THE EFFECT OF CHAR PARTICLE SIZE ON THE EFFICIENCY OF SOLID – VAPOR SEPARATION IN A FAST PYROLYSIS CYCLONE SYSTEM

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ABSTRACT

In a fast pyrolysis process for the conversion of biomass into liquid and gas products, the role of the phase separation unit is critical to ensure the efficiency product recovery is high. For the pyrolysis system developed at Fakulti Kejuruteraan Kimia & Sumber Asli (FKKSA) Universiti Malaysia Pahang (UMP), the separation unit is designed with a cyclone separation system. Vapor product from the cyclone will enter condenser system to convert into liquid product. The collection efficiency of a cyclone separator depends on several factors including design parameters, such as dimensions of the cyclone separator, particle density, and operating temperature. The physical properties of fluid, namely the density and viscosity, and operating parameters such as the inlet velocity of the fluid into the cyclone and the outlet conditions also affect the cyclone efficiency. In this work, the effect of the particle size and temperature will be studied in order to get a higher efficiency of the separation process of cyclone system. Manual calculations of the collection efficiency were compared to the result of collection efficiency from CFD-Fluent simulation. It was found that the error is about 3.55%. Result shows that the increase of temperature vapor inside the cyclone system and particle size will decrease the separation of the cyclone system. As the temperature increase the air viscosity and density of the particle will decrease and it will lead to the lower separation efficiency of cyclone. This is same with particle size where separation efficiency decrease as the particle size increase due to the many of incomplete particle and most of the particle are stick to the cyclone wall and not being separated.

ABSTRAK

Di dalam proses 'Fast Pyrolysis' untuk pengitaran semula tenaga kepada produk cecair dan gas, di mana fungsi fasa pemisahan unit adalah sangat kritikal untuk memastikan kecekapan produk adalah tinggi. Oleh itu, satu system 'pyrolysis' telah dibangunkan di dalam Fakulti Kejuruteraan Kimia & Sumber Asli (FKKSA) Universiti Malaysia Pahang (UMP), unit pemisahan telah dibina dengan sistem pengumpulan pemisah siklon. Kemudian gas yang telah diasingkan akan memasuki system penyejukkan untuk ditukarkan kepada produk cecair. Kecekapan pengumpulan pemisah siklon bergantung kepada beberapa factor seperti dimensinya, ketumpatan partikel dan suhu beroperasi. Sifat fizikal bendalir seperti ketumpatan dan kelikatan bendalir serta parameter operasi misalnya halaju masukan bendalir juga mempengaruhi kecekapan siklon. Di dalam kerja ini, factor seperti saiz partikel dan suhu operasi akan dipelajari untuk mendapatkan kecekapan pemisahan yang tinggi. Untuk *cyclone* pemisah yang telah direka bentuk dengan semua pengiraan yang berkaitan dan peratus kecekapan pemisahan adalah dalam 70% hngga 73%. Kemudian, pengiraan manual tentang kecekapan pemisahan telah dibandingkan dengan pengiraan CFD-Fluent untuk mengesahkan pengiraan manual tersebut dengan ralat sebanyak 3.55%. Kepeutusan menunjukkan dimana peningkatan suhu di dalam sistem pengumpulan pemisah siklon dan saiz partikel akan mengurangkan kecekapan sistem pengumpulan pemisah siklon. Di mana, apabila suhu dan saiz sampel meningkat kecekapan pemisahan berkurang. Apabila suhu meningkap kepekatan udara juga menigkat dan ketumpatan saiz berkurangan dan ini membawa kepada pengurangan kecekapan pemisahan *cyclone* pemisah. Situasi ini adalah sama dengan saiz sampel dimana kecekapan pemisahan berkurang apabila saiz sampel semakin menigkat disebabkan oleh banyak sample yang melekat di dinding cyclone pemisah dan saiz sample yang tidak lengkap untuk terpisah.

