DESIGN, CONSTRUCTION AND SIMULATION OF MAIZE COBS FLUIDIZED BED COMBUSTOR

BY

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DECLARATION

I hereby declare that thisdissertationentitled "**Design, Construction and Simulation of a maize cobs Fluidized Bed Combustor""** was done by myself in the Department of Mechanical Engineering, Ahmadu Bello University Zaria, under the supervision of Prof. C.O. Folayan and Dr. G.Y. Pam. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this work has been presented for another degree or diploma in any institution.

Yusuf HabibBELLO _____ _____

Name (Signature) (Date)

CERTIFICATION

This dissertation titled "**Design, Construction and Simulation of Maize Cobs Fluidized Bed Combustor"**meets the regulations governing the award of a degree of Masters of Sciencein Mechanical Engineering of the Ahmadu Bello University Zaria, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This work is dedicated to my parents, without whose support it would not have been possible.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors Professor C.O. Folayan and Dr. G. Y. Pam for their continuous support during the course of my study, for their patience, knowledge, enthusiasm and encouragement. This project would not have been possible without their wisdom and guidance.

In the workshop, I have been aided by Engr. AuwalDayyabu, who has worked relentlessly to ensure the smooth execution of my testing procedure.Furthermore, my profound gratitude goes to MallamAbdullahi, a technician at the National Board for Technology Incubation, who has inadvertently, and without fail, given me his undivided attention and exceptional skill to procure materials and make the fabrication aspectof this project a success.

In my daily work I have been blessed with a friendly and cheerful group of fellow students, thank you for all the wonderful support.

Finally, I would like to thank my parents for supporting and motivating me throughout my life.

ABSTRACT

This study adopts the theory of fluidisation to design a combustor suitable for use in the rural communities of Nigeria. The Combustor, which will use sand particles as bed material, will burn maize cobs supplied at 5kg/h to generate heat energy for thermal applications including steam generation.

Like most African countries, lack of adequate electricity supply in Nigeria has hampered economic activities, with less than 40% of the rural community connected to the national grid due to high cost of rural electrification exercise. Furthermore, the rural population continuously rely on direct burning of solid biomass (like fuel wood) as means of obtaining much needed heat energy for basic applications like cooking and heating, constituting an environmental nuisance. The study contends that using a bubbling fluidised bed combustor, it is possible to reduce energy poverty in the rural areas of Nigeria, while complying with the sustainable development goals.

Chapter one discusses the background of the study, identifying the objectives, research problems, justification and scope of the work. Chapter two reviews the previous documentation on fluidised bed combustion including its history, principle of fluidization and advantage of fluidized beds over conventional methods of burning biomass. This chapter explains the theoretical background of the combustor and also introduces the Ergun 6.2 modeling software used in this work. The third chapter identifies the materials selected and the equations governing the design of the fluidised bed system. The simulation of the fluidised bed, construction procedure and equipment used are also defined in this chapter. Chapter four presents the result of the flue gas analysis, fluid bed and flue gas temperature measurements, with subsequent discussions. The fifth chapter summarizes and concludes the entire study.

The temperatures of the fluid bed and flue gas during combustion were measured at 837 ºC and 220 ºC respectively using the MASTECH multipurpose clamp meter. The flue gas constituents were also analysed using the gas analyser which gave the concentrations of CO, NO_x and SO_x at 2ppm, 5ppm and 1ppm respectively.

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NOMENCLATURE

U_b – Absolute bubble velocity

g - Acceleration due to gravity

ρ_a – Apparent density

Ar - Archimedes number

A – Area of the bed

A_o – Area of grid per orifice

d_t – Bed diameter

H_{mf} - Bed height at minimum fluidization

T_b - Bed temperature

ε – Bed voidage

d_b – Bubble diameter

Z – Bubble height

ρ_b - Bulk density

C_d – Coefficient of discharge

a_1, b_1 – Constants

d_{bo} - Diameter of the bubble formed initially just above the distributor plate

ρ_s - Density of the solid

C_D – Drag coefficient for spherical particle

H, L – Fluid bed operating height

ρ_g – Gas density

μ – Gas viscousity

d_{or} - Orifice diameter

U_{or} – Orifice velocity

d_p – Particle diameter

d_{sv} - Particle mean size

φ_s – Particle sphericity

ΔP_b - Pressure drop across the bed

d_{bm} – Mean bubble diameter

U_{bm} – Mean bubble velocity

U_{mf}- Minimum fluidizing velocity

N_{or} - Number of orifice

Re - Reynolds's number

Re_p- Reynold's number of particle

Re_{mf} – Reynold's number at minimum fluidization

U – Superficial velocity

U_t - Terminal velocity

u_{bs} – Velocity of a single bubble

ε_{mf} - Voidage at minimum fluidization

ε_b – Volume fraction of bubbles

D_{cy} – Vortex finder diameter

a, b – Width and height of the entrance window

CHAPTER ONE

INTRODUCTION

1.1 Background

Global demand for energy has led to rapid depletion of non-renewable energy resources (fossil fuels). This demand, along with high crude oil prices are key factors driving renewable energy development and utilisation (Omer, 2013).

Renewable energy is the energy which comes from natural sources such as the sun, wind, water and plant or animal organic matter. It is replenished by natural processes at a rate equal to or faster than the rate at which it is consumed. Biomass, a renewable energy source, refers to biological material from living or recently living plants and animals. It can either be used directly, or converted into other energy products such as biofuel . While the discovery of fossil fuels has led to a decline in the use of biomass, recent data has indicated renewed efforts towards conversion of biomass to bioenergy either by combustion, gasification, conversion of biomass to biofuels or biomass briquettes. Biomass resources include dedicated energy crops, forest residues, municipal, animal and agricultural waste (DOE, 2007).

Combustion of solid biomass fuels accounts for over 90% of the energy generated from biomass worldwide. This is mostly common in developing countries, where biomass combustion provides basic energy for cooking and heating in rural households (ECN, 2006). These traditional applications are relatively inefficient and promote environmental degradation.

Standalone biofuel combustion, which is state-of-the-art, can provide an effective means of improving Biofuel efficiency. Such standalone systems include:

a. Diesel generators where biodiesel produced from energy plants like jatropha, replace diesel fuel to produce electricity for off-grid applications.

b. In biomass-based power plants, heat produced by direct biomass combustion can be used to generate electricity via a steam turbine. The electrical efficiency of this system is currently low, but provides the cheapest and most reliable means of producing power from biomass for standalone applications (IEA, 2009).

c. Co-generation is the process of producing two useful forms of energy, normally electricity and heat, from the same fuel source. Co-generation significantly increases the overall efficiency of a power plant and hence its competitiveness (IEA, 2009). The application of heat from biomass combustion for industrial processes like drying is well established in the pulp and paper industries, sugar mills and palm oil mills.

d. Waste-to-energy technology has been unexploited despite its potential in most countries. Waste-to-energy plants based on municipal and agricultural wastes require robust technologies and strict air emission controls, increasing the costs of waste-to-energy facilities (IEA, 2009).

The above waste-to-energy standalone systems can be realised through Fluidised Bed Combustion (FBC) technology, in which, a fluidised bed of sand like particles is initially heated and then the fuel (which can be agricultural waste) is thrown on the bed for combustion.

1.2 Statement of the Problem

Every year, a significant volume of agricultural waste is generated within the rural areas in Nigeria. The waste is a potential source of fuel for heat and power generation. Consequently, the energy that could be generated is wasted by indiscriminate dumping and burning. It therefore becomes necessary to generate useful energy using suitable waste-to-energy technologies. While the use of fossil fuels has become synonymous with environmental concerns like global warming and acid deposition, emission of gases like carbon dioxide, sulphur and nitrogen oxides is also a major problem of the 21st century. Furthermore, poverty, unemployment and lack of electricity are key factors encouraging rural-urban migration. Public infrastructure in the urban centres becomes strained while shortage of labour in the agricultural sector develops within the rural areas (Ladan, 2012).

1.3 Justification of the Research

A significant part of global population relies on biomass fuel particularly for heating and cooking. Unfortunately, this comes at a high economic cost. Although biomass fuel is relatively cheap, many illnesses prevalent in villages especially those related to respiratory and heart diseases are attributed to indoor emissions from biomass-fired cooking.

Furthermore, connection to the national electrical grid is a rare occurrence in rural areas of the developing world. In majority of the world's poorer countries, it is estimated that significantly less than 5% of the rural population are connected to the national grid. In such communities, localized grid can be established using a local power source such as agricultural waste. Individual households can also be connected to standalone systems which can be powered by any of a wide variety of energy sources.

There are several benefits of introducing electricity to rural communities. While obvious reasons include social gains like lightening, cooking and water pumping, electricity will help to stem the flow of rural-urban migration which is a common problem in many developing countries like Nigeria. Introduction of electricity also helps to provide productive employment in rural areas thereby creating a positive impact on economic as well as social growth.

Fluidised bed combustor when combined with a boiler can provide efficient and affordable source of energy thereby boosting rural education and development, since it uses agricultural waste as a fuel source. Flue gases generated can either be used for electricity production in a gas turbine, generate steam in a boiler or simply burned indoors. Fluidised bed technology has high greenhouse gas mitigation potential since it eliminates sulphur and nitrogen oxide emissions, thereby curbing global warming and acid deposition.

The biomass energy resource base of Nigeria is expected to be 144million tonnes per year. In Kaduna state alone, production estimate for maize was 1,027,790 MT (NAERLS and NFRA, 2009). This shows enough potential of biomass waste to generate electricity. Supplying electricity to rural areas will not only reduce poverty and unemployment, but also decentralize national grid connection where it exists.

1.4 Aim and Objectives of the Study

The aim of this project is to design, construct and simulate an agricultural waste bubbling fluidised-bed combustor.

The specific objectives of the work are:

a. To design the various parts of the combustor

b. To select appropriate materials for the fluidised bed combustor

c. To simulate the performance and validate the results by test on the fluidised bed combustor constructed

Estimate the cost of a prototype of the fluidised bed combustor.

1.5 Scope

The current work focuses on the design, construction and simulation of a bubbling fluidised-bed combustor, which will use agricultural waste as fuel to produce heat energy. The heat produced can then be used to generate steam for power and thermal applications. Thermal energy from the fluidised bed combustor can be used to generate steam in a boiler for power generation. Bubbling fluidised bed (BFB) technology is well suited for biomass fuels and will be utilised in this work.

The agricultural wastes include maize cobs, groundnut shells, rice and millet husks, millet stalks, sorghum stalks, maize stalks and cotton stalks among others. However, this research will focus on maize cobs because of its availability and energy content.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background History

Development of the Fluidised Bed Combustors started in 1922, with the Fritz Winkler patent for gasification of lignite. In 1960, Winkler's efforts ultimately resulted in the design of coal firing test units. The first bubbling fluidised bed test facility started operating in 1965, and was used primarily to establish potential for air emission control (Koornneef*et al.*, 2007). Since then, fluidised bed technologies have been developed and vigorously used for different operations such as transportation systems and chemical reaction processes. Increased utilisation of coal triggered by oil crisis during the 1970s, followed by the pressure to limit environmental pollution due to coal combustion led to the development of coal-based technologies. These technologies include pre-combustion coal cleaning, post-combustion environmental emission controls, advanced coal combustion, gasification and liquefaction (Tavoulareas, 1991).

2.2 Renewable Solid Fuels

Over the years, the definition of biomass has evolved to include diverse sources like construction debris and algae. Biomass can be defined as the non-fossilised and biodegradable organic matter of living or recently living plants, animals and micro-organisms. This also includes industrial products, by-products, residues, agricultural and municipal wastes (UNFCCC/CCNUCC, 2008). The line between biomass and waste is drawn differently from country to country. Some countries refer to biomass as plant-derived organic matter available on a renewable basis, thereby including dedicated energy plants, crop residues, agricultural and municipal waste, aquatic plants and animals. Other countries categorise biomass as waste fuels from waste products of human

and industrial processes. Biomass residues refer to biomass by-products, residues and waste from agriculture, forestry and related industries (UNFCCC/CCNUCC, 2008).

There are numerous conversion technologies from biomass resource to fuel, heat and power. Figure 2.1 shows a summary of the various biomass conversion processes.

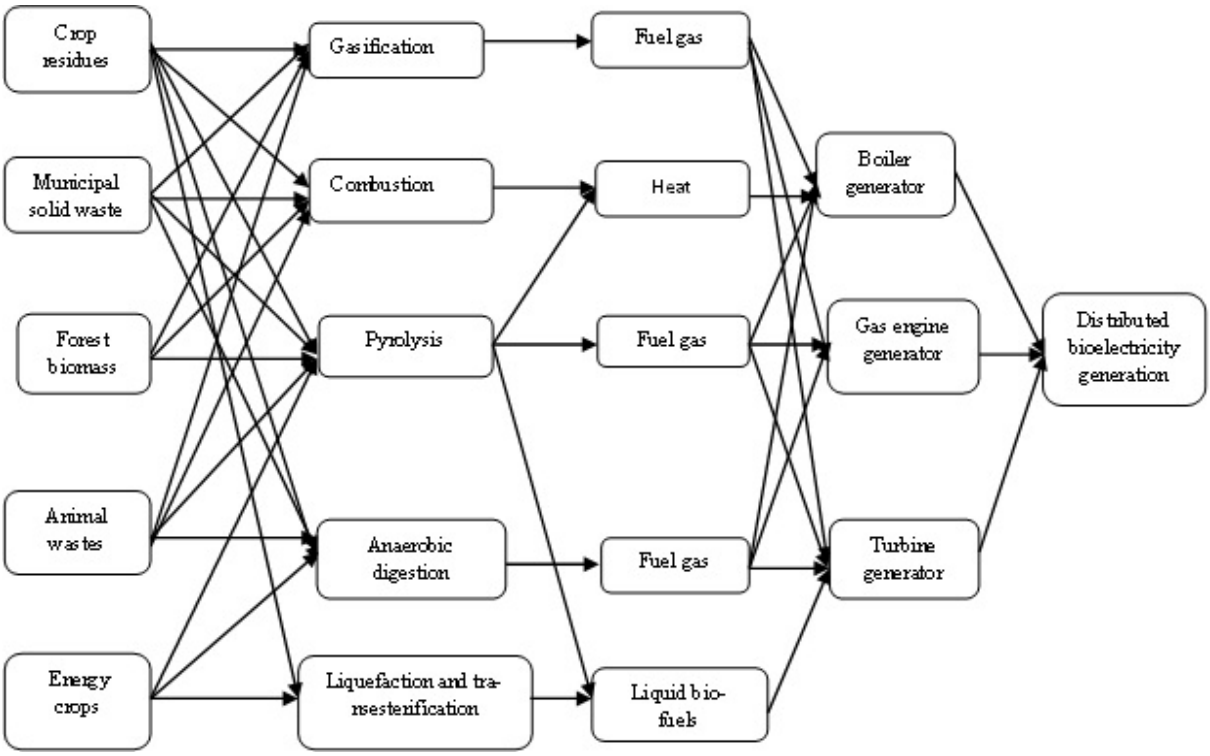


Fig 2.1: Biomass Energy Conversion Overview

Source: (Suberu*et al.*, 2012)

2.3 Characteristics of Fluidised Bed Combustion

Fluidised bed combustion is a relatively new method of burning fuels, while complying with SOx and NOx emission regulations. In fluidised bed combustion, fuel is introduced into a bed of limestone or sand particles which is kept in a fluidised state by upward-blowing jets of air. Combustion takes place in the bed. Any sulphur present combines chemically with the

limestonein the bed to form calcium sulphate and calcium sulphite, which can be removed with the ash handling system, eliminating the need for scrubbers to clean the flue gas. The main advantage of the fluidised bed combustor is thus its ability to reduce sulphur dioxide emissions. However, it also has the ability to burn a wide variety of fuels. In the past, fluidised bed combustor has been used exclusively to supply steam and heat by burning low-grade coal in the presence of limestone (Basu, 2006). Combustion in fluidised beds occur at a relatively low temperature (800^oC – 1000^oC) (Basu, 2006), much lower than the reaction temperature of nitrogen. At high temperatures, usually above $1{,}600^oC$ nitrogen and oxygen molecules in combustion air disassociate into their atomic states and participate in a series of reactions (Walter and Lang, 2004).

2.4 Types of Fluidised Bed Combustors

Fluidised bed combustion systems are generally categorised into atmospheric fluidised bed combustion systems (AFBC) and pressurized fluidised bed combustion systems (PFBC). These can be further classified as bubbling or circulating fluidised beds (BFB or CFB). Figure 2.2 shows a schematic of the atmospheric and pressurised bubbling and circulating fluidised beds.

2.4.1 Atmospheric fluidised bed combustor AFBC is more efficient at producing energy at lower cost and removing sulphur and nitrous oxide from the exhaust gases (Solem, 1974).In this system, jets of air suspend the mixture of bed material and burning fuel during combustion, converting the mixture into a suspension of red-hot particles that flow like a fluid (Sunjay, 2009).It operates at atmospheric pressure.

2.4.2 Pressurized fluidised bed combustor This system is similar to AFBC, but with higher operating pressure. The bed material and fuel are kept in a fluidised state by a stream of high pressure air from (Forced Draft) FD fans. PFBC is highly efficient but has

added electrical operating cost associated with the large combustion air fans necessary for fluidising the bed.

2.4.3 Bubbling fluidised bed The BFB is well suited for solid biomass and waste co-combustion. Very little material leaves the bubbling bed since only 2-4 kg of solid is recycled per tonne of fuel burned.

2.4.4 Circulating fluidised bed In CFB, the gas velocity is sufficiently high to blow the gas-solid mixture out of the furnace. The majority of the solid leaving the furnace is captured by the cyclone separator, and is recirculated back to the base of the furnace (Basu, 2006). Circulation gives more residence time for the limestone used for sulphur removal.

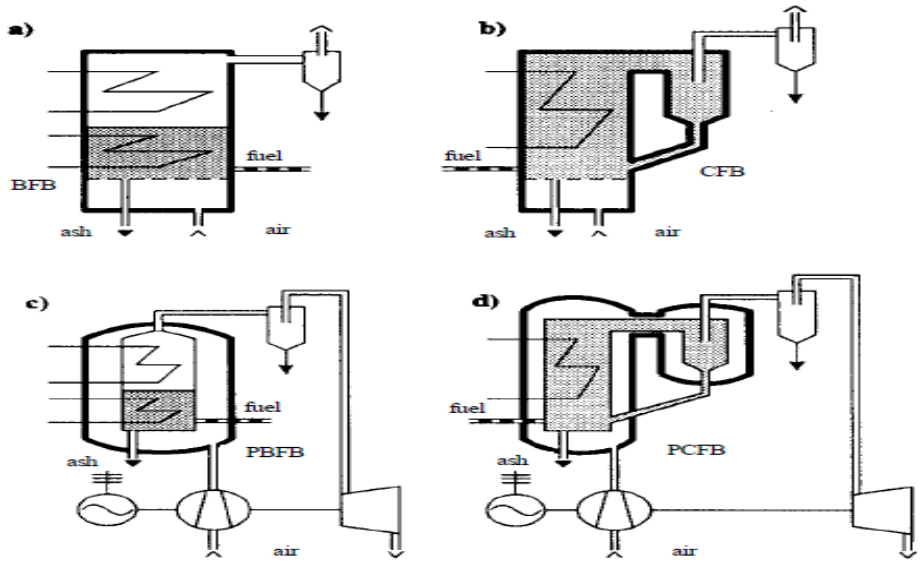


Fig. 2.2: Bubbling Fluidised Bed (a), Circulating Fluidised Bed (b), Pressurized Bubbling Bed (c) and Pressurized Circulating Fluidised Bed (d)

Source: (Kovács, 2001)

2.5 Advantages of Fluidised Bed Combustion

i. FBC can burn fuel with a combustion efficiency of over 95%

ii. It has the ability to operate with a variety of fuels. Even fuels like agricultural waste can be burnt efficiently either independently or in combination with coal.

iii. High flexibility in accepting solid/liquid/gaseous fuels even with low calorific value (waste) and high moisture content (biomass).

iv. SOx emissions can be reduced by adding limestone for high sulphur coals. 3% limestone is required for every 1% sulphur in the coal feed. Low combustion temperature prevents NOx formation.

v. Fluidised bed technology can be useful for gasification and pyrolysis.

vi. It can be used to generate hot pressurized gases to power a gas turbine. This can be combined with a conventional steam turbine to improve the efficiency of electricity generation.

vii. Simplicity in construction and the absence of mechanical moving parts lowers the maintenance cost of FBC systems.

