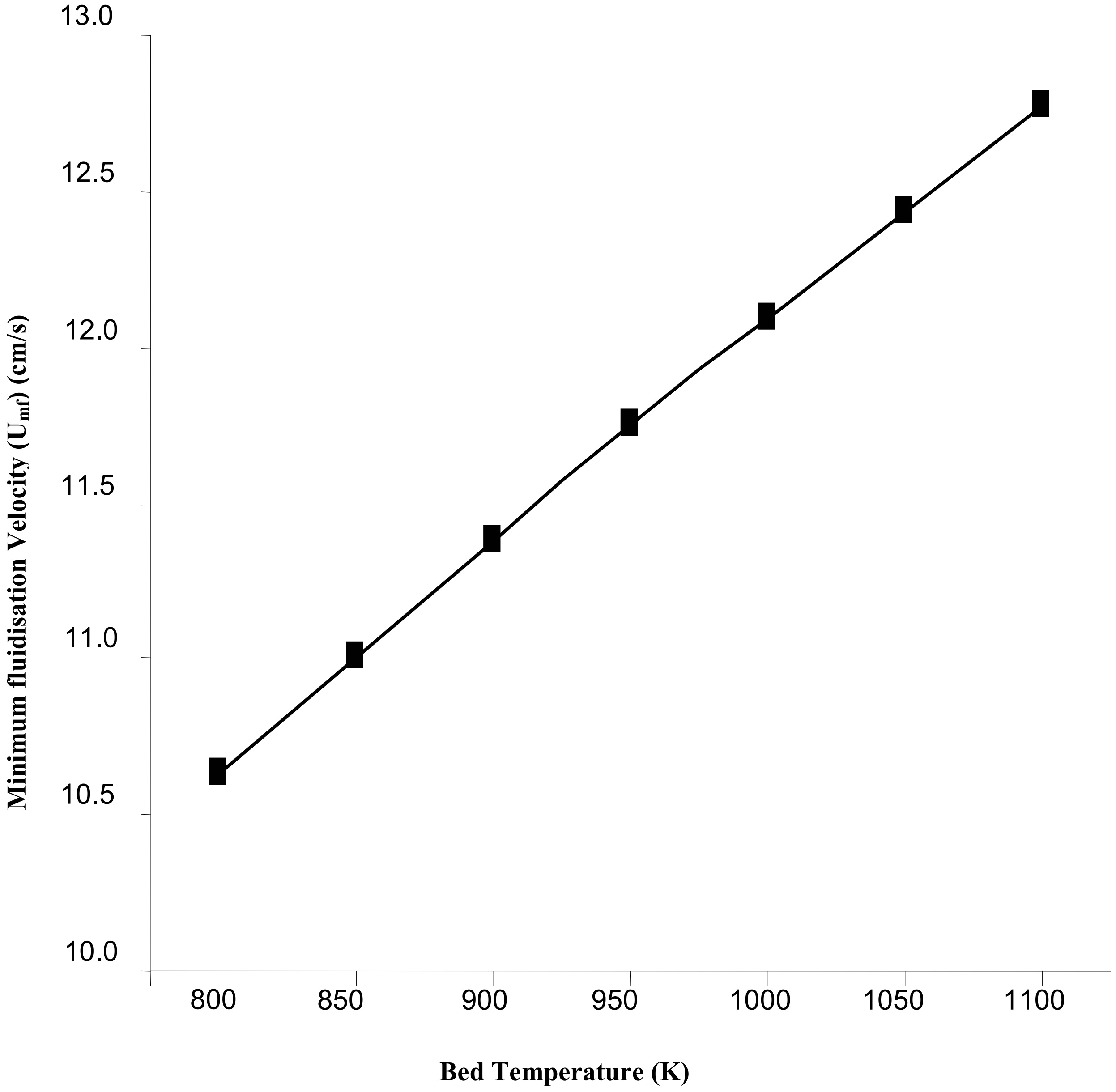


Figure 8.3: Effect of Bed Temperature on Minimum Fluidisation Velocity

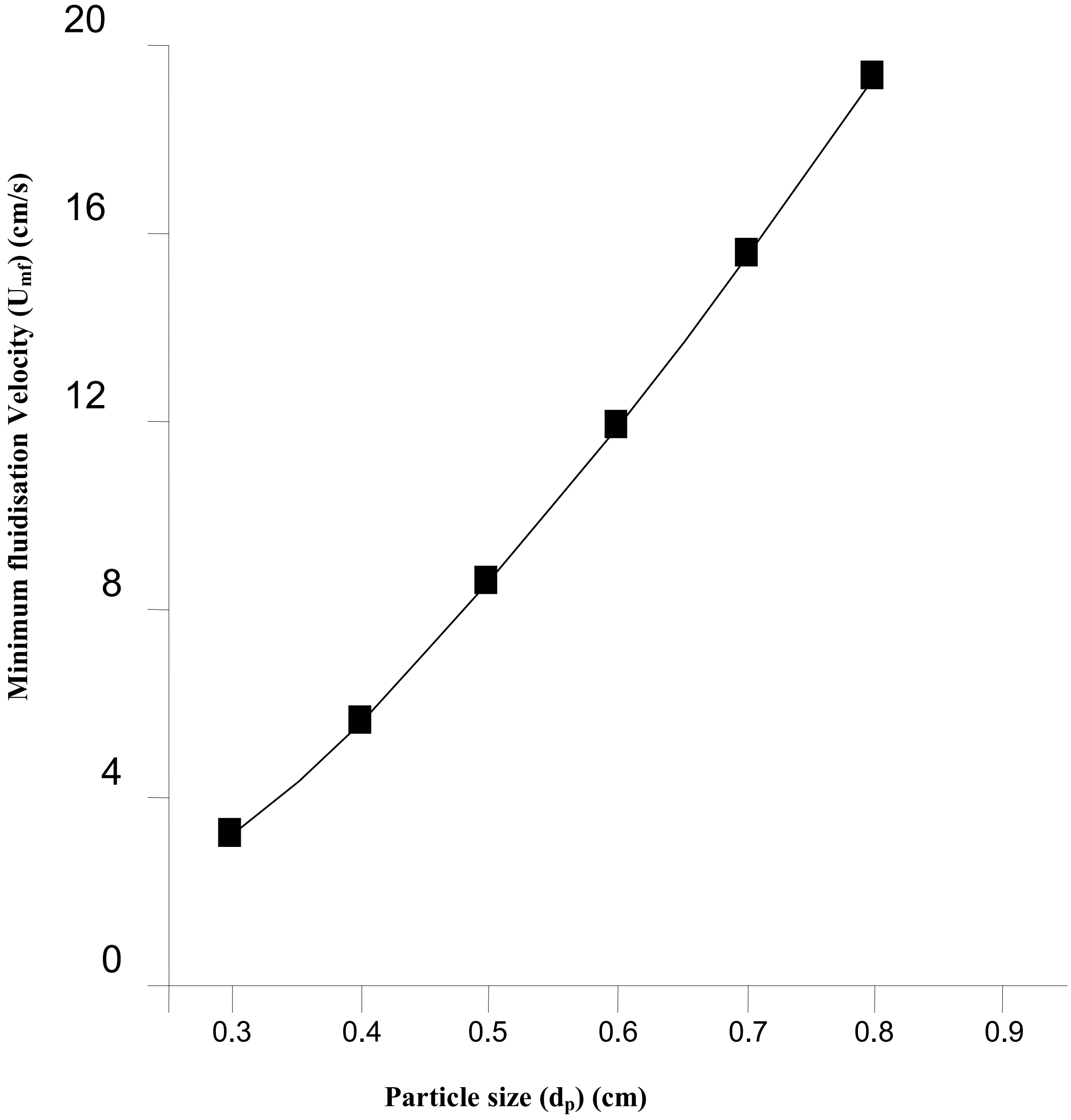


Figure 8.4: Effect of Particle Size on Minimum Fluidisation Velocity

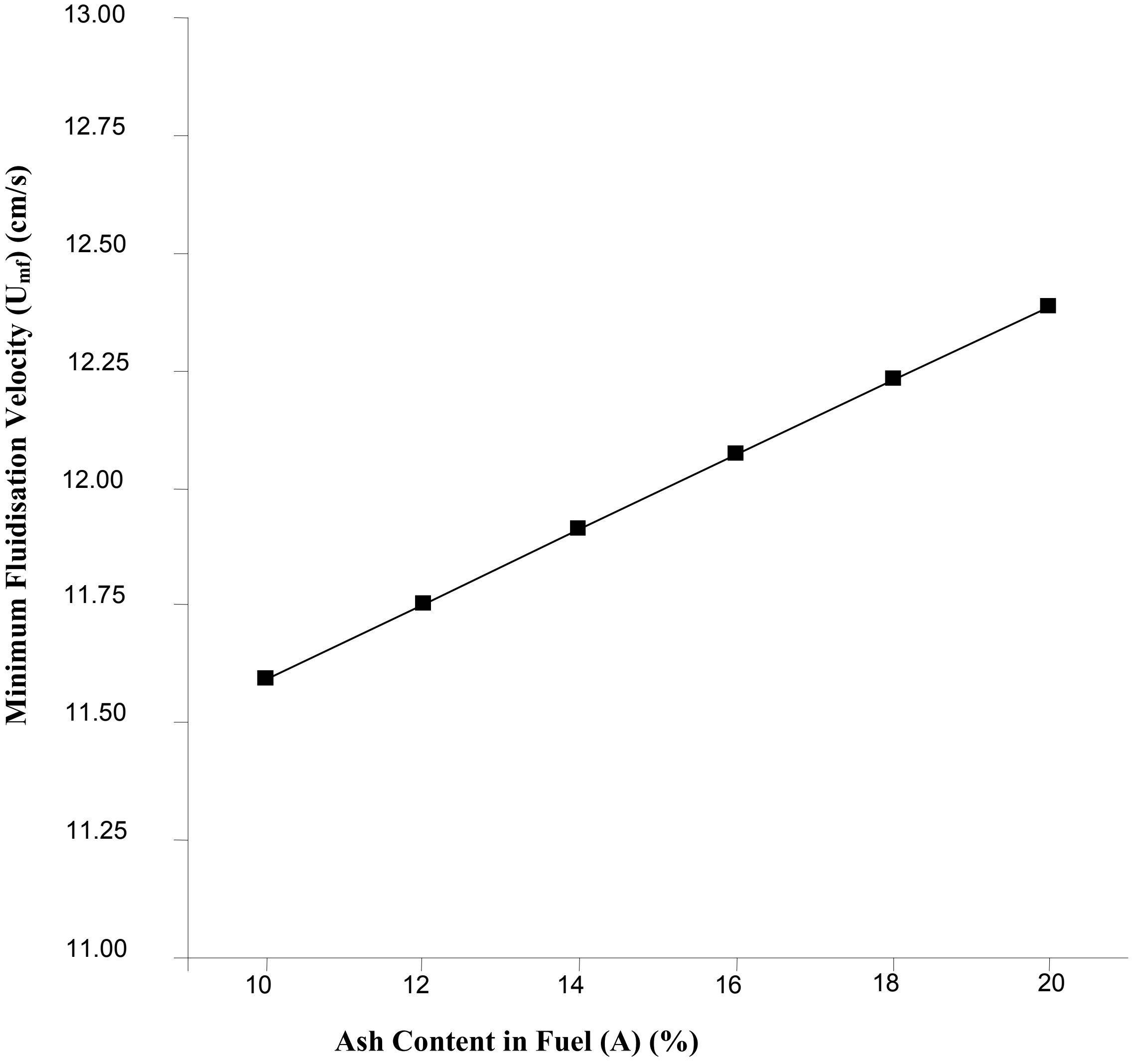


Figure 8.5: Effect of Ash Content on Minimum Fluidisation Velocity

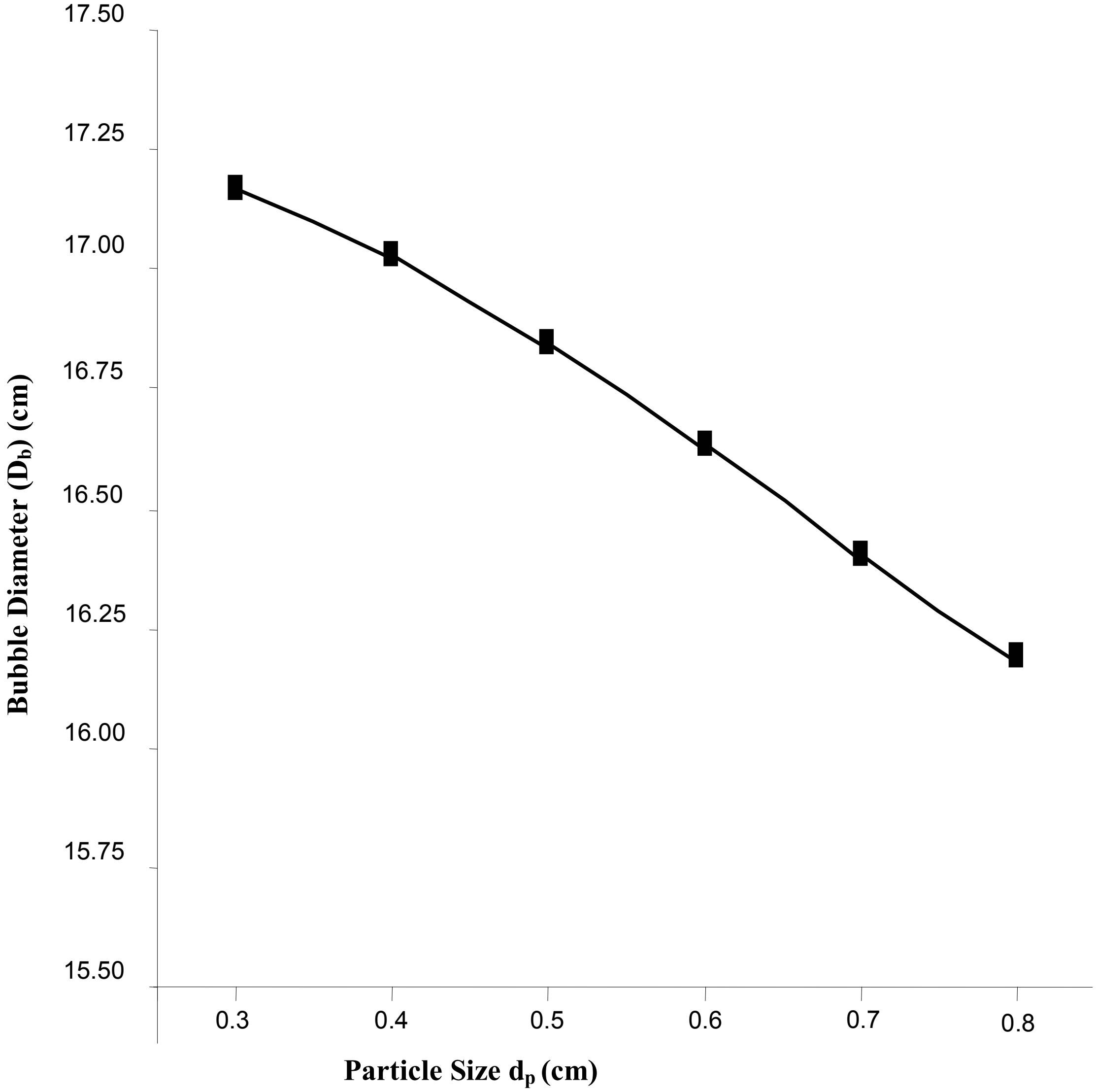


Figure 8.6: Effect of Particle Size on Bubble Diameter

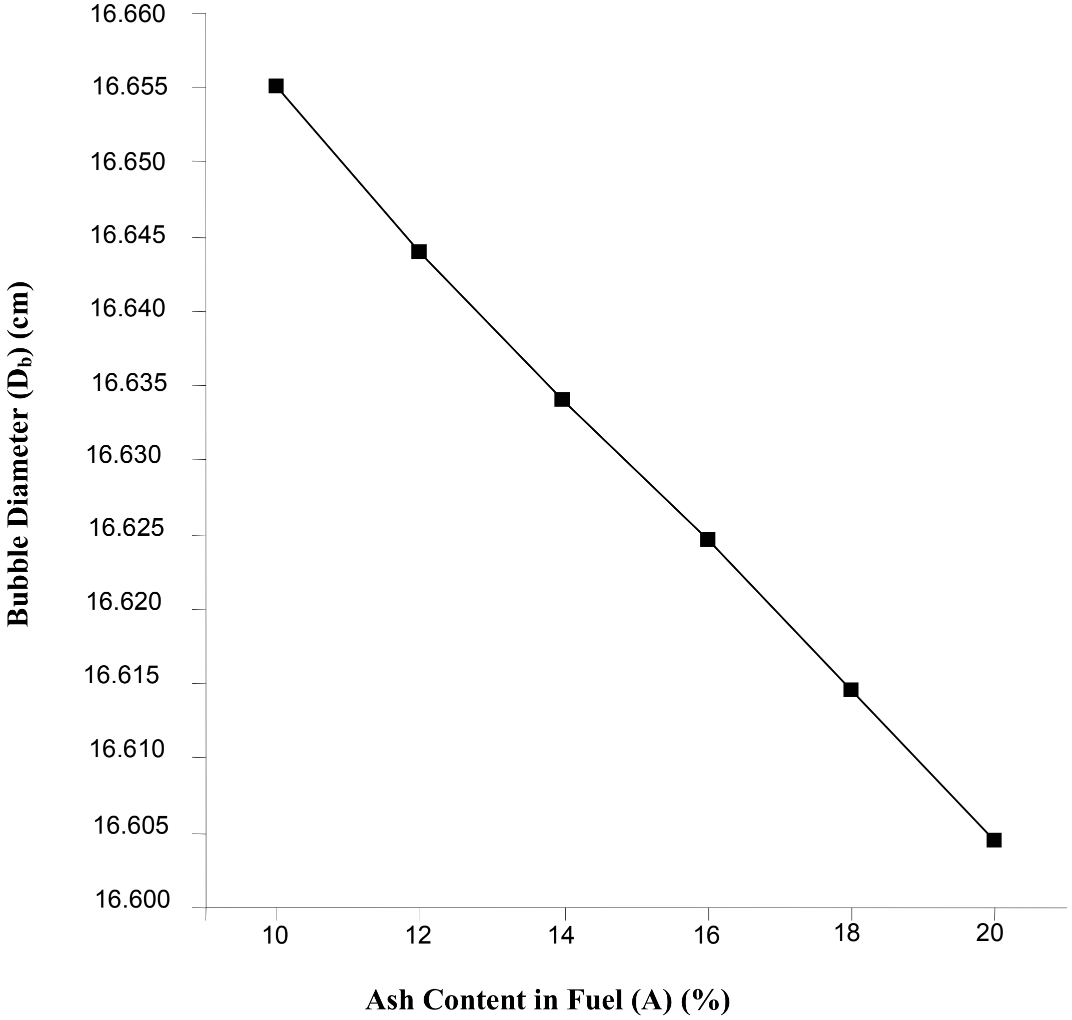


Figure 8.7: Effect of Ash Content on Bubble Diameter

CHAPTER 9