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g	-	gram
s	-	second
min	-	minute
^0C	-	degree celcius
Mol/g	-	mole per gram
Wt%	-	weight percentage
mm	-	millimeter
Mg/l	-	milligram per liter
Kcal	-	kilo calori
mL/min	-	milliliter per minute
in	-	inch
bar	-	pressure
µL	-	microlitre
LHV	-	low heating value
HHV	-	high heating value
Mj/Kg	-	mega joule per kilogram
Dp	-	diameter particle
L	-	length
G	-	Wall friction factor

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the quest for renewable energy from biomass, the pyrolysis process can be employed to produce the gas and liquid fuel product. Where, the gas and liquid product can be produced from the separation process using a cyclone system. However, the efficiency of the product recovery is depends on the separation process. Cyclones are among the oldest types of industrial particulate control equipment and air sampling device. The primary advantages of cyclones are economy and simplicity in construction and design. Since there are no moving parts, cyclones are relatively maintenance-free. By using suitable materials and methods of construction, cyclones can be adapted for use in extreme operating conditions: high temperature, high pressure, and corrosive gases. Cyclone collection efficiencies can reach 99% for particles bigger than 5 μm and can be operated at very high dust loading. Applications of cyclone in industry include the removal of saw dust, as a spray dryer, and for catalyst recovery in fluid bed reactor.

The performance of a cyclone separator depends on several factors including design parameters, such as scaling and dimensions of the cyclone separator, and particle parameters such as its density and shape factor. The physical properties of fluid such as density and viscosity, and operating parameters such as the inlet velocity of the fluid into the cyclone and the outlet conditions also affect the cyclone performance. An accurate prediction of cyclone efficiency is very important because an inaccurate prediction may result in an inefficient design of cyclone separators.

There are a number of different forms of cyclone, but the reverse flow cyclone is the most common design used industrially. The cyclone consists of four main parts that is the inlet, the separation chamber, the dust chamber, and the vortex finder. Tangential inlets are preferred for the separation of solid particles from gases.

1.2 Problem Statement

From the previous thesis (M. Hafizi, 2009), the main purpose of the research is to analyze the effect of the particle size to the bio-oil production. Particle size, residence time and temperature are the three parameter of pyrolysis. The effect of particle size to the bio-oil production had being tested by analyzing the yield of the bio-oil product that being pyrolized using the electrical furnace for the laboratory scale.

There are various effects which lead to the lower cyclone performance such as particle size, temperature, inlet velocity and particle density. Particle size is one of the important factors that will lead to lower separation efficiency if the particle size of the inlet product is too small or too large. Where most particles will flow-up to the upper outlet of the cyclone system if the particle sizes of inlet product are too small and the particle will stuck and collected at the bottom outlet of the cyclone system if the particle size of the inlet product are too large. Not only that, the increase of temperature also will lead to the dramatically decrease of separation efficiency.

Inlet gas velocity is an important factor for cyclone sizing in order to get good separation efficiency. Inlet velocity is a result of driving the inlet flow rate to the cyclone inlet area. At high flow rate the inlet velocity becomes larger thus, the tangential velocity also increase. The tangential velocity in the cyclonic system must be in range 1.5 to 2.5 larger than the inlet velocity in order to get a good separation efficiency of separation process.

1.3 Objectives Research

The study was mainly concerned on separation efficiency of the cyclone system. Thus, in order to coincide with the problem identified the following objectives have been formulated:

1. To study on the effect of char particle size on the separation efficiency of solid-vapor separation in a fast pyrolysis cyclone system.

2. To study on the effect of the temperature vapor inside the cyclone system on the separation efficiency of solid-vapor separation in a fast pyrolysis cyclone system.

1.4 Scope of Works

On this research, the scope has been focused on designing the cyclone separation system. In order to design the cyclone there are calculation should being done that is area of the cyclone, pressure drop, tangential velocity, wall velocity and efficiency of the cyclone and all this calculation was being made after considering all the affect that will lead to the decreasing the separation efficiency of the cyclone.