2.6 Applications of Fluidised Bed Combustion

Fluidisation has widely been used in commercial operations on a global scale. Fluidised bed technology has been used in mineral treatment to recover gold from gold industry waste, incineration of woodchips and carbon to enable recovery of precious metals (IEA, 2007). PFBC units have been built as a part of combined cycle power generation to produce heat and power.

Other applications of fluidised bed combustors can be found in power generation, transportation, heating, absorption, mixing of fine powder, reactions of gases on solid catalysts and reactions of solids with gases.

2.7 Principle of Fluidisation

The principle of operation of fluidised systems is based on the fact that if a gas is allowed to flow through a bed of particulate solids at velocity greater than the settling velocity of the particles and equal to the minimum velocity of fluidisation, the mean velocity of the solids increase and they become partially suspended in the stream of upward moving gas (Gohel*et al.*, 2007). For good heat transfer and intimate contact, the difference between the mean solid and gas velocities must be maximum. In fluidised beds, size of bed material directly influences the hydrodynamics of the reactor column. The fluidisation quality is closely related to the intrinsic properties of the fluidising medium, properties such as particle density, particle size and surface characteristics definitely affect the outcome of fluidisation (Johariand Taib, 2007). Combustion occurs at a temperature below 1000^{o}C. Gas velocity is maintained between minimum fluidisation velocity and particle entrainment velocity, thereby ensuring stable operation in the bed and avoiding particle entrainment in the gas stream.

Limestone can be used as bed material or part of bed material. This will help control SOx emissions, eliminating the need for scrubbers.

2.8 Fluidisation Regimes

Deviating from the designed fluidisation regime lowers the performance of a fluidised bed boiler or gasifier significantly. Thus, understanding the hydrodynamics of the gas-solid motion is very important. The fluidisation stages that occur when a gas passes through a bed of particles is

shown in Figure 2.3.When a gas flows through a bed of particles, few particles vibrate within the same height as the bed at rest. This is known as the fixed or packed bed regime. Further increase in gas velocity causes the drag force of the upward moving gas to be equal to the weight of the particles. Hence, the void of the bed slightly increases to commence the minimum fluidisation state. At this stage, any increase in gas velocity forms fluidisation bubbles. When the velocity of the gas exceeds the terminal velocity of the particles, a turbulent motion of solid clusters and voids of gas is observed. Eventually, the fluidised bed becomes an entrained bed in which we have disperse, dilute or lean phase fluidised bed, amounting to pneumatic transport of the particles. Slugging may be encountered if the bed is narrow and deep. The bubble increase to a size comparable to the width of the bed, thereby passing through the bed as a slug (Basu, 2006). Slugging is undesirable and should be avoided if possible.

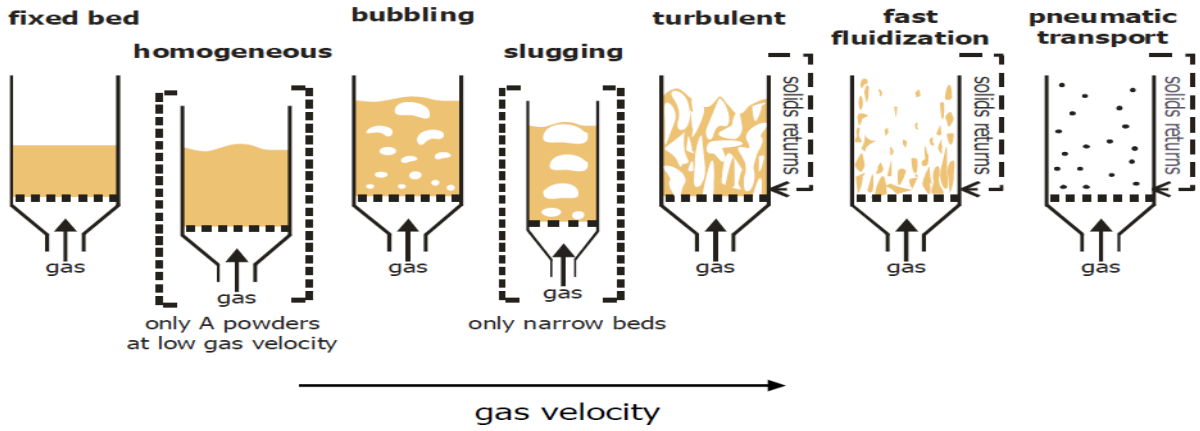


Fig. 2.3: Fluidised bed flow regimes
Source: (Van Ommen and Ellis, 2010)

2.9 Review of Related Works

Although research into fluidised bed technology started in 1922, its commercialization did not start until 1942, with the production of the first commercial fluidised bed combustion system. These researches have ranged from experimentation and theoretical modelling, to computational

fluid dynamic (CFD) simulations. Numerous factors affecting the thermal performance and combustion efficiency of fluidised beds have also been investigated and documented. Fluidised bed technology has found application in various parts of the world, particularly in Europe and the United States (Hack, 2013).

Analysis of development and economic performance of fluidised bed technology was done by Koornneef et al. (2007). Their study highlighted the important drivers for fluidised bed combustors and the effect of technological experience on economic performance of fluidised beds.

Attempt to improve the combustion efficiency in a fluidised bed of dolomite was also investigated by Morita *et al.* (1999). By using dolomite, combustion efficiency higher than 98% above bed temperature of 850^{o}C was recorded. It was also observed that dolomite was effective in reducing concentration of NOx and H_2S in flue gases to very low levels at temperatures below 900^{o}C. Furthermore, highlighting the main technologies for the incineration of waste in Europe, Bontoux (1999) emphasized the typical maximum operating temperature range for fluidised bed furnaces as 750^{o}C to 1000^{o}C, with high combustion efficiency.

Several studies on fluidising velocity have also been conducted. Effect of temperature on hydrodynamics of fluidised beds was analysed by Sanaei*et al.* (2007). They concluded that mean velocities of upward and downward-moving particles increase by increasing the superficial gas velocity. In addition, at each superficial gas velocity, mean velocities of particles increase by increasing temperature up to around 300^{o}C. However, the velocities decrease with continued increase in temperature to beyond 300^{o}C.

Temperature values of 115 °C and 63 °C have also been used by Soponronnarit (1999) and Oluleye*et al.* (2012) respectively for grain drying purposes, with the latter recording drying efficiency as high as 89% for rice and wheat grains.

Fluidisation behaviour in the fluidised bed can best be categorised into three modes of flow regimes namely laminar, turbulent and slugging. The quality of fluidisation reported in the study of hydrodynamics of circular and rectangular columns was observed to be dependent on several factors including mean sand size and fluidisation number. Effect of different sand sizes on the fluidisation behaviour in circular and rectangular columns was studied by Johariand Taib (2007). The research revealed that fluidisation quality can be affected by the mean sand size. Bigger columns are also required to produce good fluidisation behaviour and column shape has no effect on the fluidisation process.

2.10 Theoretical Background

2.10.1 Thermal stress analysis

Changes in temperature can induce substantial deformations, strains, and stresses. Thermal stress analysis refers to static analysis that includes the effect of temperature. Calculations of thermal stresses have been carried out for a hollow cylinder of constant elasticity and heat conductivity, with the temperature throughout it following the steady logarithmic law and the material expanding according to the linear law (Lees, 1922).

When most materials are heated, they tend to expand. The material is assumed to be isotropic, and thus, the expansion is uniform in all directions. The non-dimensionalised form of this expansion is called thermal strainwhich is given in the form:

$e = \alpha \Delta T$ ---------- (2.1)

ΔT is the temperature difference between the temperature where the reference length of the cylinder is considered and the final temperature. α is a material property known as the thermal expansion coefficient.

Hence for hollow cylinder heated internally, after an equilibrium temperature distribution is established, the maximum tensile stress is given by:

$$\sigma_t = \frac{E\alpha\Delta T}{2(1-\nu)}\left\{1 - \frac{2r_i^2}{r_0^2 - r_i^2}\ln\left(\frac{r_o}{r_i}\right)\right\} \text{---------- (2.2)}$$

2.10.2 Geldart's Classification

The nature of a bed material influences its fluidisation quality. Fine/sticky particles tend to be cohesive and create channels through which aeration gases escape, while large particles tend to be very turbulent and form a spout. Geldart (1973) classified bed material into aeratable, cohesive, sand-like and spoutable. He further grouped bed material as Group A, B, C and D as shown in Figure 2.4

i. Group A

Materials having mean size less than 1.4 g/cm^3 tend to expand considerably after minimum fluidisation and before bubbling commences. The bed collapses when the supplied gas is cut-off at a rate similar to the superficial velocity of the gas in the dense phase.

ii. Group B

These are materials within the mean size and density ranges from 40 μm <d_{sv}<500 μm and 4 g/cm^3>ρ_s> 1.4 g/cm^3 respectively. Bubbles start to form in this type of powder at or

only slightly above minimum fluidisation velocity. Bed expansion is small and the bed collapses very rapidly when the gas supply is cut off. Sand is the most typical powder.

iii. Group C

Group C materials are very cohesive and are difficult to fluidise. This difficulty is generally the result of very small particle size, strong electrostatic charges or the presence of very wet or sticky material. The gas passes through voids extending from the distributor to the bed surface.

iv. Group D

Particles in Group D form stable spouted beds. They are large/or very dense. The gas velocity in the dense phase is high, solid mixing is relatively poor and consequently, back mixing of the dense phase gas is small. The flow regime around particles in this group may be turbulent.

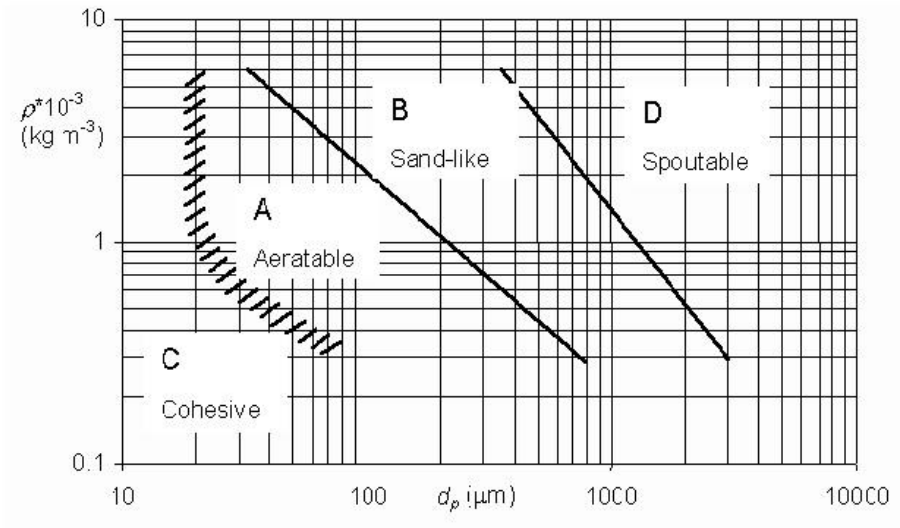


Fig. 2.4Geldart's Classification of Powders according to fluidisation properties

Source: (Hoffman, 2000)

2.11 Energy Potential in Maize Cobs

According to a report by National Agricultural Extension and research Liason Services and National Food Reserve agency of federal ministry of agriculture and water resource, 1,027,790tonnes of maize was produced by Kaduna State in 2009.While adopting a stover to grain ratio of 1:1, maize cobs make up to 15–20% of maizestover (Zych, 2008). Hence, based on 15-20% stover that is maize cobs, an estimated 154,000 – 205,000 tonnes of maize cobs was produced in Kaduna State.

If we consider 154,000 tonnes/y of maize cobs produced in Kaduna state in 2009, then the amount of maize cobs produced per hour is 18 tonnes/h.

1kcal/kg = 4.1868 kJ/kg = 0.004183 MJ/kg

Therefore, the calorific value of the fuel, 3850kcal/kg (maize cobs), can be re-written as 16.12 MJ/kg or 16120 MJ/tonne. Since 18 tonnes/h of waste was generated in 2009, the corresponding energy content of 290160 MJ/h or 80.6 MJ/s could be obtained. This implies that 80.6 MJ/s of energy for heating is available from maize cobs generated in Kaduna state alone in 2009.

However, less than 60% of energy in a fuel is converted to power, with average efficiency of around 33% for centralised power systems (Wade, 2014). Generally, electrical generating efficiencies of 36% for large utilities and just 10% for small utilities are typical of steam turbine plants (ICF Inc., 2008). Adopting 10 – 36% conversion efficiency, 8.06 MW – 29.02 MW of electrical power is obtainable from maize cob waste generated in Kaduna state.

Since the fluidised bed combustor can accommodate fuel feed rate of 5 kg/h, the total heating energy obtainable, using 16.12 MJ/kg heating value is 0.022 MJ/s. Consequently, electrical power output of the system should be within the ranges of 2.2 kW – 7.92 kW. For a system scheduled to operate for 4000 hours in a year, energy consumption of 8800 kWh – 31680 kWh could be recorded.

The fluidised bed combustor can help farmers and villagers harness some of this energy through more efficient combustion in order to arrest energy demand problems plaguing rural Nigeria.

2.12 Brief Description of ERGUN 6.2 Software

Ergun 6.2 program, developed by Divergent S.A in France, is the product of a long research in the field of fluidization. The program is user friendly partly because it is a menu driven program and well suited for engineers. In the program, projects consist of items combined together to produce a global model. This means that for design of fluidized beds, items required include:

i. Particle
ii. Grid design
iii. Bubbling properties and bed expansion
iv. Entrainment of fines from the bed
v. Cyclone design

Data from individual item design is used to build a global model of the fluidized bed and check its operating conditions. The final design is always very important because it requires different components to work harmoniously. The main screen of Ergun 6.2 software is shown in Plate I (Appendix C).

However, preliminary calculation has to be carried out in order to define the initial operating conditions.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Description of Bubbling Fluidised Bed Combustor

The design of the fluidised bed system using maize cobs as fuel consists of three units. These are the main combustor or fluidised bed column, the distributor plate and the cyclone separator.

The fluidised bed combustor contains sand as the bed material and is capable of burning a wide range of fuel to generate heat energy. Air from the force draft fans or blower is supplied into the fluidised bed column. The air passes through holes in the distributor grid, lifting the bed material. This makes the sand particles behave like a fluid. The solid fuel (biomass feed) is then introduced into the bubbling bed and is immediately burned as the bed is agitated. Hot flue gases generated during combustion flow into the cyclone where the combustion gas and entrained solids are separated. The temperature of the gas is then measured using the thermocouple wire to determine its suitability for power generation.Fig. 3.1 shows a schematic of the fluidised bed model.

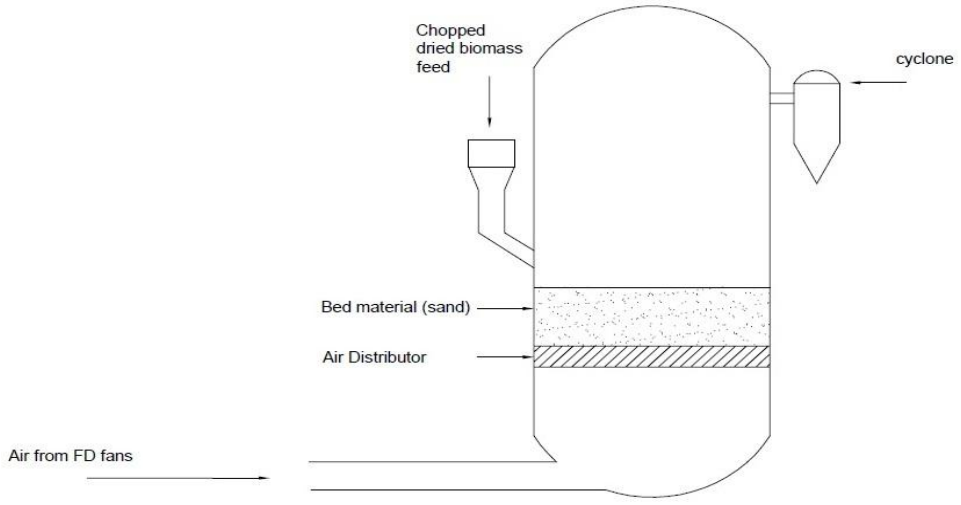


Fig. 3.1A schematic of the fluidised bed model

3.2 Materials

3.2.1 Maize cobs

The agricultural waste used in this work was maize cobs.The sample was acquired from Soba local government area of Kaduna State, North Western Nigeria. Plate II (Appendix C) shows a picture of the agricultural waste obtained.

3.3 Material Selection

In selecting appropriate materials for the fluidised bed combustor, it is necessary to consider the corrosion potential, heat transfer and structural requirements of the various components of the system.

The internal pressure and temperature are two important criteria considered when selecting appropriate material for fluidised bed combustor. The operating metal temperature is a determinant of the maximum allowable stress of the chosen material as shown in Fig. 3.2.

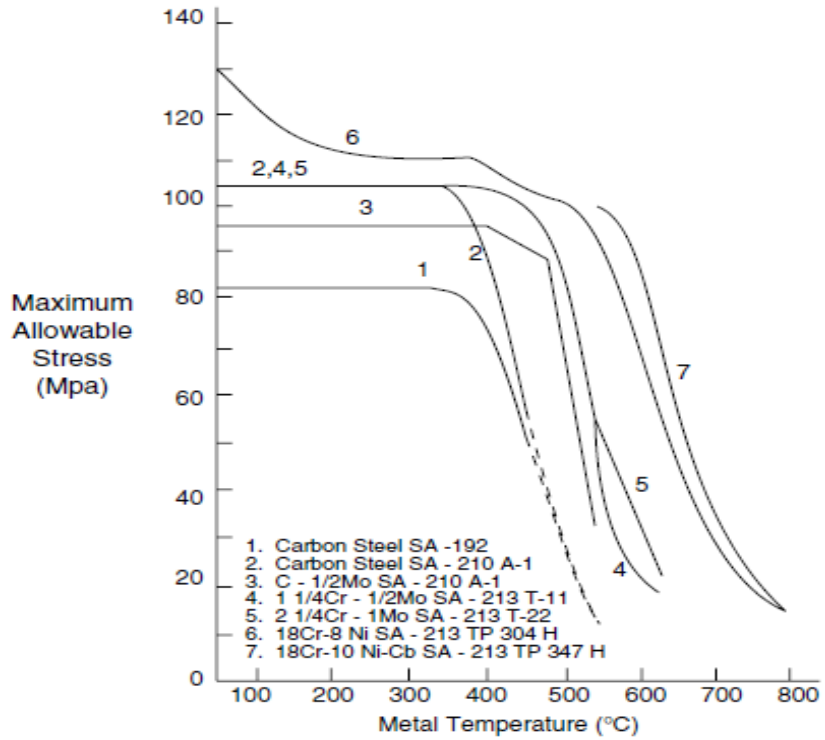


Fig. 3.2: Operating metal temperature vs maximum allowable stress
Source: (Basu, 2006)

3.3.1 Fluidised bed cylinder

This is the most important component of the system. The combustor is basically a cylindrical reactor within which fluidisation occurs and heat is generated through combustion. Since heat generated in the combustor has to stay within the system, the material chosen for this component should reduce heat loss to the external environment. Hence, in addition to financial restrictions, a trade-off has to be maintained between the conductivity of the available material and its ability to be moulded into cylindrical form. For this reason, mild steel was selected in this work due to its low cost, availability and malleability.