CONCLUSIONS AND SCOPE OF FUTURE WORK

9.1 Conclusions

1. Superficial velocity increases with increase in bed temperature and decreases with increase in moisture content in the fuel.
2. Minimum fluidisation velocity increases with increase in bed temperature, particle size and ash content in the fuel.
3. Bubble diameter decreases with increase in particle size and ash content in fuel.

9.2 Scope of Future Work

1. The following additions may be made in future in the experimental CFBC test rig in the laboratory:
    - Provision of a hopper for continuous fuel feeding system.
    - An I.D. fan of proper specification is required near chimney for proper exhaust of flue gas.
2. A solid population balance model is to be incorporated in the mathematical model to account for carbon utilization efficiency in F.B.C. system that will help in the optimisation of the combustion process in the industrial scale combustors.

BIBLIOGRAPHY

[1] Albertson, D.M., Design Characteristics of a 12 MW AFB Power Station Firing Agricultural Waste, *Proceedings of the 10th International Conference on FBC*, (1989).

[2] Arcate, James R., Biomass Charcoal for PFBC Power Plants, *Bioenergy*'98, (2005).

[3] Avedesian, M.M., and Davidson, J.F., Combustion of Carbon Particles in a Fluidised Bed, *Trans. Inst. Chem. Engg.*, 51, 121, (1973).

[4] Bacon, D.W., Downie, J., Hsu C., and Peters, J., Modelling of Fluidised Bed Wood Gasifiers, Fundamentals of Thermochemical Biomass Conversion, Overend, R.P., Mille, T.A., and Mudge, K.L. (eds.), London: *Elsevier Applied Science*, 717-732, (1985).

[5] Bahillo, A., Cabanillas, De Diego, L, and Adanez, J., Co-Combustion and Biomass in FB Boilers: Model Validation with Experimental Results from CFB Pilot Plant, *Int. Energy Agency*, Florida, (2003).

[6] Bird, R.B., Stewart, W.E., and Lightfoot, F.N., *Transport Phenomena*, Wiley, New York, (1960).

[7] Chungsangunsit, T., Gheewala, S.H., and Parumsawad, S., Environmental Assessment of Electricity from Rice Husk: A Case Study in Thailand, *Issues and Prospect for Asia*, (2004)

[8] Davidson, J.F., Harrison, D., Darton, R.C., and La Nauze, R.D., *Chemical Reactor Theory, Review*, (Prentice Hall, England Cliffs), Chpt. 10, (1977).