CHAPTER 2

LITERATURE REVIEW

Renewable energy is of growing importance in satisfying environmental concerns over fossil fuel usage. Wood and other forms of biomass are one of the main renewable energy resources available. In contrast to other renewable, that give heat and power, biomass represents the only source of liquid, solid and gaseous fuels. Wood and other biomass can be treated in a number of different ways to provide such fuels. In general such methods are divided into biological (anaerobic digestion and fermentation) and thermal. The role of thermal conversion is to provide a technology option for improving the economic viability by converting the faction of the biomass resources that are not amenable to biochemical conversion technologies into biofuel

2.1 Pyrolysis Process

The pyrolysis of biomass is a thermal treatment which results in the production of char, liquid and gaseous product. Pyrolysis, can be simply put as the breaking apart of chemical bond by the use of thermal energy and this process also is mainly carried out in the absence of oxygen. The fragmentation that occurs during pyrolysis is analogous to the process that occurs during the production of mass spectrum. Then, the energy is put into the system as a result the molecules break apart into stable fragments. There were three types of pyrolysis that is conventional pyrolysis (slow pyrolysis), flash pyrolysis and fast pyrolysis.

For the slow pyrolysis processor conventional pyrolysis is a traditionally been used for the production of charcoal and is been defined as the pyrolysis which occurs under slow heating rate. This conditions permits the production of solid, liquid, and gaseous pyrolysis products in significant propotions.. For the flash pyrolysis this pyrolysis is carried out by a fluidized bed of solid as heat carrier. This process is capable of high liquid yields that are up to 40 to 60 percent and it is entirely energy self-sufficient. Lastly, fast pyrolysis is a high temperature in which biomass is rapidly heated in the absence of oxygen. Fast pyrolysis is a thermal decomposition process that occurs at high temperature ranges with a high transfer rate to the biomass particles and a short hot vapour residence time.

Pyrolysis type	Residence time	Heating rate (°C/s)	Operating temperature (°C)
Conventional	5-30 min	0.1-1	400-600
Fast	1-2 sec	10-200	400-600
Flash	< 1	>1000	450-600

Table 2.1: Types of pyrolysis technology (source: Bridgewater and Bridge,1991).

The pyrolysis of biomass may be endothermic or exothermic, depending on the temperature of the reactant. For most biomass containing highly oxygenated hemicellulosics and cellulosics as the major component, pyrolysis is endothermic at temperature below about 400 to 450°C and exothermic at higher temperature. The pyrolysis temperature should be high enough to generate the requisite hydrogen for reduction of the carbon dioxide. (Klass, 1998)

2.2 Fast pyrolysis

Fast pyrolysis is a high temperature process in which biomass is rapidly heated in the absence of oxygen. As a result it decomposes to generate mostly vapours and aerosols and some charcoal. After cooling and condensation, a dark brown mobile liquid is formed which has a heating value about half that of conventional fuel oil. While it is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process which is carefully controlled to give high yields of liquid. (Bridgewater, 1999)

Fast pyrolysis occurs in a time of few seconds or less. Therefore, not only chemical reaction kinetics but also heat and mass transfer processes, as well as phase transition phenomena, play important roles. The critical issue is to bring the reacting biomass particle to the optimum process temperature and minimize its exposure to the intermediate [lower] temperatures that favour formation of charcoal. One way this objective can be achieved is by using small particles.

Types	Result	Liquid	Char	Gas
Fast pyrolysis	moderate temperature, short residence time particularly vapour	75%	12%	13%
Carbonisation	low temperature, very long residence time	30%	35%	35%
Gasification	high temperature, long residence times	5%	10%	85%

Table 2.2: Typical product yields [dry wood basis] obtained by different modes of pyrolysis of wood (source: Bridgewater and Bridge,1991)

The essential features of a fast pyrolysis process for producing liquids are it must have a very high heating and heat transfer rates that usually requires a finely ground biomass feed. The reaction temperature of the fast pyrolysis is being careful controlled that is about 500°C and vapor phase temperature of 400 to 450°C. For the resident time features fast pyrolysis gives short vapor residence times typically less than 2 seconds and the rapid cooling of the pyrolysis vapor is to give bio-oil product. The typical yields for fast pyrolysis is oil (60 -70%), char (12-15%), and gas (13-25%).