3.3.2 Distributor

The distributor grid can be made of synthetic, ceramic or sponge metal. Low carbon steel was utilised for this purpose.

3.3.3 Cyclone

In line with the main combustor, the operating metal temperature in Fig.3.2 can also be used to identify material for cyclone construction subject to similar selection criteria, namely temperature, pressure and heat transfer. Furthermore, potential for severe erosion in the cyclones require the use of special erosion resistant refractory material. 2mm thin sheet of mild steel was used for the cyclone. However, the cyclone was not lagged with any erosion resistant refractory.

3.3.4 Feed hopper

In some parts of the fluidised bed combustor like the feed hopper, corrosion problems may be encountered as a direct result of fuel combustion. In fluidised bed combustors, corrosion is usually initiated by fuels with high chlorine content, poor combustion control, high gas temperature, high metal temperature and local reducing atmosphere. Since the fuel in the gravity chute feeder is not well dispersed, much of the volatile matter is released near the outlet of the feeder, which causes a pressure surge and a reducing atmosphere. While a wide range of

materials could be used for the feed hopper, coating the outlet of the feeder with corrosion resistant material will be desirable. The upper part of the feed hopper was made of mild steel, while the lower part, towards the exit of the feed hopper was made of galvanized steel to mitigate corrosion.

3.3.5 Insulator

Insulation serves to minimize loss of heat to the environment. The insulating material can be either light weight or insulating fire brick. Most light weight insulations are adequately strong and of low thermal conductivity (< 1.5 W/mk) and with density range of 400 to 1600 kg/m^3.

Table 3.1.Available insulating materials.

Material	Thermal conductivity(W/m□C)
Air	0.03
Foam	0.03
Fiber glass	0.04
Cotton	0.06
Saw dust	0.06

Source: (**FAO, 2003)**

Hence, fiberglass with thermal conductivity of 0.04 W/m□C was be utilised in this research because at high temperatures, insulating materials like cotton and saw dust are liable to ignite owing to their lower flash points.

3.4 Design Analysis

3.4.1. Bed temperature, T_b

In Fluidised Bed Combustors, mean bed temperature in the range of 850^{o}C to 950^{o}C is ideal(Rusheljuk, 2006). This is because a higher bed temperature favours the formation of NOx pollutants. Bed temperature has enormous impact on pollution control and can be controlled by

controlling the fluidizing air. Increasing the fluidizing air flow increases the bed temperature, and decreasing fluidizing air flow lowers bed temperature (Kraft, 1998). An Experiment on the combustion of residual oils in a fluidised bed of dolomite showed that combustion efficiency as high as 98% could be obtained at 850^{o}C (Morita *et al*, 1999).Furthermore, concentrations of SOx and H_2S as low as 10ppm were recorded under this temperature.

3.4.2 Bed depth

The bed depth in almost all atmospheric fluidised bed combustors is usually 0.9m – 1.5m deep (UNEP, 2007). However, bed height as low as 400mm have been used for experimental purposes (Morita et al., 1999). Since part load operations are usually considered in designing BFB boilers, heat absorption in the bed can be changed by adjusting the bed depth allowing load change of up to 5% per minute (Basu, 2006). Deeper beds give greater combustion efficiency since they provide longer residence time for combustion, consequently increasing the fan power requirement and entrainment rate of solids. Choices of fuel and combustion requirements are factors to consider when determining the bed depth (Basu, 2006).

3.4.3 Bed material and particle size

Fluidisation largely depends on particle size and air velocity. Recent test suggests that sand particles of about 350μm give better bubbling compared with alumina abrasive and china clay (UNEP, 2007).

3.4.4 Minimum fluidisation velocity, U_{mf}

The minimum fluidizing velocity determines the beginning of fluidisation in a bed of particles. The minimum fluidizing velocity, assuming small spherical particles, is given by (Kunii and Levenspiel, 1991)

$$U_{mf} = \frac{(\emptyset_s d_p)^2(\rho_s - \rho_g)\varepsilon^3 g}{150\mu(1-\varepsilon)} \text{---------- (3.1)}$$

$$Re_p < 20$$

For large particles,

$$U_{mf} = \left[\frac{(\emptyset_s d_p)^2(\rho_s - \rho_g)\varepsilon^3 g}{1.75\ \rho_g}\right]^{1/2} \text{---------- (3.2)}$$

$$Re_p > 20$$

3.4.5 Terminal velocity, U_t

In fluidised bed combustion, solids are generally retained within a certain height above the bed (Basu, 2006). Except for some entrainment, there is no large-scale migration of particles with the gas. This is because the superficial velocity of the particles is under the maximum fluidisation velocity, which is the terminal velocity. Hence particles with terminal velocity lower than the superficial velocity in the free board are carried away.

Mathematical expression of terminal velocity according to Kunii and Levenspiel (1991), is given by

$$U_t = \sqrt{\frac{4gd_p(\rho_s - \rho_g)}{3C_D\rho_g}} \text{---------- (3.3)}$$

Where C_D is the drag coefficient for spherical particles, and is given by (Basu, 2006)

$$C_D = \frac{a_1}{Re^{b_1}} \quad \text{---------- (3.4)}$$

Where the constants a_1 and b_1 can be approximated as given in Table 3.2

Table 3.2 Approximation of constants a_1 and b_1 for different ranges of Reynolds's number

Range of *Re*	**Region**	**a_1**	**b_1**
0 <*Re*< 0.4	Stoke's law	24	1.0
0.4 <*Re*< 500	Intermediate law	10	0.5
500 <*Re*	Newton's law	0.43	0.0

Source: (Basu, 2006)

Calculation of terminal velocity is interactive since Reynolds's number is a function of U_t and vice versa.

3.4.6 Superficial velocity, U

This is the operating velocity at which the fluidising gas is supplied to the fluidised bed combustor. The superficial velocity is selected between the minimum fluidising velocity and terminal velocity and hence, has no specific value. As a rule of thumb, the operating velocity is usually three to five times the minimum fluidisation velocity (Gupta and Sathiyamoorthy, 1999).

A comparison of the physical features of fluidised bed boilers with other types of boilers reveal that bubbling fluidised beds have a superficial velocity ranging from 1.5 – 2.5 m/s (Basu, 2006).

3.4.7 Gas viscosity, μ

Viscosity is a property of the fluidizing gas (air) and is obtainable from mathematical expression for viscosity according to Subramani*et al* (2007), and is given by Equation 3.5

$$\mu = \left[1.46(10^{-6})\left(\frac{T_b^{1.504}}{T_b+120}\right)\right] \text{ ---------- (3.5)}$$

3.4.8 Gas density,ρ_g

Gas density is a function of bed temperature according to Bird *et al.* (1960) ,shown in Equation 3.6

$$\rho_g = \frac{353.2}{\sqrt{T_b}} \text{ ---------- (3.6)}$$

3.4.9 Bed voidage,ε

The bed voidage depends on a large number of factors, such as terminal velocity, type of

particles, vessel diameter, fluidisation regime, and fluidisation velocity. Fluidisation velocity is the one most affecting the voidage (Basu, 2006).

The value of ε for packed beds can be obtained from appendix A. Equation for bed voidage has also been recommended by Nag (2002) as

$$\varepsilon = 1 - \frac{\rho_b}{\rho_a} \text{ ---------- (3.7)}$$

Where ρ_b – bulk density

ρ_a – Apparent density

Generally, the voidage at minimum fluidizing conditions ε_{mf} may be assumed to be 0.45 (Karimipour, 2010). Attempts have been made to establish an empirical correlation of ε_{mf}as a function of Re_{mf} and Ar(Singh, 2008)

$$\varepsilon_{mf} = 0.3507 Ar^{0.0387} Re_{mf}^{-0.0704} \text{ ---------- (3.8)}$$

Where Ar is the Archimedes number given by

$$Ar = \frac{\rho_g d_p^3 (\rho_s - \rho_g)}{\mu^2} \text{ ---------- (3.9)}$$

and

$$Re_{mf} = \frac{\rho_g U_{mf} d_p}{\mu} \text{ ---------- (3.10)}$$

3.4.10 Design of gas distributor

The primary combustion air enters the furnace through an air distributor. The distributor plate supports the bed materials and homogeneously distributes the fluidizing gas into the bed of solids. This is an important aspect of the design of fluidised bed because, beyond the distributor plate, there is no other physical means for influencing the distribution of air through the solids. Non-uniform distribution of air may result in a number of problems; from reduced performance of the combustor to complete collapse of the bed due to agglomeration.

3.4.11 Distributor grids for bubbling fluidised beds

A Bubbling Fluidised Bed boiler or gasifier uses a relatively coarse particle and low fluidizing velocity. If the fluidizing air above its grid is not uniformly distributed, the air velocity in one

region could drop below the minimum fluidizing velocity of the coarser fraction of the bed materials. In a bubbling bed, the operating velocity is low (0.5 to 1.7 m/sec) but particle size is large (1 mm). Thus, the fluidisation number is low and its superficial velocity is not far from the defluidisation velocity of average particles. Due to this, a faulty distribution of air may take the bed close to defluidisation, which could eventually lead to clinkering. This and other issues make the design of distributor plates for bubbling fluidised beds rather critical.

For perforated distributors, important factors to consider are:

a. Pressure drop across the grid, which should be 0.3 times pressure drop across the fluid bed

b. Diameter of the orifice

3.4.11.1 *Pressure drop, ΔP_b*

At minimum fluidisation, pressure drop across the bed according to Kunii and Levenspiel (1991), can be expressed as

$$\Delta P_b = L(1-\varepsilon_{mf})(\rho_s - \rho_g)g \text{ ---------- (3.11)}$$

3.4.11.2 *Orifice velocity, U_{or}*

According to Werther and Karri (2003), the orifice velocity can be obtained from the orifice equation given by

$$U_{or} = C_d\sqrt{\frac{2\Delta P_d}{\rho_g}} \text{ ---------- (3.12)}$$

Where $C_d$is the coefficient of discharge

3.4.11.3 *Orifice number, N_{or}*

For a selected orifice diameter, the orifice number according to Werther and Karri (2003) is obtained from the expression

$$U_{mf} = \frac{\pi d_{or}^2 U_{or} N_{or}}{4} \text{ ---------- (3.13)}$$

3.4.12 Distributor thickness

The flow through plates can be described theoretically by a wide range of models. For perforated plates however, the Hagen-Poiseuilles law can be used to describe the relationship between pressure drop across the distributor and superficial velocity (Nilsson, 2007).

$$\frac{\Delta P_d}{t} = \frac{32 \mu U_{mf}}{d_{or}^2} \text{ ---------- (3.14)}$$

Where t is the thickness of the distributor

Some of the most important assumptions implied in the development of the Hagen-Poiseuilles law are that the flow in the channels is laminar, the density is constant and the fluid behaves as a continuum.

3.4.13 Plenum chamber

The major advantage of plenum design is to achieve uniform pre-distribution of fluidizing gas before it passes the distributor grid. Different plenum designs have been proposed based on the location of gas entry into the fluidisation column. In order to ensure uniform distribution of the gas, the gas entry point must be separated from the distributor plate by a distance H_{plenum}.

Litz(1972) assumed that a high velocity gas stream entering the plenum horizontally or vertically expands as a conical-free jet until it dissipates itself. He proposed the following correlations.

For horizontal gas entry,

$D_{entry} > D_{plenum}/100\ H_{plenum} = 0.2D_{plenum} + 0.5D_{entry}$ ---------- (3.15)

$D_{entry} < D_{plenum}/100\ H_{plenum} = 18D_{entry}$ ---------- (3.16)

For vertical gas entry,

$D_{entry} > D_{plenum}/36\ H_{plenum} = 3\left(D_{plenum} - D_{entry}\right)$ ---------- (3.17)

$D_{entry} < D_{plenum}/36\ H_{plenum} = 100D_{entry}$ ---------- (3.18)

3.4.14 Bed expansion design

When the superficial gas velocity is equal to U_{mf}, the minimum fluidisation velocity, there are no bubbles, and only emulsion phase remains. However, for Group B and D particles, further addition of any gas triggers the formation of bubbles, which push their way into the emulsion phase of solids, resulting in bed expansion. The following is an expression for bed expansion, assuming the bubble velocity to be constant at a mean value of U_{bm} as derived by Davidson and Harrison (1963).

$\frac{H-H_{mf}}{H_{mf}} = \frac{U-U_{mf}}{U_{bm}}$---------- (3.19)

3.4.15 Bubble velocity, u_b

A single bubble rises through the emulsion phase with a velocity (Kunii and Levenspiel, 1991):

$u_{bs} = 0.711\sqrt{gd_b}$---------- (3.20)

The above velocity of bubbles is not the absolute velocity; it is with respect to the emulsion phase.

When a new bubble enters the bottom of the bed, it pushes up the emulsion phase by a volume corresponding to its own. Thus, the emulsion phase itself rises up with an absolute velocity$(U - U_{mf})$up to the bed surface. The absolute velocity of the bubble,$U_b$is (Kunii and Levenspiel, 1991):

$U_b = (U - U_{mf}) + u_{bs}$ ---------- (3.21)

3.4.16 Bubble diameter, d_b

In BFB, the amount of gas passing through the emulsion phase is equal to that required for minimum fluidisation, AU_{mf}. Therefore, the remaining gas, $A(U - U_{mf})$ passes through the bubble phase. The equivalent volume diameter d_b, of a bubble at a height Z, above the distributor is a function of the nozzle area of the distributorA_o, and the superficial gas velocity through the bubble phase$(U - U_{mf})$. Calculation for bubble diameter can be expressed using the equation given by Darton *et al.* (1977) as:

$$d_b = 0.54\left(U - U_{mf}\right)^{0.4}\left(Z + 4\sqrt{A_o}\right)^{0.8} g^{-0.2}$$---------- (3.22)

Where g is the acceleration due to gravity in m/sec^2

Mori and Wen's (1975) developed a method for group B and D particles. In this method, the expression for d_b is as follows:

$$d_b = d_{bm} + (d_{bo} - d_{bm}) exp\left(-\frac{0.3Z}{d_t}\right)$$---------- (3.23)

Where

$$d_{bm} = 0.65\left[A_o\left(U - U_{mf}\right)\right]^{0.4}$$---------- (3.24)

$$d_{bo} = \frac{2.78\left(U - U_{mf}\right)^2}{g}$$---------- (3.25)

and

A_0 = area of the grid per orifice

Note that U and U_{mf} are in cm/sec and A_o is in cm^2

3.4.17 Volume fraction of bubbles in the bed, ε_b

The following continuity equations are used to calculate the volume fraction of bubbles in the bed according to Fogler and Brown (1981),

$$1 - \varepsilon_b = \frac{1-\varepsilon}{1-\varepsilon_{mf}} = \frac{H_{mf}}{H}$$---------- (3.26)

Or

$$\boldsymbol{\varepsilon_b} = \frac{U - U_{mf}}{u_b - U_{mf}(1+\alpha)}$$---------- (3.27)

3.4.18 Transport disengagement height (TDH)

Beyond a certain height, only a negligible amount of particles disengage from the gas to return to the dense bed. This height is known as transport disengaging height (Fig. 3.3). Beyond this height, only particles whose weight is sufficiently small to be balanced by the fluid drag are carried up.

More specifically, particles with terminal velocities lower than the superficial velocity in the freeboard are carried away. The flux of particles carried away beyond the TDH is known as the elutriation rate. Numerous research has been done in an effort to evaluate the TDH. Amitin*et al.* (1968) proposed an empirical correlation for the TDH taking the superficial velocity, U, and the acceleration due to gravity,g into account.

$$TDH = 1.08U^{1.2}(6.71 - 1.21gU) \text{---------- (3.28)}$$

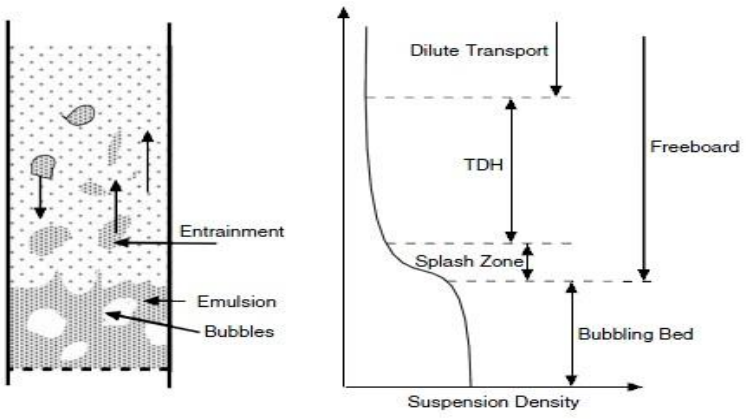


Fig.3.3 Bubbles erupt on the surface of a bubbling bed ejecting solids which travel up through the freeboard. The solid concentration reduces along the height but remains unchanged beyond the TDH.

3.4.19 Cylinder thickness

A cylindrical pressure vessel is classified as thick or thin walled based on its thickness to radius ratio. Hence for thin walled cylinders (Hartog, 1952),

$$t/r \leq \frac{1}{10} \text{ ---------- (3.29)}$$

For thick cylinders,

$$t/r \geq \frac{1}{10} \text{ ---------- (3.30)}$$

3.4.20 Insulation thickness

One of the primary purposes of insulation is to conserve energy and minimize financial and thermal loses. In a cylindrical piece, additional insulation increases the conduction resistance of the insulation layer but decreases the convection resistance of the surface because of the increase in the outer surface area for convection. The heat transfer from the pipe may increase or decrease, depending on which effect dominates.

Consider a cylinder of outer radius r_1 whose outer surface temperature T_1 is maintained constant. The cylinder is now insulated with a material whose thermal conductivity is *k* and outer radius is r_2. Heat is lost from the cylinder to the surrounding medium at temperature T_2, with a convection heat transfer coefficient *h.* The rate of heat transfer from the insulated cylinder to the surrounding air can be expressed as (Totala*et al.*, 2013)

$$q_r = \frac{(T_1 - T_2)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} + \frac{1}{h(2\pi r_2 L)}} \text{ ---------- (3.31)}$$

Where L is the length of the cylinder

Hence the value of r_2 (the critical radius) at which heat transfer rate reaches maximum is determined from the requirement that $\frac{dq_r}{dr} = 0$

3.4.21. Entrainment

3.4.21.1 *Design of cyclone*

Cyclones are always an essential part of fluidised beds. The absence of moving parts, simple construction, and high efficiency make a cyclone especially suitable for FB combustors.