[9] Double, J.M., Smith, E.L., and Bridgwater, A.V., Computer Modeling of Fluidised Bed Gasification, Pyrolysis and Gasification, Ferrero, G.L., Maniatis, K., Buekens, A., and Bridgewater, A.V.,(eds.), London: *Elsevier Applied Science*, 651-655, (1985).

[10] Double, J.M., Smith, E.L., and Bridgwater, A.V., Sensitivity of Theoretical Gasifier Performance to System Parameters. Energy from Biomass, Palz, W., Coombs, J., and Hall, D.O. (eds.), London: *Elsevier Applied Science*, 915-919, (1985).

[11] Geldart, D., Behavior of Fines in a Fluidised Bed of Coarse Solids, *Electric Power Research Institute*, Palo Alto, Final Report, EPRI CS, 2094, (1981).

[12] Kwong, Philip C.W., Wang, J.H., Chao, Christopher, Cheung, C.W., and Kendall, Gail, Effect of Co-combustion of Coal and Rice Husk on Combustion Performance and Pollutant Emissions, *The Seventh Asia-Pacific International Symposium on Combustion and Energy Utilization*, (2004).

[13] Le Truonget, Nguyen and Quang Cu Tran., Potential of Distributed Power Generation From Biomass Residues in Vietnam – Status and Prospect, *Issues and prospect for Asia*, Hong Kong, (2004).

[14] Maniatis, K., Fluidised Bed Gasification of Biomass, Ph.D. Thesis, Aston University, U.K., (1986).

[15] Mansaray, K.G., Al-Taweel, A.M., Ghaly, A.E., Hamdullahpur, F., and Ugursal, V.I., Mathematical Modeling of a Fluidised Bed Rice Husk Gasifier: Part I- Model Development, *Energy Sources*, 22, 83-98, (2000).

[16] Mansaray, K.G., Al-Taweel, A.M., Ghaly, A.E., Hamdullahpur, F., and Ugursal, V.I., Mathematical Modeling of a Fluidised Bed Rice Husk Gasifier: Part II- Model Sensitivity, *Energy Sources*, 22, 167-185, (2000).

[17] Mansaray, K.G., Al-Taweel, A.M., Ghaly, A.E., Hamdullahpur, F., and Ugursal, V.I., Mathematical Modeling of a Fluidised Bed Rice Husk Gasifier: Part III- Model Verification, *Energy Sources*, 22, 281-296, (2000).

[18] Mansaray, K.G., Ghaly, A.E., Physical and Chemical Properties of Rice Husk, *Energy Sources*, 19, **9**, 989-1004, (1997).

[19] Mohapatra, S.K., Modeling of Fluidised Bed Coal Combustor, Ph.D. Thesis, ISM Dhanbad, India, (1997).

[20] Mori, S., and Wen, C.Y., Simulation of Fluidised Bed Reactor Performance by Modified Bubble Assemblage Model, *Fluidisation Technology* (Ed. D.L. Keirns), 1, Hemisphere Washington, 179-203, (1975).

[21] Rajaram, S., and Malliah, K.T.U., A 10 MW Fluidised Bed Power Plant for Paddy Straw, *Proceedings of the 9th Intentional Conference on FBC*, (1987).

[22] Rowe, P.N., *Chem Eng. Sci.*, 31, 285, (1976).

[23] Shyam, M., Agro-Residue Based Renewable Energy Technologies for Rural Development, *Energy for Sustainable Development*, 6, **2**, 37-42, (2002).

[24] Stubington, J.F., Barret, D., and Lowry, G., Bubble size measurements and correlation in a fluidised bed at high temperature, *Chem. Eng. Res. Des.*, 62, 173-178, (1984).

[25] Thipwimon Chungsangunsit, Shabbir Gheewala, H., and Suthum Patumsawad, Environmental Assessment of Electricity Production from Rice Husk: A Case Study in Thailand, *Electricity Supply Industry in Transition: Issues and Prospects for Asia,* Thailand, 20, 51-62, (2004).

[26] Beenackers, A.A.C.M., van den Aarsen, F.G., and van Swaaij, W.P.M., Performance of Rice Husk Fuelled Fluidised Bed Pilot Plant Gasifier, *International Producer Gas Conference*, Sri Lanka, 381-392, (1982).

[27] Wen, C. Y., and Yu, Y. H., *AIChE*, 12, 610, (1966).