2.3 Fast pyrolysis system

A fast pyrolysis system consists of an integrated series of operations starting with a roughly prepared feedstock such as whole tree chips from short rotation coppice, energy crops such as miscanthus or sorghum, or agricultural residues such as straw. A conceptual fluidized bed fast pyrolysis system is shown in Fig. 2 indicating the main components that are discussed below.

2.3.1 Reception and storage

It is always necessary to provide for reception and handling and some storage of feed material. Low capacity systems of up to around 3 t/h feed can consist of a concrete pad for tipping delivered feed and a front end loader to move it between steps. As plants get larger, increasingly sophisticated reception, storage and handling systems will be required analogous to those employed in pulp and paper mills. This will include a weighbridge, tipping units, conveyors, bunker storage and reclamation.

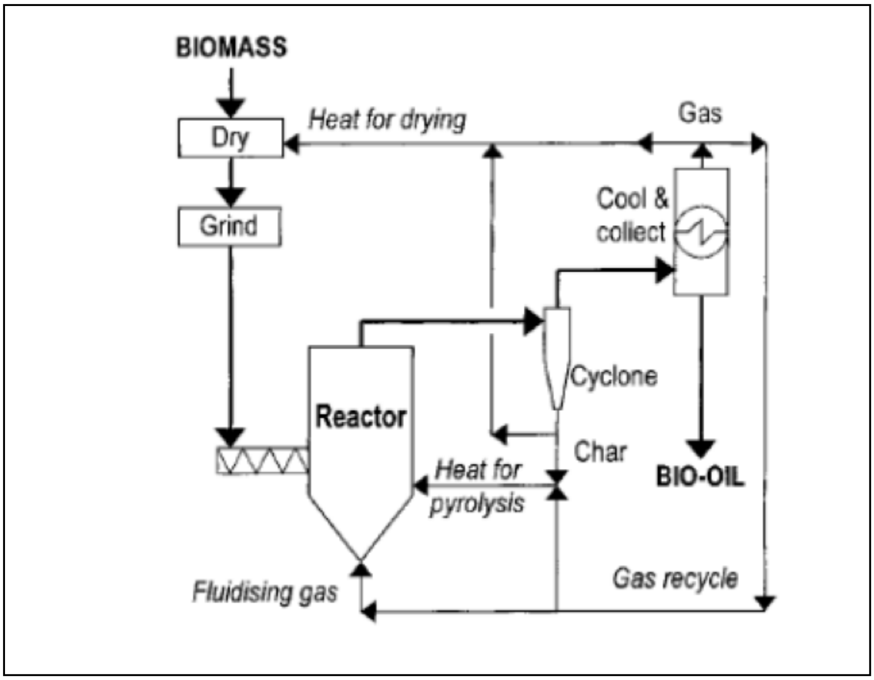

Figure 2.1: Fast pyrolysis process principles**. (**Bridgewater, 1999)

2.3.2 Feed drying

Unless a naturally dry material such as straw is available, drying is usually essential as all the feed water is included in the liquid product. Low grade process heat would usually be employed, for example flue gases from by-product gas or char combustion using a rotary kiln. A detailed review of biomass drying has been prepared.

2.3.3 Grinding

Particles have to be very small to full the requirements of rapid heating and to achieve high liquid yields. Feed specifications range from less than 200 mm for the rotating cone reactor to less than 2 mm for fluid beds and less than 6 mm for transported or circulating fluid beds. Ablative reactors can utilize whole tree chips as the mechanism of heat transfer is different. Size reduction becomes increasingly expensive as size reduces and reactors using larger particles have an advantage in this respect.