The most common cyclone design has a tangential inlet, consisting of an upper cylindrical part referred to as barrel and a lower conical part referred to as cone.

There are different cyclone configurations which include 1D2D, 2D2D and 1D3D. However, previous research by Wang (2000) indicated that, compared to other cyclone designs, 1D3D and 2D2D are the most efficient cyclone collectors especially for fine dust (particle diameters less than 100 μm). The D in the cyclone configurations refers to the barrel diameter of the cyclone. The digits before each D relate to the length of the barrel and cone sections, respectively. A 2D2D cyclone has barrel and cone lengths two times the barrel diameter, whereas a 1D3D cyclone has a barrel length equal to the barrel diameter and a cone length of three times the barrel diameter (Wang *et al*, 2006).

Hence in the scope of this work, the 2D2D configuration will be adopted. This configuration is shown in Fig.3.4.

3.4.21.2 *Cyclone diameter,* D_c

The cyclone diameter $D_c$as defined by Kalen and Zenz's model is given by

$$D_c = 0.0502\left[\frac{Q\rho_g^2(1-K_b)}{\mu\rho_p K_a K_b^{2.2}}\right]^{0.454} \text{---------- (3.32)}$$

Where D_c is the optimum cyclone diameter (ft), Q is the gas flow rate (ft^3/sec), ρ_g is the gas density (lb/ft^3), μ is the viscosity (lb/ft.sec), $\rho_p$is the particle density (lb/ft^3) and K_a and K_b are design parameters.

a. 2D2D cyclone dimension correlations:

$$B_c = \frac{D_c}{4} \text{---------- (3.33)}$$

$$D_e = \frac{D_c}{2} \text{---------- (3.34)}$$

$$H_c = \frac{D_c}{2} \text{---------- (3.35)}$$

$$J_c = \frac{D_c}{4} \text{---------- (3.36)}$$

$$L_c = 2xD_c \text{---------- (3.37)}$$

$$Z_c = 2xD_c \text{---------- (3.38)}$$

$$S_c = \frac{D_c}{8} \text{---------- (3.39)}$$

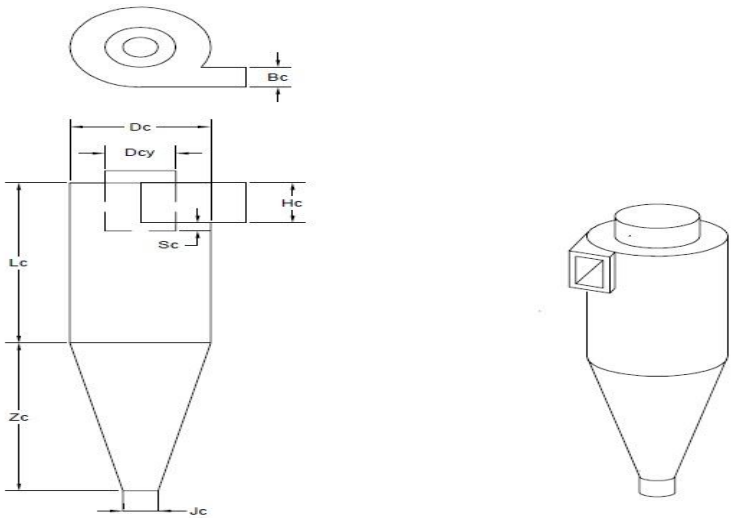


Fig.3.4. 2D2D cyclone configuration

3.5 Design Consideration

3.5.1 Calorific value

The fuel has a significant effect on the design and operation of fluidised bed combustor. Fuels with higher reactivity have greater combustion efficiency. Studies by Lijunin 2005show that the unburnt carbon content in the fly ash decreases with increasing ratio of the volatile content and the heating value of the fuel (Basu, 2006).A maize cob with calorific value of 3850kcal/kg was considered in this design (UNEP, 2012).

3.5.2 Combustion temperature

Typical combustion temperature for fluidised beds falls within the range of 800 – 900 ºC (Basu, 2006). Although this temperature range minimizes the formation of sulphur and nitrogen oxides, higher temperatures reduce the combustible losses in unburned fuel particles which escape through the cyclone before completing their combustion. Thus higher temperatures will ensure that the combustion rate in the bed is accelerated thereby reducing the combustible loss. Combustion temperatures in the neighbourhood of 900 – 950 ºC may be sufficient to balance

emission of nitrogen and sulphur oxides with the amount of unburned carbon in the fly ash. However, it must be noted that some biomass fuels like rice husk (which could be burned at temperatures as low as 600 – 700 ºC) could attract value-added use for their ash when burned at low temperatures (Basu, 2006).

3.5.3 Minimization of combustible losses

In fluidised bed combustors, the residence time of carbon particles is affected by the type of feed, particle size and fluidizing velocity. Particles with terminal velocity lower than their minimum fluidizing velocity are likely to be entrained, thereby having a shorter residence time to complete their combustion. This leads to higher fraction of unburned carbon in the fly ash than in the bed drain. This consideration favours a low operating velocity for the fluidised bed combustor. However, if the operating velocity is too close to the minimum fluidizing velocity, the bed will run the risk of defluidisation.

3.5.4 Gravity chute feed hopper

A gravity chute is a simple device where biomass fuel is fed into the bed via a chute which functions with the help of gravity. The system requires the pressure in the furnace to be slightly lower than the atmospheric pressure. This is necessary to prevent the fuel feed from being blown back into the chute. This type of feeder creates a fuel-rich zone at the exit of the chute. Since the fuel is not well dispersed, much of the volatile matter is released near the outlet of the feeder, which causes a pressure surge and a reducing atmosphere. This pressure surge might blow back fine fuel particles into the chute while reducing conditions might encourage corrosion.

3.5.5 Bed material and bed height

Since the size of bed material influences fluidisation quality, sand particles with mean size and density of 220μm and 1602 kg/m^3 respectively was adopted. Most calculations involving bed height have not been solved satisfactorily, and empirical relations do not yield good results. Consequently, bed height of 300mm was used in this design.

3.5.6 Power requirement

Power requirement in fluidisation has been suggested by Shott*et al*(1975). The suggested horse power requirements for different flow types and operations are shown in Table 3.3.

Table 3.3: Fluidisation fan power requirement for various operations

Type of flow	**Power requirement (hp/1000 gal)**	**Types of operation**
Mild	0.5 – 2	Mixing, blending
Medium	2 – 5	Heat transfer, suspension, gas absorption
Violent	5 – 10	Reactions, emulsification

Source: (Oluleye*et al.,* 2012)

3.6 Design Calculations

Please refer to Appendix A for all calculations relating to the fluidised bed combustor.

3.7 Equipment

The equipment used in fabricating the fluidised bed combustor is as follows (Please refer to Appendix C for plates).

i. Arc welding machine. The constant current arc welding machine was used for this work.
ii. Veniercaliper which is used to carry out length measurement for improved accuracy
iii. Self-retracting tape
iv. Drilling machine
v. Spanner
vi. Plastic chalk
vii. Grinding machine. The hand grinding machine was used throughout this work for cutting and grinding welded joints
viii. Rolling machine. The rolling machine was primarily used to roll mild steel sheets into cylindrical form.
ix. Hammer

Construction

The fluidised bed system was designed such that it can be disassembled into its various components. This makes it easier to checkmate design errors and modify any part of the system when necessary. The fabrication was carried out at National Board for Technology Incubation, farm centre, Kano, Kano State. The following are the major components of the fluidised bed combustor.

- Cylinder
- Distributor grid (Perforated type)

- Cyclone separator
- Feed hopper
- Blower
- Insulation

3.8.1 Cylinder

The cylinder was fabricated using 120 x 240 cm mild steel sheet of 2mm thickness. The adopted diameter of the fluidised bed column was 40cm. The surface area of the column was first marked out using the plastic chalk before finally cut and rolled to produce a hollow cylinder of the desired diameter. The base of the cylinder was then cut out from the same 2mm mild steel sheet using the grinding machine. It was then welded through arc welding to produce the fluidised bed column open at one end (Plate XII, Appendix C).

The fluidised bed column is one of the most important parts of the system because all other components are attached to this unit. Combustion also takes place inside the column.

3.8.2. Distributor grid

The perforated distributor was constructed using mild steel sheet of 5mm thickness. The overall diameter of the distributor is 40cm, but the active diameter is 30cm which consequently contains the perforations. The distributor grid contains 2000 holes of 2mm diameter each, made using the drill machine. The distributor was mounted to the fluidised bed column at three fastening positions inside the cylinder. The fastening was done with the help of bolts (Plate XIII, Appendix C).

3.8.3. Cyclone

The 2D2D configuration was adopted in designing and constructing the cyclone. This configuration is discussed in greater detail in Section 3.4.21.2. The diameter of the cyclone was calculated with an adopted flow rate of $0.22m^3/s$ using Equation (3.32). Like other components of the combustor, the performance of the cyclone was pre-simulated using Ergun 6.2 software prior to construction. The cyclone was constructed using mild steel sheet of 1mm thickness (Plate XIV, Appendix C). Sections of the cyclone like the barrel, cone, downer, vortex finder and wind box were separately cut and rolled before being joined through arc welding. Note that all other dimensions of the cyclone are defined in terms of the barrel diameter.

3.8.4. Feed hopper

The feed hopper is the point through which agricultural waste enters the fluidisation column prior to combustion. It was constructed using mild steel sheet of 2mm thickness (Plate XV, Appendix C). Individual parts of the feed hopper were connected using arc welding.

3.8.5. Blower

The blower utilised in this design is a three phase seimens blower with a capacity of 0.2/0.28 kW(Plate XVI, Appendix C). It was first converted into single phase with the help of a capacitor before being used in the fluidised bed system.

3.8.6. Insulation

Insulationhas tremendous benefit in fluidised beds. The heat energy generated has to be contained within the bed and in the flue gases in order to be utilised effectively. The insulation material used in this work is fiberglass with thermal conductivity of 0.04W/mk .

3.9 Simulation of Fluidised Bed

3.9.1. Introduction

With the advent of powerful computers, simulation of complex engineering processes has become a real possibility. A computer model of a fluidised bed can be constructed and wide range of possible designs or parameter changes can be investigated. Outputs from the model can be set up to provide accurate predictions of the dynamic behaviour of the fluidised bed and its interaction with the solid fuel. Individual simulation of other parts of the system can be carried out, and levels of temperature and pressure can be checked against standard values to ensure safe operation.

Inputs to the model are usually made at each module. Typical inputs are solid density, gas density, gas viscosity, particle size and volume flow rate. These can be standard, calculated or measured values from an instrument. Additional parameters may be specified such as minimum fluidizing velocity and superficial velocity.

Computer tools have been developed from routines and programs used by researchers and engineers in the field of fluidisation, and the theoretical basis of the mathematical modelling used are now mature and reliable. Programs originally written by research institutes have been developed into powerful, validated and user-friendly packages.

The Ergun software used in this research can be used to run a variety of analysis. However, it is necessary to specify

i. A new data file
ii. The gas and solid phase data of the fluidised bed
iii. Data required for individual modules. For example, data required for particle, grid and bubbling design have to be supplied by the user.

iv. Additional configurations like the type of grid, number and position of the cyclone when building the global model

The main parts of the program include

i. The main menu
ii. Design item
iii. Fluidised bed modelling and analysis
iv. Data base

i. **The main menu** is a classical windows type menu that contains general functions as well as notations, references, help and tutorials.

ii. **Design item** concerns the calculation of various elements like the grid, bubbling, entrainment, cyclone and other essential elements in the fluidised bed design. These calculations were carried out at conditions near those of the operating system. Hence the user needs to carryout preliminary calculations to define proper operating conditions because of the interactive characteristics of fluidised bed calculations.

iii. **FB modelling and analysis**. Once the different items of the fluidised bed have been studied separately, this module allows the user to put all items together and make a global model of the fluid bed. Expert comments are inserted in the result file, along with recommendations to optimize the design where necessary.

iv. **Data base** module lets the user to study and prepare physical data for upto 60 different gases and solids.

3.9.2. Parameters for fluidized bed simulation

The Ergun software accepts a wide range of input values. These values can be measured, calculated or adopted. While the software allows data entry at the beginning of each module, it is always recommended to enable the "automatic data transfer" button to automatically share data across all modules, thereby facilitating program usage. The following are some of the input parameters required by the Ergun software

i. **Solid and gas properties.**The solid and gas chosen in this simulation are sand and air respectively. The "gas – solid data bank" module allows the user to select the desired gas and bed material at a specified temperature and pressure. Properties like solid density, gas density and gas viscosity are all provided by this module.

ii. **Minimum fluidisation velocity** is another important input parameter required in the particle, grid, bubbling and entrainment modules. The value of minimum fluidizing velocity has to be manually calculated by the user.

iii. **Superficial velocity** while it is always difficult to accurately determine the superficial/operating velocity of the system, it is necessary to ensure that the superficial velocity lies between the minimum fluidisation velocity and the terminal velocity of particles in the fluid bed. The superficial velocity is considered to be 3 times the minimum fluidizing velocity.

iv. **Orifice number** for a selected orifice diameter, the number of orifice can be calculated in terms of the minimum fluidizing velocity. The calculated value is required in the grid module of the Ergun software.

v. **Orifice diameter** this value is adopted from literature as 2mm.

vi. **Cyclone diameter** this parameter is calculated in terms of the flow rate into the cyclone and standard properties of the flue gas. Other dimensions of the cyclone are predefined in terms of this parameter. The cyclone diameter is one of the few parameters that directly affect cyclone efficiency.

vii. **Particle diameter** the size of the particle is vital in predicting fluidisation behaviour. Bed material of 350μm is considered to give high quality fluidisation. The size of bed material is measured.

viii. **Volume flow rate** with the help of a flow meter, the volume flow rate of fluidizing gas from the blower, and flue gases going into the cyclone can be measured.

ix. **Bed voidage**the voidage of the fluidised bed at minimum fluidisation velocity may be assumed to be 0.45. However, at higher fluidisation velocities, the voidage tends to increase and hence, can be calculated.

All other parameters including the bubble diameter, volume fraction of bubbles and the transport disengagement height are automatically calculated by the software. The fluidised bed modelling flow chart is shown in Figure 3.5

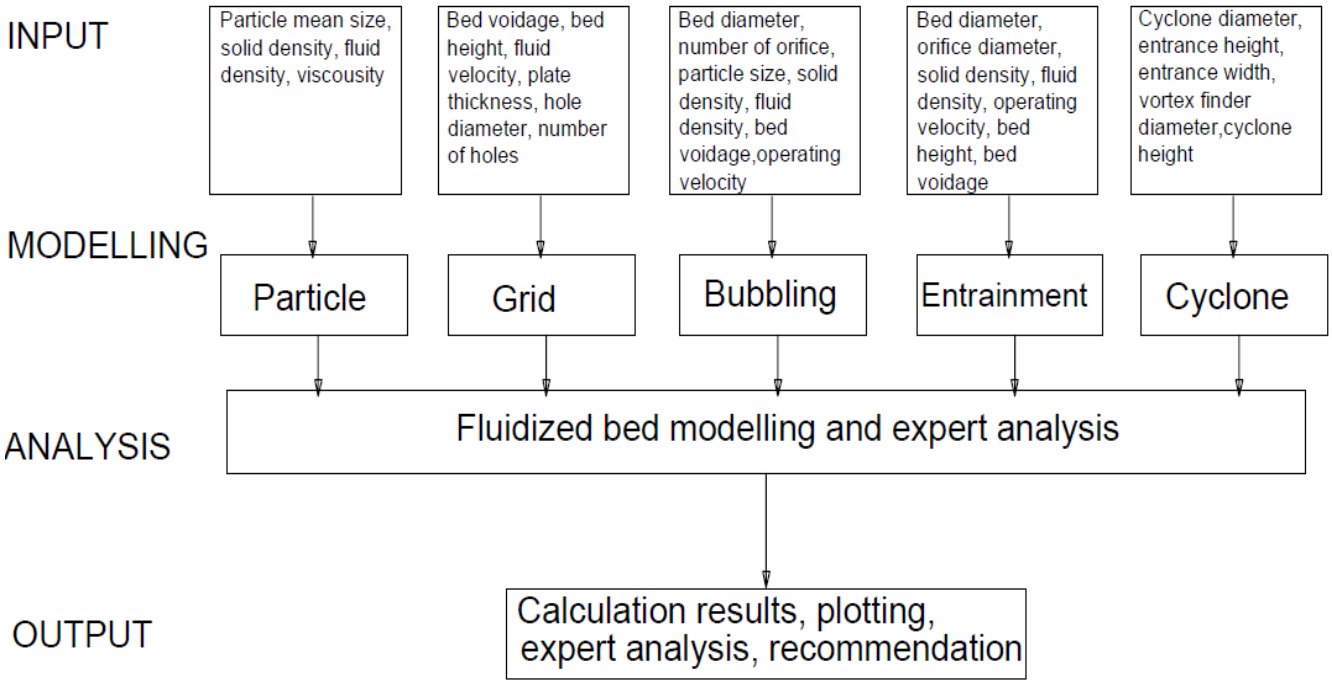


Fig. 3.5: Simulation flow chart

3.9.3. DATA REQUIREMENT

Table 3.4. Ergun 6.2 input data

Particle		**Data**	**Unit**
	Particle mean size	2.20E-04	m
	Solid density	1620	kg/m^3
	Fluid density	1.164	kg/m^3
	Viscosity	1.945E-05	N/m^2s
Grid			
	Particle mean size	2.20E-04	m
	Solid density	1602	kg/m^3
	Fluid density (Wind box conditions)	0.960	kg/m^3

	Fluid viscosity (Wind box conditions)	2.04E-05	N/m^2s
	Bed voidage at minimum fluidisation	0.5024	
	Min. fluidisation bed height	0.300	m
	Fluid velocity in the wind box	0.250	m/s
	Grid plate thickness	0.005	m
	Holes diameter on the plate	0.002	m
	Number of holes per m^2 of the plate	2000	
Bubble			
	Particle mean size	2.20E-04	m
	Solid density	1602	kg/m^3
	Fluid density	1.164	kg/m^3
	Viscosity	1.945E-05	N/m^2s
	Bed diameter	0.400	m
	Min. fluidisation voidage	0.5024	
	Min. fluidisation bed height	0.300	m
	Operating velocity	0.1208	m/s
	Number of orifice per m^2 of grid	2000	
Entrainment			
	Bed diameter	0.400	m
	Bed diameter at entrainment zone	0.400	m
	Solid density	1602	kg/m^3

	Fluid density	1.164	kg/m^3
	Viscosity	1.945E-05	N/m^2s
	Operating velocity	0.1208	m/s
	Bed height at min. fluidisation	0.300	m
	Bed voidage at min. fluidisation	0.5024	
	Grid orifice or jet diameter	0.002	m
	Number of orifice per m^2 of grid	2000	
	Total solid feed rate (if any)	1000	Kg/h
Cyclone			
	Gas flow rate per cyclone	0.22	m^3/s
	Solid density	1602	kg/m^3
	Fluid density	1.164	kg/m^3
	Viscosity	1.945E-05	N/m^2s
	Cyclone diameter	0.15	m
	Entrance height	0.075	m
	Entrance width	0.040	m
	Vortex finder diameter (Gas exit tube)	0.075	m
	Downer diameter (solid exit)	0.040	m
	Cyclone height	0.300	m
	Cone height	0.155	m
	Vortex finder height	0.093	m

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Ignition/Testing Procedure

The system was assembled outside the boiler room, mechanical engineering departmental workshop, ABU Zaria. The bed material (sand) was prepared by removing larger particles which can potentially affect the quality of fluidisation using a sieve. The bed material was then poured over the distributor grid. A shallow bed of 150mm was maintained in this case owing to the size of the sand particles.

The three-phase constant speed blower used during this test was converted to a single-phase blower with the help of a 50 microfarad capacitor.

To initiate combustion, a small amount of charcoal, sprayed with kerosene was spread evenly across the bed before being ignited with matches as shown in Plate XVII, Appendix C. The charcoal was allowed to burn for about 2 to 3 minutes to allow heat penetrate some parts of the bed, before the blower was switched-on.

The combustor was then enclosed with the feed-hopper, and the agricultural waste (mostly maize cobs) was supplied at a rate of 5 kg/h manually. The bed and flue gas temperature rise are shown in Table 4.1 and Table 4.2 (Appendix D) respectively.

4.2 Bed Temperature

The temperature of the bed immediately after ignition was initially measured to be 35 °C. The bed temperature rose proportionally with time, reaching a maximum of 837 °C as shown in Fig. 4.1. The MASTECH multipurpose clamp meter was the instrument used to carry out temperature

measurements in this work. It is basically a digital multimeter which uses the k- type thermocouple wire to measure and display temperature readings directly in ºC on its display screen (Plate XIX, Appendix C).

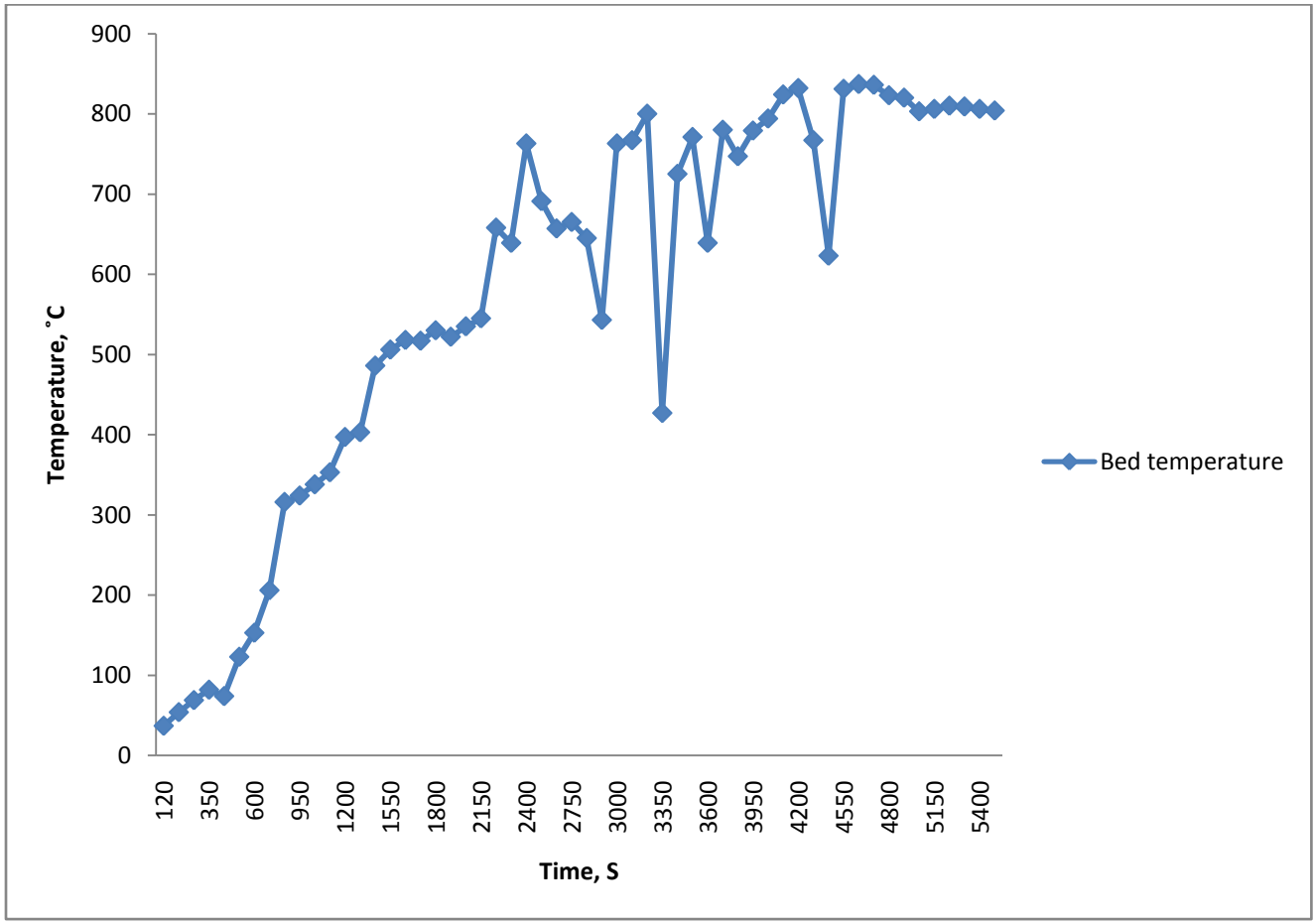


Fig. 4.1: Rise of bed temperature with time

Bed temperature is an important property considered in fluidised bed combustors. Fig. 4.1 shows that the system can produce temperatures as high as 837 ºC. However, the bed temperature has the tendency to rise beyond the measured values over prolonged periods of operation especially during co-combustion, where the agricultural waste (maize cobs) is burned along with high carbon fuels like coal. In some cases, agglomeration occurs in the bed causing the bed material to

fuse and form a lump mass. This often leads to total collapse of the bed, thereby affecting the performance of the combustor.

The total combustion of maize cobs (Plate XVIII, Appendix C) shows that the obtained bed temperature is adequate for utilizing the chemical energy contained to produce the desired heat output.

The char obtained after the combustion of maize cobs can be converted to briquettes for use in advanced cooking stoves.

4.3 Flue Gas Temperature

The temperature of the flue gas was also measured using the k- type thermocouple wire accessory of the MASTECH digital multimeter. The measurement was carried out after thirty minutes of normal operation of the fluidised bed combustor. During measurement, the flue gas temperature rose sharply to 220°C in 34 minutes. The result is shown on Fig. 4.2.

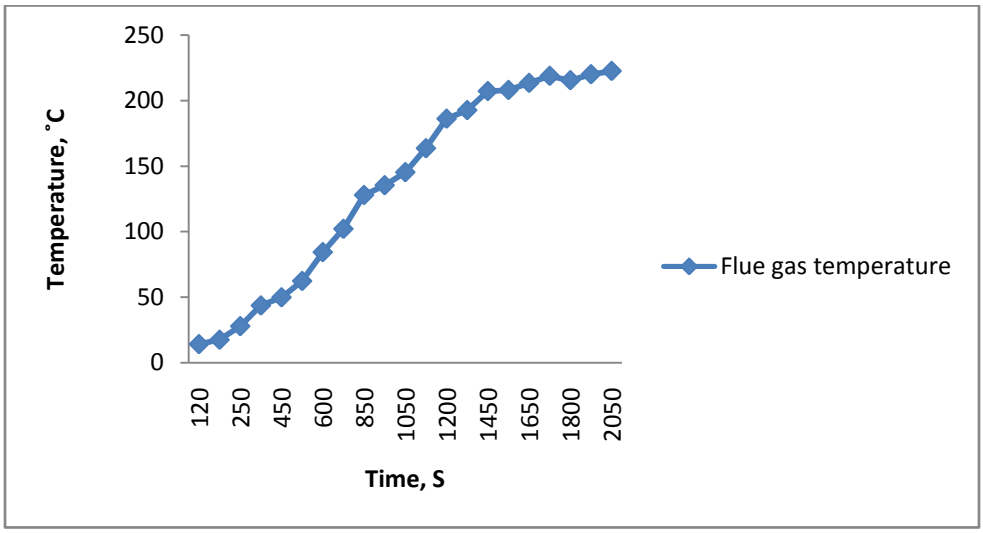


Fig. 4.2: Flue gas temperature rise with time

Fig. 4.2 presents the temperature in ºC obtained from the flue gas. Although the temperature obtained is as high as 220 °C, the amount of energy obtained from the flue gas will largely depend on the efficiency of the heat exchanger, through which this energy can be transferred for some light load applications.

The flue gas contains enough heat energy for low energy applications like pre-heating and drying which require minor heat workouts. The temperature may not be sufficient for high energy applications especially where the point of application is farther away from the heat source (Combustor).

The IMR 1400 gas analyser, which is a user friendly unit equipped with sensors for detecting O_2, CO, NO_x, and $SO_x$was used in analysing the flue gas (Appendix C). It also has a K-type thermocouple for gas temperature measurement. The flue gas contained 2ppm of CO with traces of NO_x and SO_x at 5ppm and 1ppm respectively. Table 4.3 shows the safe concentration standards for six principal pollutants.

Table 4.3. US – EPA Standards for Six Principal Pollutants

Pollutants	**Safe concentration zone**
Carbon monoxide	9ppm
Sulphur dioxide	0.017ppm
Nitogen dioxide	10ppm
Ozone	0.075ppm
Lead	0.15 µg/m3
Particulate matter (Pm10)	150 µg/m3

Source: (Dibofori-Orji, 2013)

The concentrations of CO and NO_x in the flue gas are well within the international safe standard limit. This is possible because the fluidized bed combustor is sufficiently supplied with oxygen from the blower, making the oxidation of CO to CO_2 achievable,while the lower concentration of

nitrogen oxide in the flue gas is due to low combustion temperature in the fluid bed. Although sand was used as the bed material in the combustor, the higher concentration of SO_x (1ppm) implies the need to use scrubbers for gas cleaning or burn fuel with low sulphur content.

Generally, the designed fluidised bed combustor has been successful because the operating/bed temperature of the system is high enough for steam generation and the flue gas temperature is adequate for low-heating applications. Furthermore, the boiler to be incorporated within the system can be designed in such a way as to increase the residence time of the generated steam before it leaves the combustor, consequently increasing its dryness fraction.

In terms of fluidisation quality, the designed combustor recorded mixed results ranging from partial to near complete fluidisation of the bed. The partial fluidisation can be attributed to the fact that different categories of bed materials (sand) were used over different test periods.

4.4 Volume Flow Rate

The volume flow rate of the blower air and flue gas was determined using the continuity equation, Q = AV. To achieve this, it is necessary to measure the air and flue gas velocities from the blower and cyclone respectively. The instrument used for this purpose is the anemometer (Appendix C), which provides air speed measurements in both kg/hr and m/s, and displays the measured value on a small LCD screen as shown in Plate XX. The readings obtained are tabulated in Table 4.4.

Table 4.4: Air speed measurements using the anemometer.

Item	**Velocity (m/s)**	**Area (m^2)**	**Flow rate (m^3/s)**
Blower air	23.1	0.00196	0.045
Flue gas	7.5	0.0177	0.03317

4.5 Results Of Simulation

4.5.1 Particle

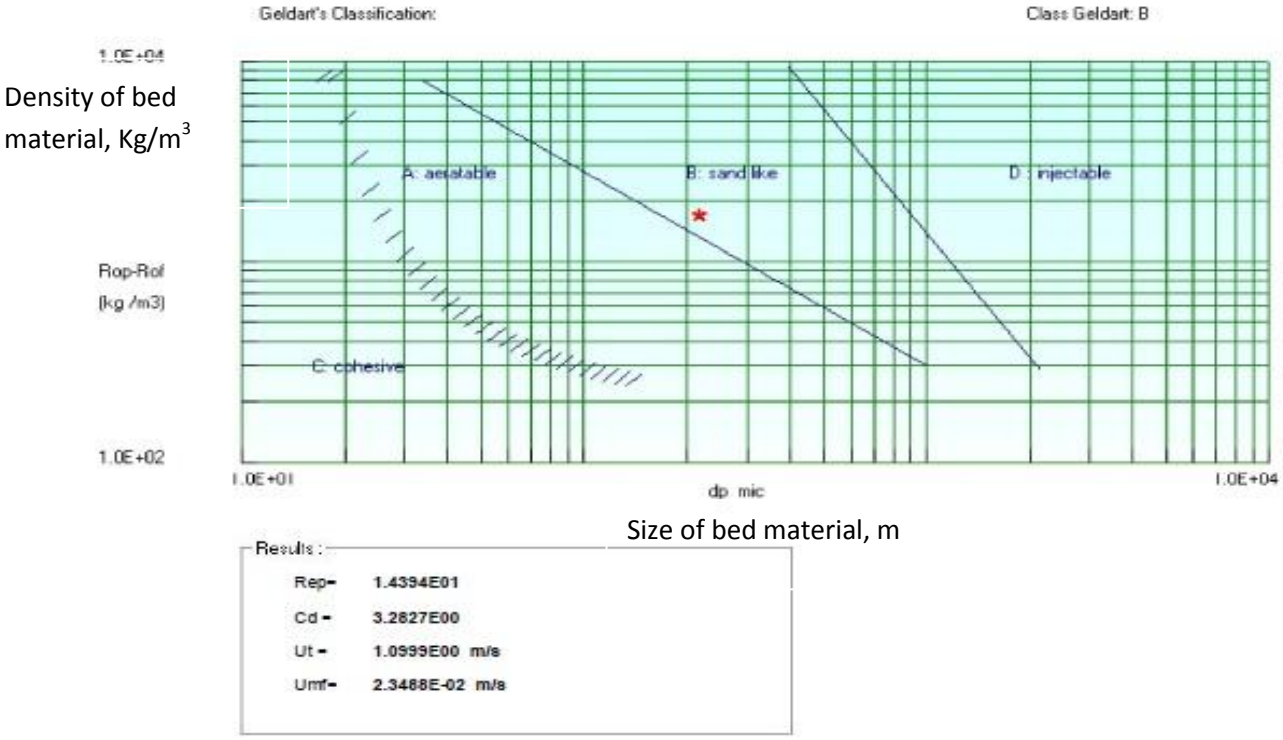


Fig. 4.3: Result of particle simulation

Figure 4.3 shows the result of particle analysis by the ERGUN software in-line with Geldart's classification. The chart was produced from particle input data in Table 3.4. The star sign indicate the position of the bed material by virtue of its size and density. The particle falls under group B category, which is considered suitable for fluidised bed applications, they are sand like in nature.

4.5.2 Grid

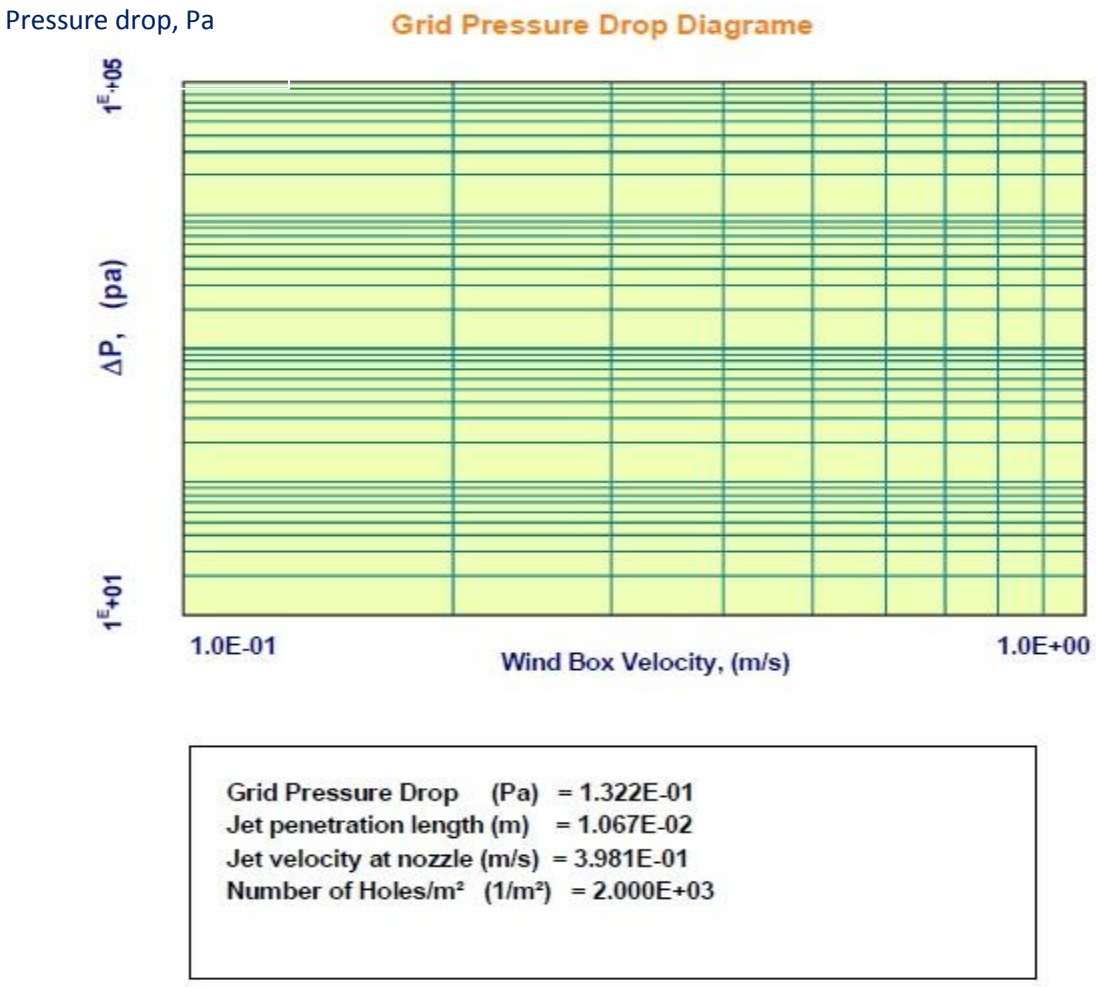


Fig. 4.4: Results of grid simulation

Grid pressure drop of 0.1322 Pa was calculated from grid input data in Table 3.4 by the ERGUN software as shown in Figure 4.4. Very low grid pressure drop is risky in fluidised beds because slight changes in operating parameters like fluidising velocity could lead to poor gas distribution. On the other hand, the pressure drop through the grid is supposed to be held at its lower possible value.