2.3.4 Reactor Configuration

A wide range of reactor configurations have been investigated that show considerable diversity and innovation in meeting the basic requirements of fast pyrolysis. The `best' method is not yet established with most processes giving between 65±75% liquids based on dry wood input. The essential features of a fast pyrolysis reactor are very high heating and heat transfer rates; moderate and carefully controlled temperature and rapid cooling or quenching of the pyrolysis vapors. Commercial operation is currently only being achieved from a transport or circulation fluid bed system that are used to produce food flavourings. Fluid beds have also been extensively researched and are an ideal R&D tool and have been scaled up to pilot plant size with plans in hand for demonstration in several locations. Substantial developments can be expected in performance and cost reduction in coming years. (A.V. Bridgwater, 2000)

2.3.4.1 Batch reactor

The Batch reactor is the generic term for a type of vessel widely used in the process industries. Its name is something of a misnomer since vessels of this type are used for a variety of process operations such as solids dissolution, product mixing, chemical reactions, batch distillation, crystallization, liquid/liquid extraction and polymerization. In some cases, they are not referred to as reactors but have a name which reflects the role they perform (such as crystallizer, or bio reactor).

In a batch reactor the reactant mixture is added to the reactor. The reactor is a cylindrical chamber in which reaction takes place. In this reactor a fixed amount of reactant mixture is added to the reactor and allows for a particular time period for stirring inside the reactor. The stirring operation is done by a mechanical agitator. While the reaction is going on inside the reaction chamber ame concentration is maintained inside it. After some time the product is removed from the tank.

A typical batch reactor consists of a tank with an agitator and integral heating/cooling system. These vessels may vary in size from less than 1 litre to more than 15,000 litres. They are usually fabricated in steel, stainless steel, glass lined steel, glass or exotic alloy. Liquids and solids are usually charged via connections in the top cover of the reactor. Vapors and gases also discharge through connections in the top. Liquids are usually discharged out of the bottom.

2.3.4.2 Continuous reactor

As their name implies, continuous reactors (alternatively referred to as flow reactors) carry material as a flowing stream. Reactants are continuously fed into the reactor and emerge as continuous stream of product. Continuous reactors are used for a wide variety of chemical and biological processes within the food, chemical and pharmaceutical industries. A survey of the continuous reactor market will throw up a daunting variety of shapes and types of machine. Beneath this variation however lie a relatively small number of key design features which determine the capabilities of the reactor. When classifying continuous reactors, it can be more helpful to look at these design features rather than the whole system.

2.3.5 Char and ash separation

Some fine char is inevitably carried over from cyclones. Almost all of the ash in the biomass is retained in the char, so successful char removal gives successful ash removal. Char separation, however, is difficult and may not be necessary for all applications. Char contributes to secondary cracking by catalyzing secondary cracking in the vapor phase. Rapid and complete char separation is therefore desirable.

2.3.6 Condenser

In systems involving heat transfer, a condenser is a device or unit used to condense a substance from its gaseous to its liquid state, typically by cooling it. In so doing, the latent heat is given up by the substance, and will transfer to the condenser coolant. Condensers are typically heat exchangers which have various designs and come in many sizes ranging from rather small (hand-held) to very large industrial-scale units used in plant processes. For example, a refrigerator uses a condenser to get rid of heat extracted from the interior of the unit to the outside air. Condensers are used in air conditioning, industrial chemical processes such as distillation, steam power plants and other heat-exchange systems. Use of cooling water or surrounding air as the coolant is common in many condensers.

In chemistry, a condenser is the apparatus which cools hot vapors, causing them to condense into a liquid. See "Condenser (laboratory)" for laboratory-scale condensers, as opposed to industrial-scale condensers. Examples include the Liebig condenser, Graham condenser, and Allihn condenser. This is not to be confused with a condensation reaction which links two fragments into a single molecule by an addition reaction and an elimination reaction.

A surface condenser is an example of such a heat-exchange system. It is a shell and tube heat exchanger installed at the outlet of every steam turbine in thermal power stations. Commonly, the cooling water flows through the tube side and the steam enters the shell side where the condensation occurs on the outside of the heat transfer tubes. The condensate drips down and collects at the bottom, often in a built-in pan called a hotwell. The shell side often operates at a vacuum or partial vacuum, often produced by attached air ejectors.