4.5.3 Bubbling

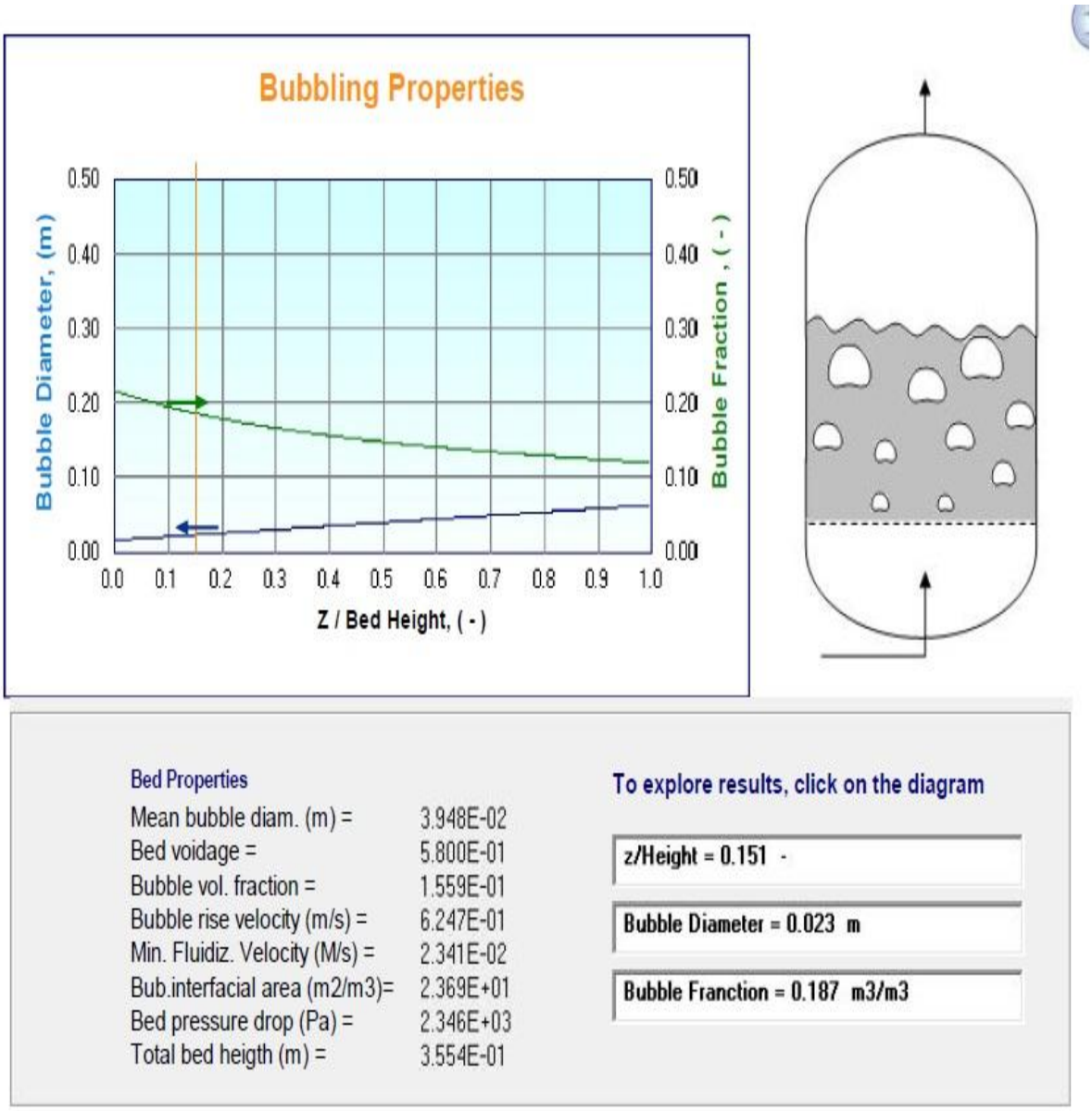


Fig. 4.5: Result of bubbling simulation

The bubbling characteristics were calculated using bubble input data in Table 3.4 and displayed in Figure 4.5 by the ERGUN software. It is a graph of bubble diameter against bed height. Bed properties like voidage and mean bubble diameter are displayed. The result at a bed height of 150 mm was also explored by clicking on the diagram.

4.5.4 Reh diagram

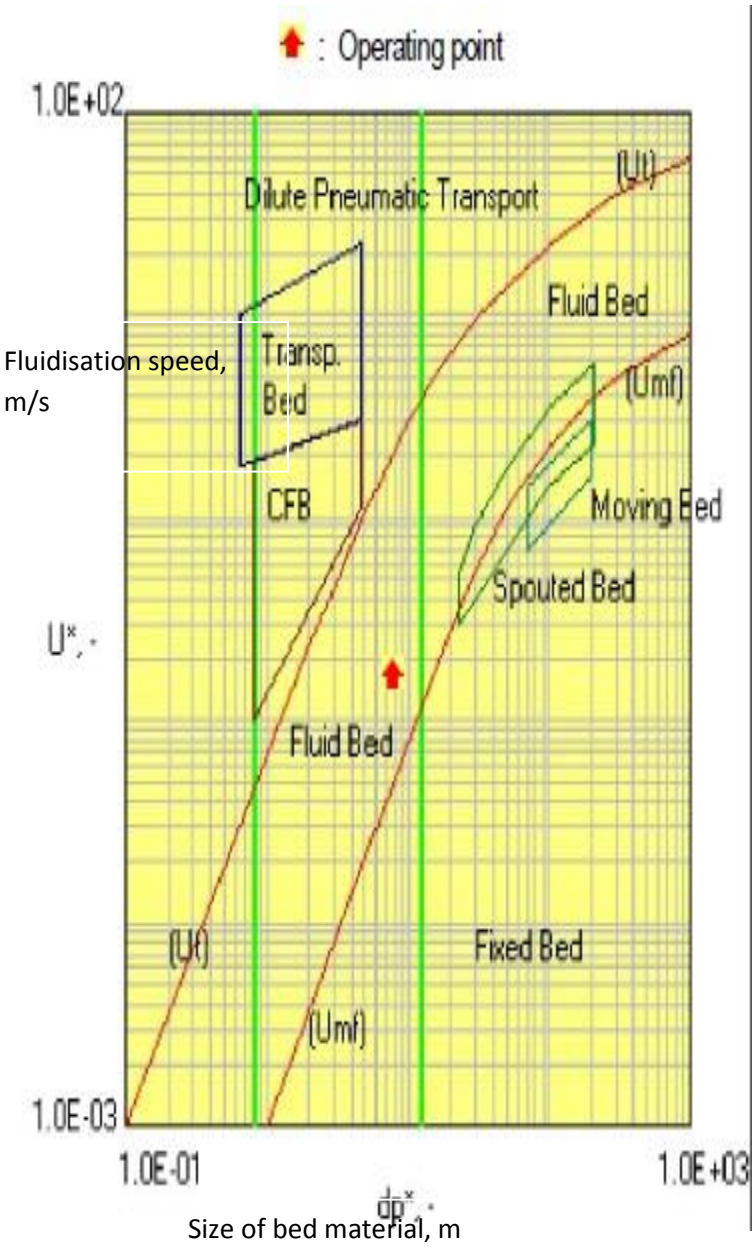


Fig. 4.6: The Reh diagram

The Reh diagram is a graph of fluidisation speed against particle size. It is also simulated from bubble input data in Table 3.4. The upward arrow shows the operating point of the bed, which is in the fluid bed region. Higher fluidising velocity will lead the fluid bed towards pneumatic transport as shown in Figure 4.6, which is not desirable in bubbling fluidised beds.

4.5.5 Entrainment

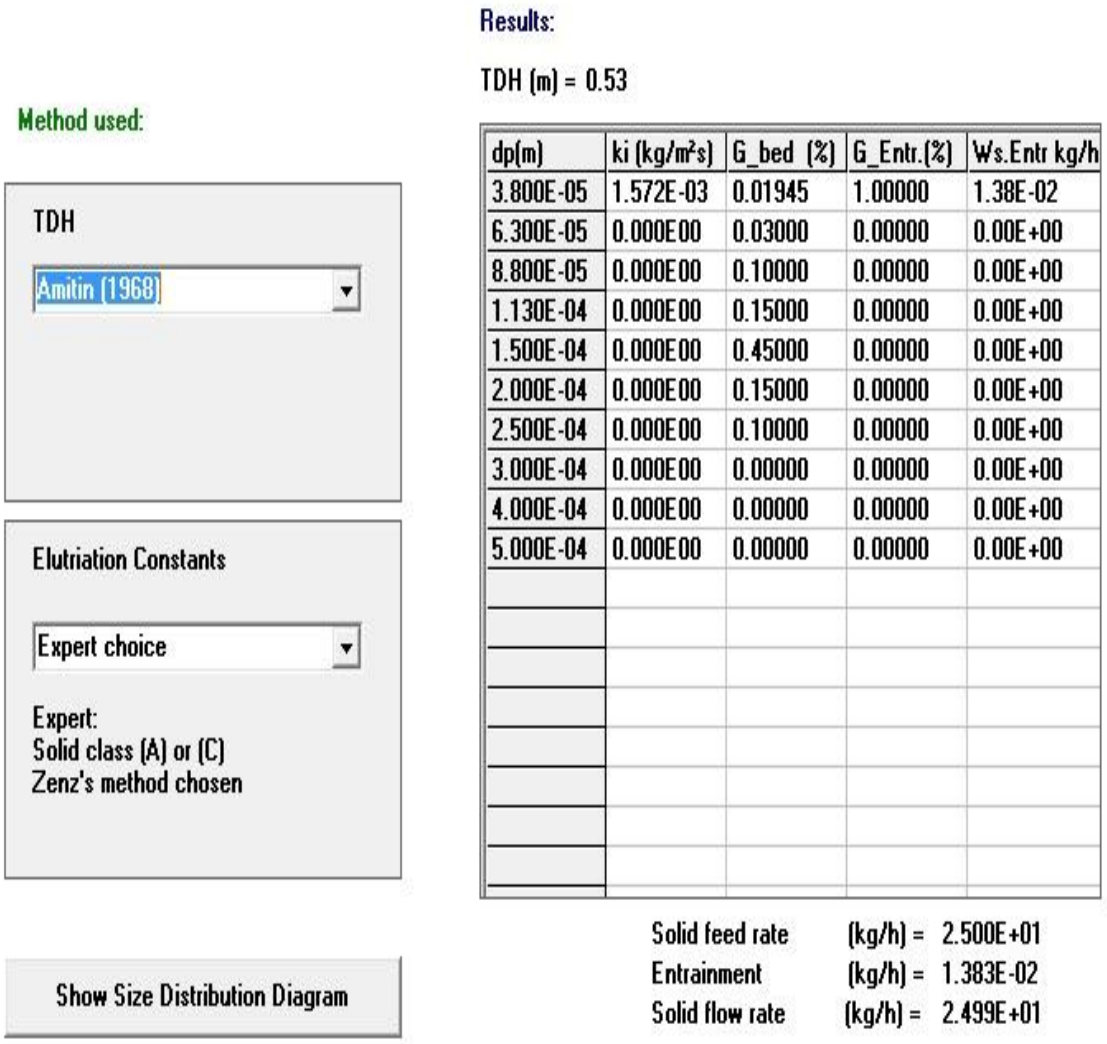


Fig. 4.7: The result of entrainment simulation

Figure 4.7 shows particle entrainment result simulated from entrainment input data in Table 3.4 by the ERGUN software. The result shows bed particle size distribution ranging from 3.8E-05m to 5.0E-04m . Since the mean particle diameter is 220µm, maximum solid size distribution in the bed is 2.5E-04 (G_bed %). Similarly, only small particle size of 3.8E-05 m is expected to be entrained (G_Entr, %). Entrainment at transport disengagement height of 0.53m is expected to be very low for various size distributions as indicated by the entrainment coefficient, ki.Ws. Entr is the mass flow rate of the entrained solid.

4.5.6 Cyclone

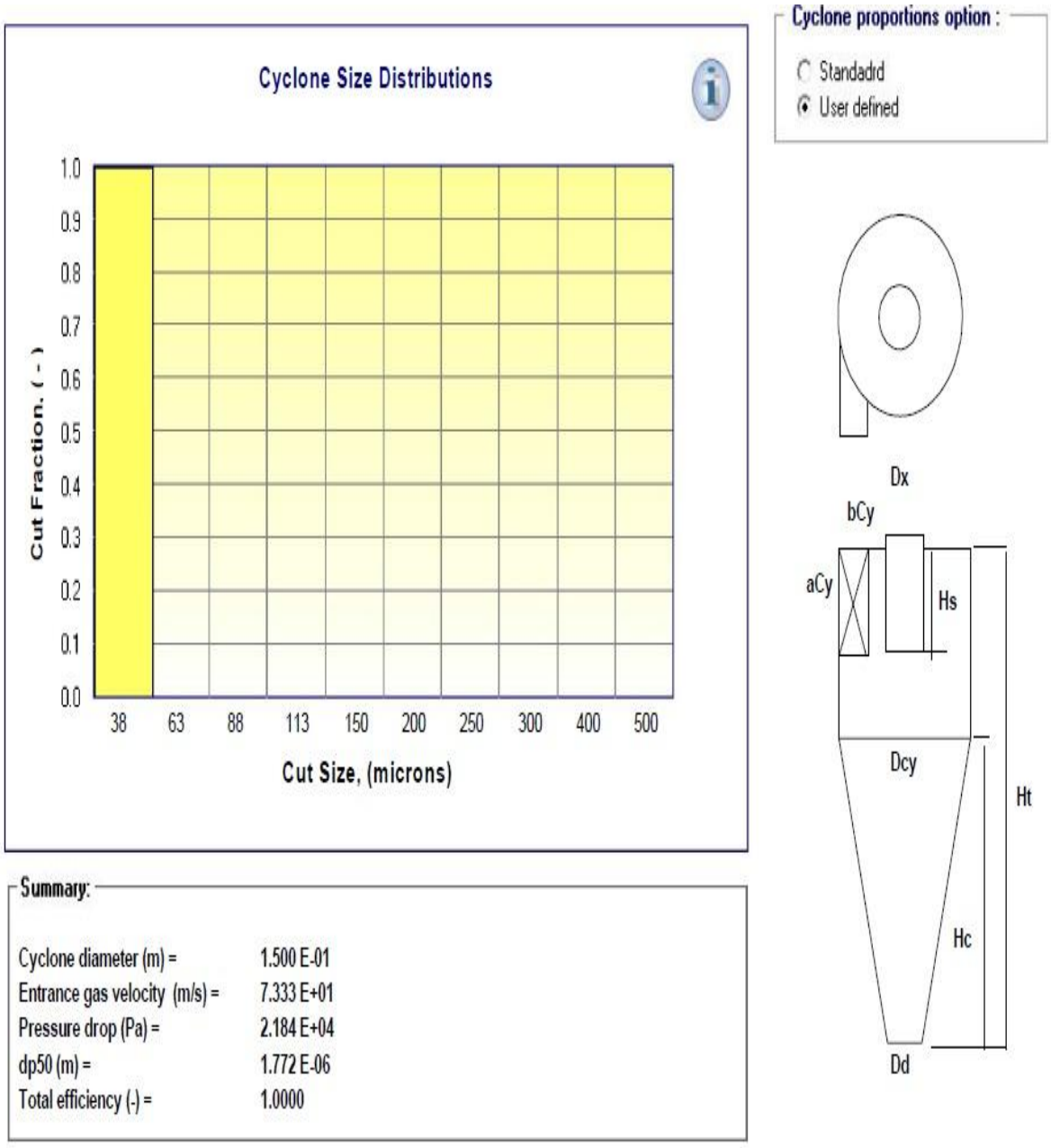


Fig. 4.8: The result of cyclone simulation

The cyclone efficiency and size distribution is displayed in Figure 4.8. The result is obtained from cyclone input data in table 3.4. Again, only particles of 3.8E-05m (38 microns) are expected to be captured by the cyclone.

4.5.7 Fluidised bed modelling and expert analysis

```
Bed expertise result file:
_____________________________________________________________________

Checking grid...
1/3 of Bed weight     (Pa)   = 7.814E+02
Grid Pressure Drop    (Pa)   = 8.914E+02
Jet penetration length (m)   = 2.494E-02
Grid Pressure Drop: expert -->> Low pressure drop.
Low pressure drop may cause bad gas distribution.
Solution: change grid configuration or design.
Jet penetration length: Expert -->> ok
_____________________________________________________________________

Checking bed expansion...
Bubble mean diameter (m) = 0.03578
Bubble max. diameter (m) = 0.40000
Bed voidage          (-) = 0.58670
Bubble fraction      (-) = 0.16942
Min.fluid.velocity (m/s) = 2.355E-02
Expanded bed height  (m) = 3.612E-01
Expert -> Bubble fraction: ok
Expert  -> Bed voidage ok.
Expert  -> Bubble diameter ok.
_____________________________________________________________________

Checking TDH and Entrainment...
TDH   (m) = 0.53
Solid size distribution above TDH :
  Size,m    Mass fraction, %
3.8000E-05  1.0000E+00
6.3000E-05  0.0000E+00
8.8000E-05  0.0000E+00
1.1300E-04  0.0000E+00
1.5000E-04  0.0000E+00
2.0000E-04  0.0000E+00
2.5000E-04  0.0000E+00
3.0000E-04  0.0000E+00
4.0000E-04  0.0000E+00
5.0000E-04  0.0000E+00
_____________________________________________________________________

Primary cyclones...
Entrance velocity  (m/s) = 5.07
deltaP             (Pa) = 1.0422 E+02
dp50 cut size       (m) = 1.259E-05
Efficiency          (-) = 0.98650
Size,m      Efficiency    Inlet      Downflow   Upflow

Expert  -> Warning! Low entrance velocity (primary cyclones).
        This may affect cyclone efficiency.

Solution -> Choose smaller cyclone.

3.8000E-05  9.8650E-01    1.0000E+00  1.0000E+00  1.0000E+00
_____________________________________________________________________
```

Fig. 4.9: The fluidised bed expert analysis

The summary of the ERGUN 6.2 result is displayed in Fig 4.9. According to the fluidised bed expert, grid pressure drop is low. The recommendation to change the perforated grid used in this design to tuyeres should be a point of interest in subsequent study. It is important to note that

concerns have been raised regarding the level of uncertainties in the mathematical models of the ERGUN software (Tjøstheim S., 2010). Figure 4.9 also highlights low cyclone entrance velocity of 5.07 m/s. However, measured flue gas velocity of 7.5 m/s further supports uncertainty theories surrounding the ERGUN software.

4.5.8 Comparing calculated and simulated values

Table 4.5 Calculation and simulation comparison

Item	Calculated value	Simulated value	Error (%)
Bed voidage	0.5024	0.5867	17
Bubble diameter (m)	0.0299	0.023	23
Bubble fraction	0.196	0.187	5
Minimum fluidizing velocity (m/s)	0.0403	0.0235	42
Transport disengagement height (m)	0.45	0.53	18
Bubble velocity (m/s)	0.466	0.624	34
Terminal velocity (m/s)	0.6385	1.099	72
Drag coefficient	9.69	3.28	66
Reynolds number of particle	1.06	14.3	1249

Table 4.5 shows that calculation and simulation results of bubble characteristics and other important parameters like transport disengagement height and terminal velocity of the fluidised bed combustor are similar, with error less than or equal to 50%. Only the drag coefficient and Reynolds number recorded significant variations. This may be due to differences in minimum fluidisation velocity. Adopting the simulated Reynolds number of 14.3 yielded corresponding values of 2.6 and 1.22m/s for the drag coefficient and terminal velocity respectively, reducing the error margin with Ergun 6.2 values.

4.5.9 Estimated Cost of aFluidised Bed System

The cost of fabricating a fluidised bed combustor is affected by the blower capacity.The cost of agricultural waste is currently negligible, and in some cases, can even be procured freely. The expenses incurred during fabrication are summarized in Table 4.6.

Table 4.6: Estimated cost of a fluidised bed combustor

Material	**Cost (N)**
Mild steel sheet for the main combustor	8000
Mild steel sheet for cyclone and feed hopper	4000
Distributor plate	2000
Blower	13000
Fibre glass	3500
Labour cost	8500
Duct tape	750
Spray paint	1000
Total	40,750

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary

The maize cobs sample was obtained from soba local government of Kaduna State. The fluidised bed combustor along with all its relevant components was fabricated at the national board for technology incubation in Kano State, and tested for fluidisation. The insulation of the fabricated combustor was then completed at the mechanical engineering workshop, Ahmadu Bello University, Zaria. The completed system was tested for fluidisation and fired with agricultural waste (Maize Cobs). The velocities and temperatures of the flue gas and fluid bed were then measured and the results were analysed.

The system was also simulated using Ergun 6.2. The error margin between calculated and simulated values was then deduced.

5.2 Conclusion

Fluidised bed combustion is a reliable method of obtaining clean and renewable energy from maize cobs. The combustor has generated bed temperatures of 837 °C, sufficient for the production of steam, and hence, power generation. Furthermore, flue gases at over 220 °C have been generated by the system, thereby providing alternative ways for drying and other low thermal applications.

Char produced from maize cobs combustion could be converted to form charcoal briquettes for use in advanced wood stoves, hence, improving the total economic output of the combustor.

From an environmental stand point, the low concentration of CO, NOx and SOx in the order of 2p, 5p and 1p respectively is an indication of emission reduction potential of fluidised bed combustors.

5.3 Recommendations

The following recommendations are proposed to improve the fluidised bed combustor

1. Measuring key bed parameters like temperature, bubble size, bubble velocity, bed voidage and volume fraction of bubbles will continue to present challenges in fluidised bed research, and hence, the need to procure necessary equipment for fluidised bed experiments.
2. Incorporating a variable speed blower will enhance the ignition phase of the fluidised bed combustor, and allow for the bed temperature to be controlled more effectively.
3. Since the pressure of the system is higher than the atmospheric pressure, light weight fuels like rice husk and groundnut shells will be blown out of the feed hopper. It is therefore necessary to modify the feed hopper to accommodate fuels of all sizes.

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APPENDIX A

Design Calculations

Initial Data	Calculation	Results
Fluidised bed calculations: $d_p = 220\mu m$ $\rho_p = 1.602\ g/cm^3$ $\rho_g = 0.001164\ g/cm^3$ $D_t = 40cm$ $L = 1m$ $\mu = 1.95\ x10^{-4}\ \frac{g}{cm.s}$	$V_p = \frac{\pi D_t^2 L}{4} = \frac{\pi x 40^2\ x\ 100}{4} = 125600\ cm^3$ $A_p = \pi D_t L + \frac{\pi D_t^2}{2} = \pi x 40 x 100 + \pi x \frac{40^2}{2}$ $= 15072\ cm^2$ $D_p = \left(\frac{6D_t^2 L}{4}\right)^{\frac{1}{3}} = \left(\frac{6x40^2x100}{4}\right)^{\frac{1}{3}}$=78.29cm $\varphi = \frac{6V_p}{D_p A_p} = \frac{6x125600}{15072x78.29} = 0.64$	
	A. Calculation of ε_{mf} $\varepsilon_{mf} = 0.586\ \varphi^{-0.72} \left(\frac{\mu^2}{\rho_g \delta d_p^3}\right)^{0.029} \left(\frac{\rho_g}{\rho_p}\right)^{0.021}$ $\gamma = g(\rho_p - \rho_g) = 980\ (1.602 - 0.001164)$ $= 1569\ g/cm^2 s^2$ **Cross sectional area of column** $A = \frac{\pi D_t^2}{4} = \frac{\pi x 40^2}{4} = 1256\ cm^2$ $\varepsilon_{mf} = 0.586\ (0.78)^{-0.72}$	The voidage at minimum fluidisation is 0.5024

	$\left(\frac{(1.95\ x10^{-4})^2}{0.001164\ x\ 1569\ x(220\ x10^{-4})^3}\right)^{0.029}$ $\left(\frac{0.001164}{1.602}\right)^{0.021} = 0.5024$	
$d_p = 220\mu m$ $\varphi = 0.78$ $\gamma = 1569\ g/cm^2s^2$ $\varepsilon_{mf} = 0.5024$ $h = 15cm$ α = 0.39 $\mu = 1.95\ x10^{-4}\frac{g}{cm.s}$	**B. Volume fraction of bubbles** $\boldsymbol{\varepsilon_b} = \frac{U - U_{mf}}{u_b - U_{mf}(1+\alpha)}$ **Minimum fluidisation velocity** $U_{mf} = \frac{(\varphi d_p)^2 \gamma \varepsilon_{mf}^3}{150\mu(1-\varepsilon_{mf})} =$ $\frac{(0.78\ x\ 220\ x10^{-4})^2 x\ 1569\ 0.5024^3}{150\ x\ 1.95x10^{-4}x(1-0.5024)}$ = 4.03 cm/s **Superficial velocity U** $U = 3\ xU_{mf} = 3\ x\ 4.03 = 12.08\frac{cm}{s}$ $u_b = U - U_{mf} + u_{bs}$ $= 12.08 - 4.03$ $+ 0.71\sqrt{980\ xd_b}$ Maximum bubble diameter, $d_{bm} = 0.652\ \left(A(U - U_{mf})\right)^{0.4}$ $= 0.652\ x(1963.5\ x(12.08$ $- 4.03))^{0.4} = 26.08cm$ Minimum bubble diameter $d_{bo} = 0.00376\ x(U - U_{mf})^2$ $= 0.00376\ x(12.08 - 4.03)^2$ $= 0.243cm$ $\frac{26.08 - d_b}{26.08 - 0.243} = e^{-\frac{0.3h}{40}}$ $h = 30cm, ath = 15cm$	Thus 80.4% of the bed is in the emulsion phase, plus the wakes. The remaining 19.6% of the bed is in the bubble phase.

	$d_b = 26.08 - 25.837\ xe^{-\frac{0.3\ x\ 15}{40}} = 2.99cm$ For the purpose of Kunii and Levenspiel model, we shall take $d_b = 3cm$ Hence, $u_b = 12.08 - 4.03 + 0.71\sqrt{980\ x\ 3}$ $= 46.55\ cm/s$ Volume fraction of bubbles, $\boldsymbol{\varepsilon_b} = \frac{12.08 - 4.03}{46.55 - 4.03(1+\alpha)}$ For a 220μ size particle, α = 0.39 $\boldsymbol{\varepsilon_b} = \frac{12.08 - 4.03}{46.55 - 4.03(1+0.39)} = 0.196$	
$\rho_p = 1.602\ g/cm^3$ $\rho_g = 0.001164\ g/cm^3$ $L = 30cm$ $g = 9.81$ $d_{or} = 2mm$ $\mu = 1.95\ x10^{-4}\ \frac{g}{cm.s}$	**C. Grid calculations** **Pressure drop across the distributor** $\Delta p_d = 0.3\Delta p_b$ $\Delta p_b = L(1-\varepsilon_{mf})(\rho_p - \rho_g)g$ $\Delta p_b = 30\ x(1-0.5024)x(1602 - 1.1644)x\ 9.81$ $= 2341.53\ N/m^2$ $\Delta p_d = 0.3\ x\ 2341.53 = 702.5\ N/m^2$ **Orifice velocity** $U_{or} = C_d\sqrt{\frac{2\Delta p_d}{\rho_g}}$ $Re = \frac{\rho_g U_{mf} d_p}{\mu(1-\varepsilon_{mf})}$ $= \frac{0.001164\ x\ 4.03\ x\ 220\ x10^{-4}}{1.95\ x10^{-4} x\ (1-0.5024)} = 1.06$	

	From fig 2 (Orifice plate Re vs Cd relationship), Cd = 0.4 $$U_{or} = 0.4\sqrt{\frac{2\ x\ 702.5}{1.1644}} = 13.89\ m/s$$ **Orifice number** $U_{mf} = \frac{\pi d_{or}^2 U_{or} N_{or}}{4}$, for $d_{or} = 2mm$ $$N_{or} = \frac{4\ U_{mf}}{\pi d_{or}^2 U_{or}} = \frac{4\ x\ 0.0403}{\pi(2x10^{-3})^2 x\ 13.89}$$ $$= 923\ holes$$ **Distributor thickness** $$\frac{\Delta P_d}{t} = \frac{32\mu U_{mf}}{d_{or}^2}$$ $$t = \frac{d_{or}^2 . \Delta P_d}{32\mu U_{mf}}$$ $$t = \frac{(2\ x10^{-3})^2 x\ 702}{32\ x\ 1.95\ x10^{-5} x\ 0.0403} = 11.5m$$	
	D. Transport disengagement height $$TDH = 1.08\ x\ U^{1.2}(6.71 - 1.21gU)$$ $$TDH = 1.08\ x\ (12.1\ x\ 10^{-2})^{1.2}\ x\ (6.71 - 1.21\ x\ 9.81\ x\ 12.1\ x\ 10^{-2})$$ $TDH =$ 0.08565 x 5.27 $$TDH = 0.45m$$	The transport disengagement height is 0.45m
	E. Terminal velocity $$U_t = \sqrt{\frac{4d_p(\rho_s - \rho_g)g}{3C_D\rho_g}} = \sqrt{\frac{4d_p\gamma}{3C_D\rho_g}}$$	The terminal velocity of the

	$C_D = \frac{a_1}{R_e^{b_1}}$ for Re = 1.06, $a_1 = 10, b_1 = 0.5$ $C_D = \frac{10}{1.06^{0.5}} = 9.69$ $U_t = \sqrt{\frac{4\ x\ 0.2\ x\ 10^{-4} x\ 1569}{3\ x\ 9.69\ x\ 0.001164}} = \sqrt{\frac{1255.2}{0.03}}$ $= 63.85 cm/s$	bed particles is 63.85cm/s

	F. Plenum design $D_{plenum} = 40cm$ $D_{entry} = 50mm$ $H_{plenum} = 0.2\ D_{plenum} + 0.5\ D_{entry}$ $H_{plenum} = 0.2\ x\ 40\ x\ 10^{-2} + 0.5\ x\ 50\ x\ 10^{-3}$ $H_{plenum} = 0.08 + 0.025 = 0.105\ m$	The height of the plenum chamber is 0.105m

r_1 = 2mm h = 5 W/m^{2}K k = 0.04 W/m^{2}K	**G. Insulation thickness** The rate of heat transfer by conduction and convection from an insulated cylinder to the surrounding air can be expressed as $$q_r = \frac{T_1 - T_2}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi Lk} + \frac{1}{h(2\pi r_2 L)}}$$ Hence the heat transfer rate reaches a maximum when $\frac{dq_r}{dr} = 0$ $$\frac{1}{2\pi k r_{cr} L} - \frac{1}{2\pi h r_{cr}^2 L} = 0$$ $$r_{cr} = \frac{k}{h}$$ The value of the critical radius r_{cr} will be the largest when k is large and h is small. Noting that the lowest value of h encountered in practice is about 5 W/m^{2}K for the case of natural convection of gases, and that the thermal conductivity of fibre glass is 0.05 W/m^{2}K, the largest value of the critical radius we are likely to encounter is $$r_{cr} = \frac{k}{h} = \frac{0.04}{5} = 0.008m$$ The minimum insulation thickness is given by $r_{cr} - r_1$. For r_1 = 2mm $$r_{cr} - r_1 = 0.008 - 0.002 = 0.006m = 6mm$$	The minimum insulation thickness is 6mm

$\rho_g = 0.001164\ g/cm^3$

Q = 0.22 m^3/s

$\rho_p = 1.602\ g/cm^3$

$\mu = 1.95\ x10^{-4}\ \frac{g}{cm.s}$

K_a = 0.5

K_b = 0.2

H. Cyclone

The expression for calculating the cyclone diameter is given by

$$D_c = 0.0502\left[\frac{Q\rho_g^2(1-K_b)}{\mu\rho_p K_a K_b^{2.2}}\right]^{0.454}$$

$H_c = \frac{D_c}{2}$ = 0.007725 m

$B_c = \frac{D_c}{4}$ = 0.003863 m

$D_e = \frac{D_c}{2}$ = 0.007725 m

$S_c = \frac{D_c}{8}$ = 0.001931 m

$J_c = \frac{D_c}{4}$ = 0.003863 m

$L_c = 2xD_c$ = 0.0309 m

$Z_c = 2xD_c$ = 0.0309 m

E = 210 Gpa

ν = 0.29

r_o = 20.2 cm

r_i = 20 cm

α = 13x10^{-6} m/mk

ΔT = (853+273) – (29+273) = 824 k

I. Thermal Stress and Strain

$$\sigma_t = \frac{E\alpha\Delta T}{2(1-\nu)}\left\{1 - \frac{2r_i^2}{r_0^2 - r_i^2}\ln\left(\frac{r_o}{r_i}\right)\right\}$$

$$= \frac{210\ x\ 10^9 x\ 13\ x\ 10^{-6}\ x\ 824}{2x\ (1-0.29)}\left\{1 - \frac{2\ x\ 0.2^2}{0.202^2 - 0.2^2}\ln\left(\frac{0.202}{0.2}\right)\right\}$$

= 15.7Mpa

$$e = \alpha\Delta T$$

$$e = 13\ x\ 10^{-6}\ x\ (853-29)$$

$$= 0.0107\ m$$

J. Power requirement for fluidisation

$$Power = \rho_g hg(1-\varepsilon_{mf})U_{mf}A$$

$$= 1602\ x\ 30\ x\ 10^{-2}\ x\ 9.8\ (1 - 0.5024)\ x\ 4.03\ x\ 10^{-2}\ x\ \pi\ x\ \frac{(40\ x\ 10^{-2})^2}{4}$$

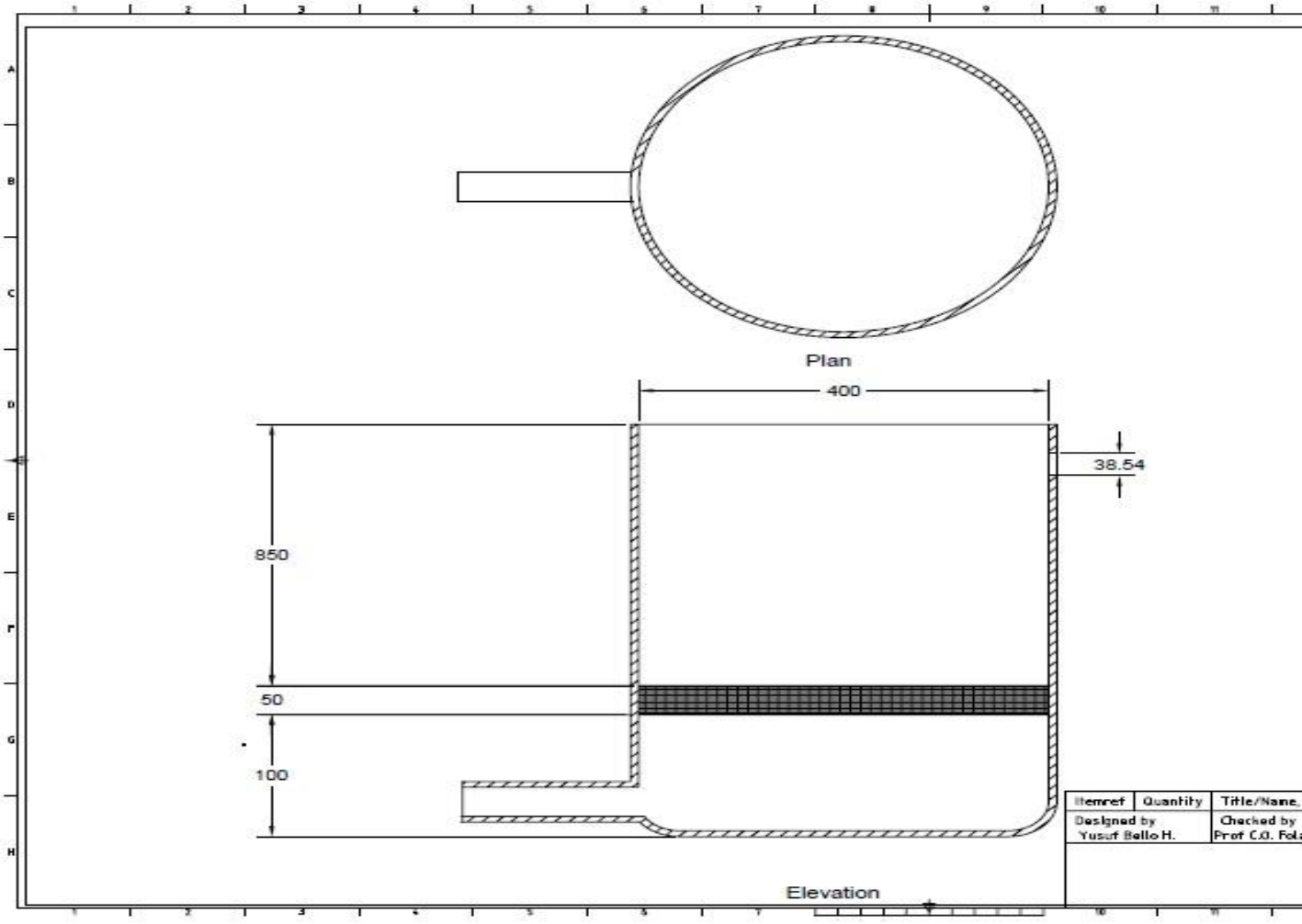
$$= 13.6\ W$$

The maximum thermal stress of the cylinder is 15.7Mpa, while 13.6W is required to commence fluidisation.