2.3.7 Liquid collection

The collection of liquids has long been a major difficulty in the operation of fast pyrolysis processes due to the nature of the liquid product which is mostly in the form of aerosols rather than a true vapor. Quenching, i.e. contact with cooled liquid is effective but careful design and temperature control is needed to avoid blockage from differential condensation of heavy ends. Light ends collection is important in reducing liquid viscosity. Electrostatic precipitation has been shown to be very effective in recovering the aerosols. In fluid bed type systems the vapor/aerosol concentration can be very low, further increasing the difficulty of product separation due to the low vapor pressure.

2.4 Cyclone

Cyclone is one of the most widely used separators, which rely on centrifugal force to separate particles from a gas stream. They are used basically for pollution control (Rob Thorn, 1998) where high efficiencies are required to meet the stringent regulations and as particulate size classifiers where aerodynamics classification of particle size plays a vital role in the production process. Cyclone are inexpensive to construct, cost-effective to operate and adaptable to a wide range of operating condition such as high temperature and pressure (Chi-Jen Chen et al., 2001). Cyclone can typically achieve moderate to high efficiency for particle large than about 5 μm in diameter and can operate at very high loading.

Various sizes of cyclone are available to suit different requirement. Usually, large scale cyclones are used to remove particles for industrial control, while small scaled cyclones are used to separate from particles for ambient and source sampling. A cyclone are consists of a gas inlet, cyclone body, vortex finder and particle exit at the bottom and is attached to a dust collector. The geometrical dimensions of the most common cyclone design with tangential inlet (Maroulis et al., 1995) are shown is Figure 2.7 where Dc = body diameter, De = gas outlet diameter, a = inlet height, b = inlet width, H = cyclone height, h = cylinder height, S = gas outlet duct length and B = cone bottom opening.