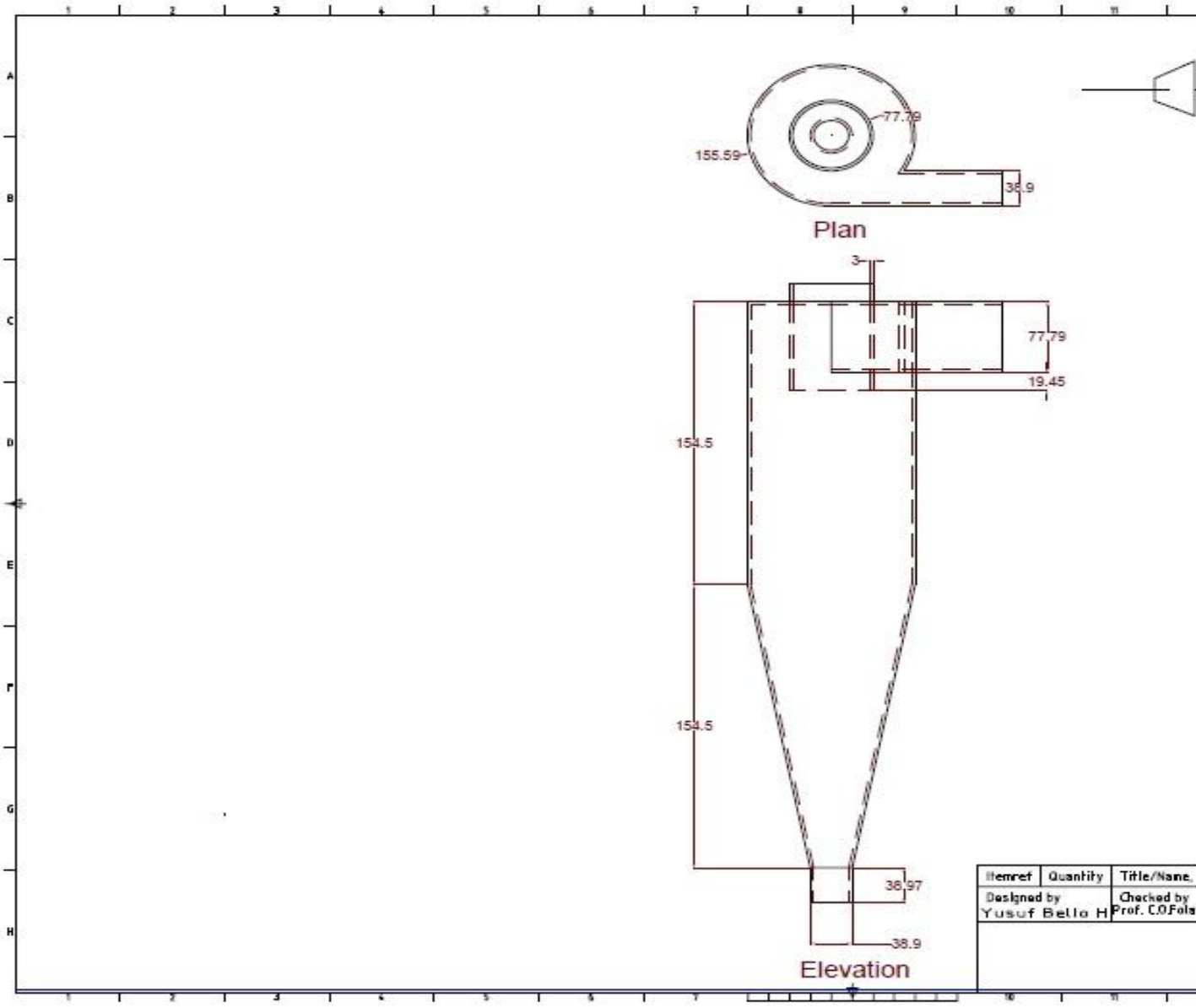
APPENDIX B

Fluidized bed drawings

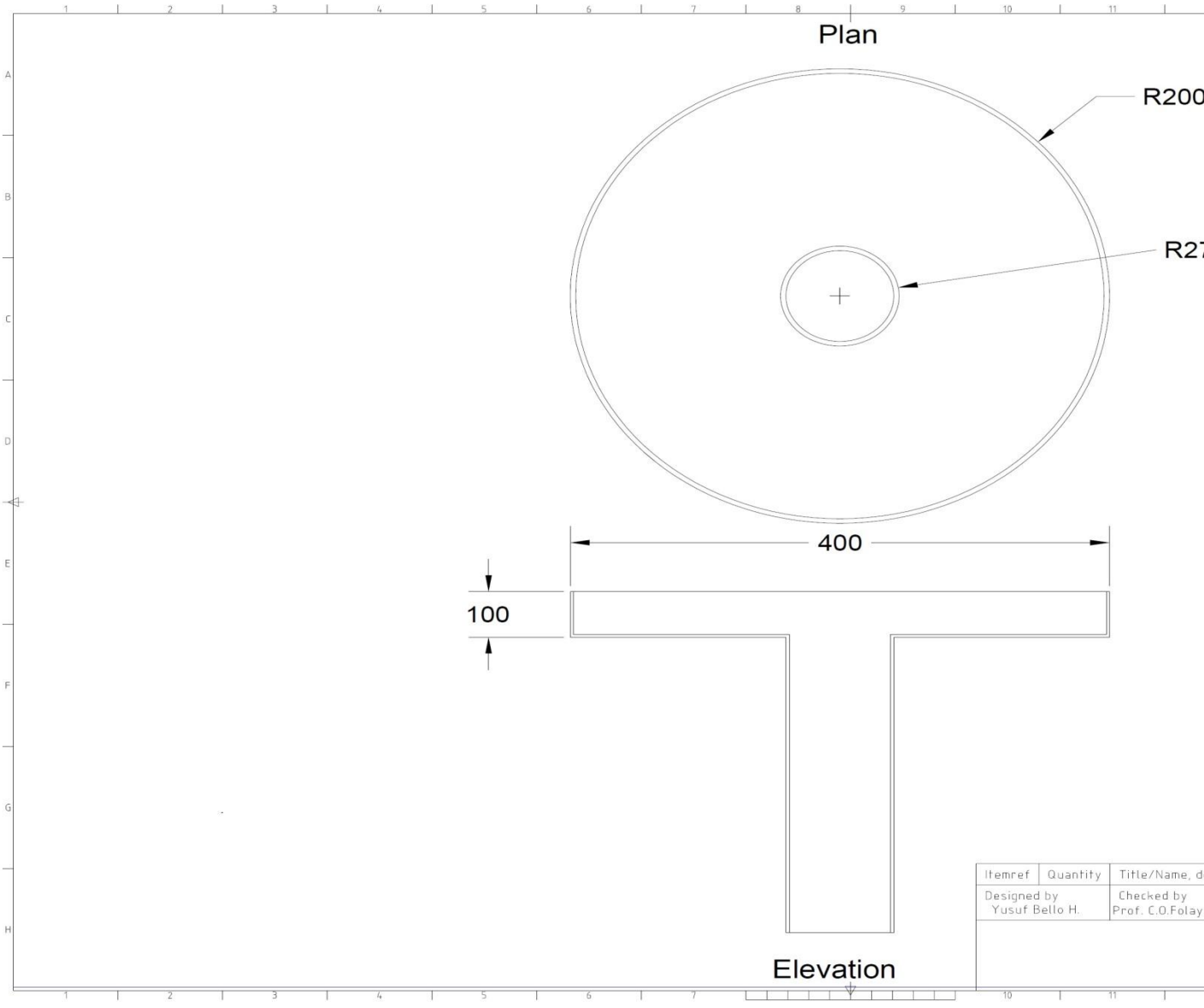
Column



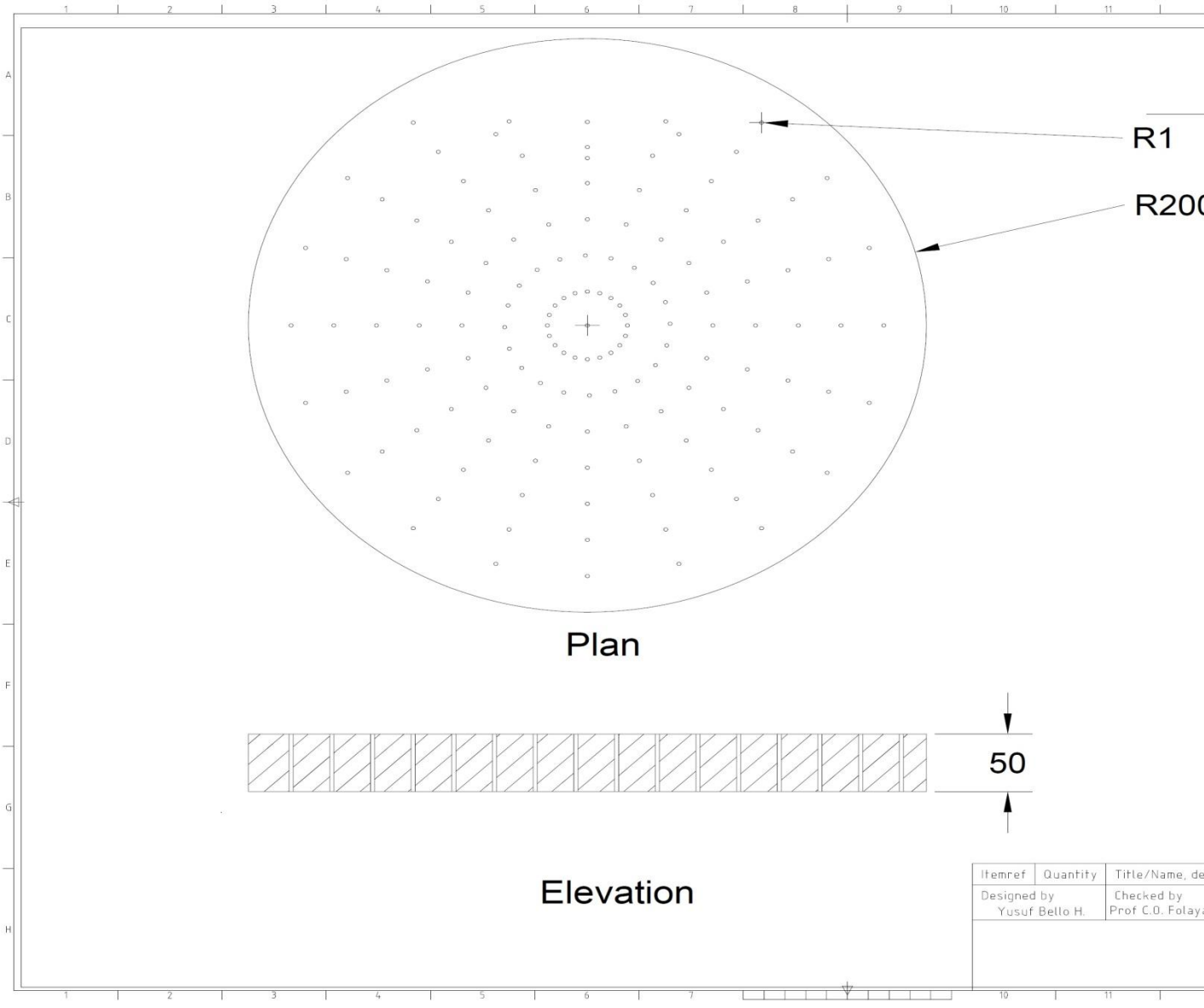
Cyclone


77.79
155.59
38.9
Plan
3
77.79
19.45
154.5
154.5
38.97
38.9
Elevation
Itemref
Quantity
Title/Name
Designed by
Yusuf Bello H
Checked by
Prof. C.O.Fols

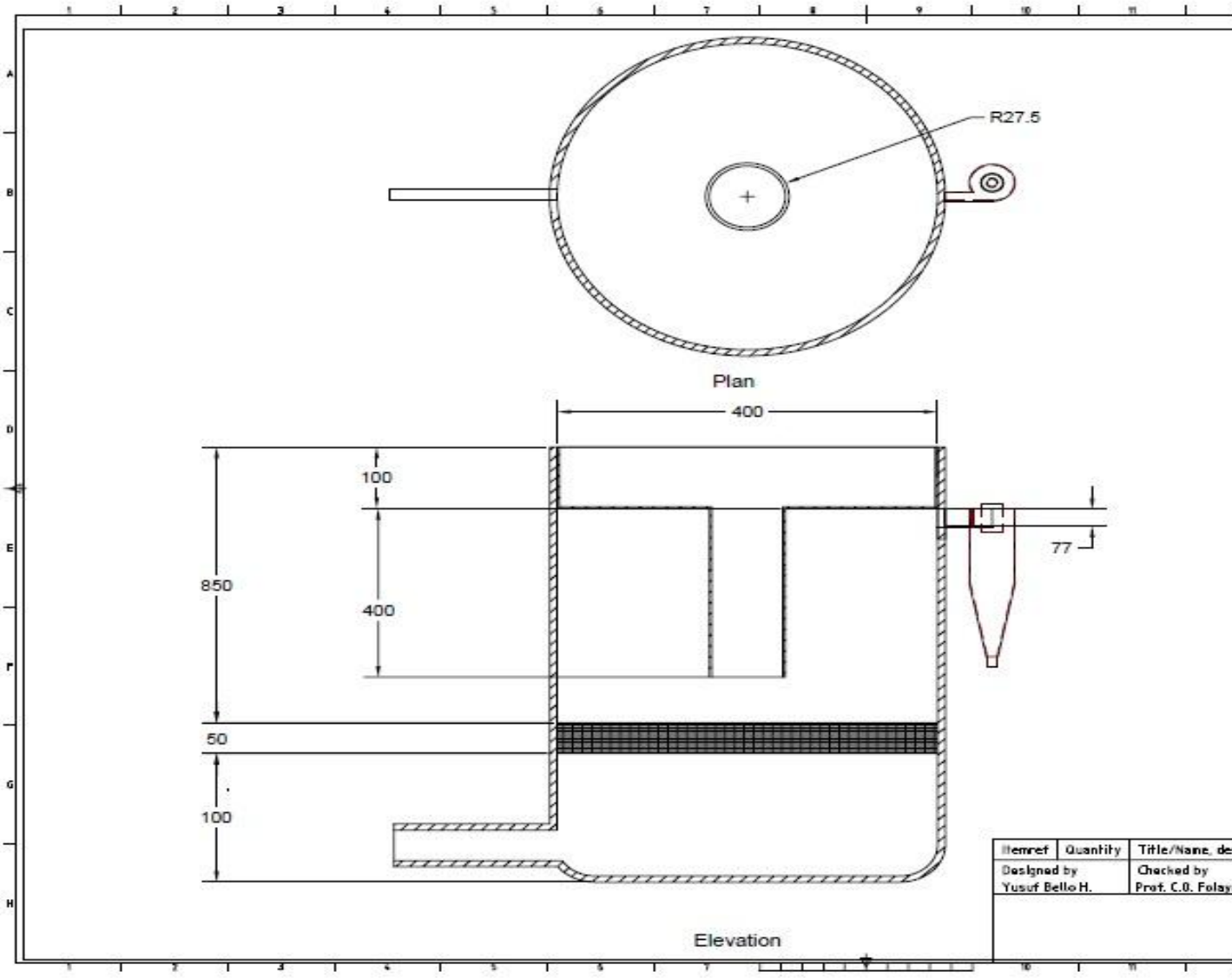
Feed hopper


Plan
R200
R27
400
100
Elevation
Itemref
Quantity
Designed by
Yusuf Bello H.
Checked by
Prof. C.O.Folay

Grid distributor



Assembly


R27.5
Plan
400
100
400
850
50
100
77
Elevation
Itemref
Quantity
Designed by
Yusuf Bello H.
Checked by
Prof. C.O. Folay

APPENDIX C

Pictures of Equipment and Materials used in the Fabrication Process



Plate I: Main screen of Ergun 6.2 software



Plate II: Maize cobs sample



Plate III.: Arc welding machine



Plate IV: Veniercaliper



Plate V: Self-retracting tape



Plate VI: Drilling machine



Plate VII: Spanner

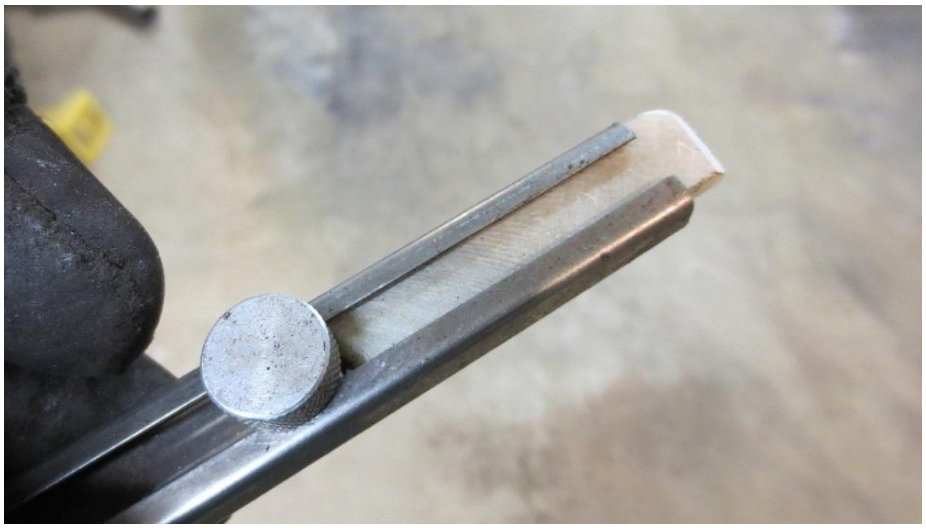


Plate VIII: Soap stone, also known as plastic chalk by local technicians



Plate IX: Grinding machine



Plate X: Rolling machine



Plate XI: Hammer



Plate XII: Fluidised bed column



Plate XIII: Perforated distributor grid



Plate XIV: The cyclone



Plate XV: The feed hopper

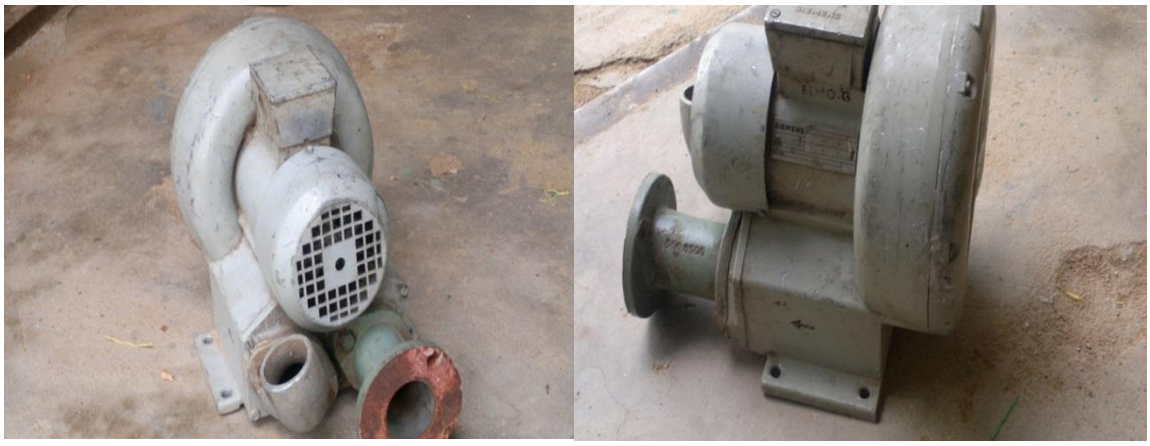


Plate XVI: The Blower



Plate XVII: Charcoal aided ignition



Plate XVIII: Burnt maize cob samples



Plate XIX: Temperature testing using MASTECH multipurpose clamp meter



Plate XX: Annemometer used in air speed measurements



Plate XXI: Assembled Fluidised Bed Combustor



Plate XXII: Gas analyser IMR 1400 used for flue gas analysis

Appendix D

Table 4.1: Measured bed temperature at various time intervals

Time (secs)	Bed Temperature (ºC)
120	37
150	54
250	69
350	82
450	74
500	123
600	153
700	206
850	316
950	324
1050	338
1100	353
1200	397
1300	403
1450	486
1550	506
1650	518
1700	517
1800	530
1900	522
2050	535
2150	545
2250	658
2300	639
2400	763
2500	691
2650	657
2750	665
2850	645
2900	543
3000	763
3100	767
3250	800
3350	427
3450	725
3500	771
3600	639
3700	780

3850	747
3950	779
4050	794
4100	824
4200	832
4300	767
4450	623
4550	831
4650	837
4700	836
4800	823
4900	820
5050	803
5150	806
5250	810
5300	809
5400	806

Table 4.2: Flue gas temperature rise with time

Time (secs)	**Flue gas temp (°C)**
120	14
150	17
250	28
350	44
450	50
500	62
600	84
700	126
850	128
950	135
1050	145
1100	163
1200	186
1300	193
1450	207
1550	208
1650	213
1700	219
1800	215
1900	220
2050	222

APPENDIX E

Re vs Cd relationship