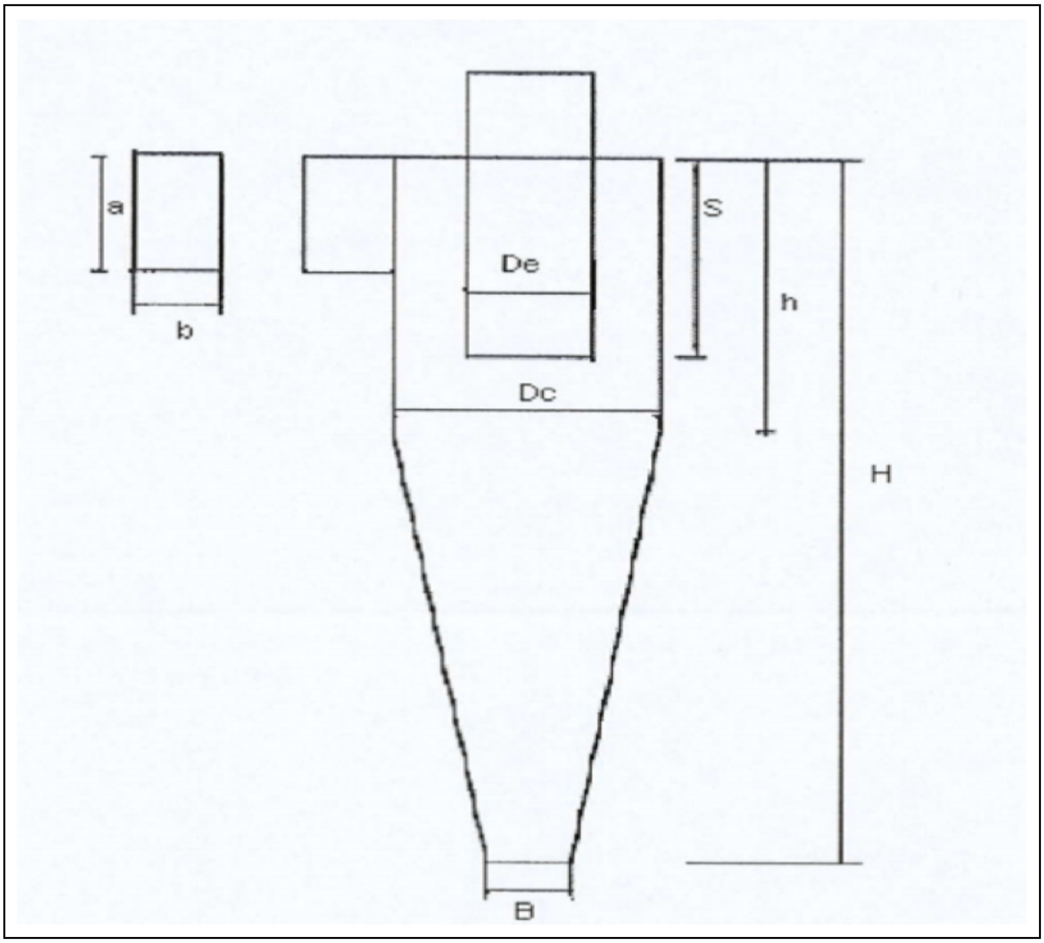

Figure 2.2: Schematic diagram of cyclone illustrating geometrical dimensions (Maroulis et al., 1995)

A cyclone is a mechanism that used to separate solid material from gases or liquid (Rob Thorn, 1998). All cyclone separators are based on centrifugal separation of particles in an induced vortex within the gas flow (Andrew, 2000). When the fluid, with the dispersed particles in suspension is injected tangentially through the inlet pipe into the cyclone, then due to the specially designed geometrical features of the cyclone, the fluid acquires a spiraling motion (Ma et al., 2000), which first descends along an outer spiral and then ascends through an inner spiral. When the vertical motion, spiraling reaches the conical section, the centrifugal forces can be several times greater than gravity contributing to particle separation (Solero et., 2000).

The dispersed particles, which have a different density to their carrying fluid are driven by the centrifugal acceleration to move perpendicular to the fluid motion. The relatively larger particles possess a larger inertia and therefore acquire a stronger centrifugal acceleration. When the centrifugal acceleration is sufficiently large, then the particles drift towards the sidewall and finally they are separated through the apex of the cyclone.

2.4.1 Cyclone Types

There are many types of cyclone that are used in industries and some of the types of the cyclone are conventional cyclone, high efficiency cyclone, multi cyclone and wet or irrigated cyclone.

2.4.1.1 Conventional Cyclone

The most commonly used cyclone is the medium efficiency, high gas throughput (conventional) cyclone. Cyclone of this type is used primarily to collect coarse particles when collection efficiency and space requirements are not a major consideration. Collection efficiency for conventional cyclone on 10 micron particles is generally 50 to 80 percent.

2.4.1.2 High efficiency cyclone

When high collection efficiency (80 – 95 percent) is a primary consideration in cyclone selection, the high efficiency single cyclone is commonly used. A unit of this type is usually smaller in diameter than a conventional cyclone, providing a greater separating force for the same inlet migrate before reaching the cyclone walls. These units maybe used singly or arranged in parallel or series. When arranged in parallel they have the advantages of handling larger gas volume at increase efficiency for the same power consumption of a conventional unit. In parallel they also have the ability to reduce headroom space requirements below that of a single cyclone handling the same gas volume by varying the number of units in operations.

2.4.1.3 Multicyclone

When very large gas volume must be handle and high collection efficiency are needed a multiple of small diameter cyclone are usually nested together to form a multicyclone. A unit of this types consists of a large number of elements joined together with a common inlet plenum, a common outlet plenum and a common duct hopper. The multicyclone elements are usually characterized by having a small diameter and having axial type inlet vanes. Their performance maybe hampered by a poor gas distribution to each elements, fouling of the small diameter dust outlet, and air leakage or back flow from the dust bin into the cyclone. These problems are offset by the advantage of the multicyclone, increased collection efficiency over the single high efficiency cyclone unit. Problems can be reduced with proper plenum and dust discharge design.

2.4.1.4 Wet or irrigated cyclone

Cyclone maybe operated wet in order to improve efficiency and prevent wall buildup or fouling. Efficiency is higher for this type of operation because dust particles, once separated, are trapped in a liquid film on the cyclone walls and are not easily re-entrained. Water is usually spared at the rate of 5 to 15 gallons per 1000 cubic feet of